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DISSERTATION

THE EFFECTIVENESS OF DRONE USE UNDER CONDITIONS OF INCOMPLETE INFORMATION AND MULTICONNECTIVITY OF CONSTRAINTS SET FOR FLIGHTS

Field of Study: J6 “Air transport”
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The thesis contains the results of the author's own research. The ideas, results and texts of other authors are used and referenced to the appropriate source.
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АНОТАЦІЯ

Лі Хаоян. Ефективність застосування дронів в умовах неповноти інформації і багатозв’язності множини обмежень для польотів. – Кваліфікаційна наукова праця на правах рукопису.

Дисертація на здобуття наукового ступеня доктора філософії за спеціальністю J6 – Авіаційний транспорт, спеціалізація – Авіаційний транспорт – «Державний університет «Київський авіаційний інститут» Міністерства освіти і науки України, м. Київ, 2026р.

У дисертації представлено комплексне дослідження ієрархічно пов’язаних задач оцінки ефективності безпілотних авіаціонних систем (БАС). Центральне місце в дисертації займає вивчення ролі, яку дрони відіграють у підвищенні ефективності вантажних перевезень. Зокрема, як дрони можуть вирішувати логістичні проблеми при доставці товарів в умовах неповної інформації, повязаних як з нормативними , так і системними обмеженнями. Завдяки детальному аналізу та застосуванню розроблених алгоритмів, дослідження демонструє, як можна значно покращити оптимізацію маршрутів та управління авіаційним парком , тим самим зменшивши експлуатаційні витрати та вплив на навколишнє середовище.

Крім того, в дисертації ретельно досліджуються методологічні аспекти оцінки ефективності безпілотників з використанням статистичних моделей, алгоритмів машинного навчання та моделювання за методом Монте-Карло. Ці інструменти допомагають зрозуміти і спрогнозувати ефективність безпілотників у різноманітних і невизначених умовах, сприяючи кращому плануванню та прийняттю рішень.

Кінцевою метою цього дослідження є висвітлення трансформаційного потенціалу технології БПЛА в сучасній логістиці та надання ефективних рішень для вирішення проблем, пов'язаних із застосуванням дронів у комерційних операціях. Пропонуючи детальні тематичні дослідження та емпіричні дані,

дисертація не тільки підкреслює практичні переваги безпілотників, але й робить свій внесок у поточні дискусії щодо їхньої нормативно-правової та операційної бази, прокладаючи шлях для майбутніх досягнень у галузі безпілотних технологій.

У вступі обґрунтовується актуальність дисертації, формулюється мета та основні завдання дослідження, дається інформація про зв'язок дослідження з науковими програмами та темами. Крім того, виділено наукову новизну та практичну значущість дослідження, відзначено внесок претендента у спільних публікаціях, викладено апробацію результатів дисертаційної роботи, наведено структуру та обсяг дисертації.

У першому розділі представлено аналіз розвитку та застосування безпілотних літальних апаратів (БПЛА або дронів), висвітлено потреба у високій мобільності та автономності. Також підкреслюється важливість розуміння та дотримання нормативно-правової бази щодо БПЛА таких організацій, як ICAO, FAA, EASA, та CAAC, а також детально досліджуються відмінності в критеріях класифікації БПЛА в різних авіаційних організаціях.

Однією з суттєвих відмінностей є підхід FAA, який в першу чергу зосереджений на класифікації дронів на основі їхньої ваги, з чітким поділом на малі дрони вагою до 55 фунтів і більші, вагою понад 55 фунтів. Крім того, FAA враховує мету використання дронів, розрізняючи комерційні, дослідницькі та рекреаційні програми. На відміну від них, EASA, ICAO та CAAC застосовують більш комплексний підхід, враховуючи, окрім ваги, експлуатаційні елементи. Вони враховують висоту польоту, обмеження швидкості, роботу за межами прямої видимості, рівень людського нагляду та географічні обмеження для визначення відповідних класифікацій.

Ця розбіжність значною мірою є відображенням регіональних відмінностей, зокрема, густонаселеного і складного повітряного простору різних континентів світу. Такі фактори, як щільність населення, конфліктний повітряний рух і складні транспортні потоки, вимагають спеціальних правил використання безпілотників в Європі та Азії, щоб зменшити ризики зіткнень, які менш поширені в більш відкритих просторах Америки.

Як наслідок, система класифікації EASA є найскладнішою і охоплює сім конкретних категорій, які забезпечують точні характеристики, функції та експлуатаційні вимоги, пристосовані до різних вагових категорій дронів. Ці категорії дозволяють проводити індивідуальну сертифікацію типу відповідно до стандартів безпечної інтеграції безпілотників, що охоплюють польоти над населеними пунктами, скупченням людей, операції за межами прямої видимості, транспортування важкого вантажу та висотні місії.

У другому розділі детально досліджується трансформаційний вплив дронів на логістику і системи доставки, з особливим акцентом на алгоритми і технології, які доповнюють ці операції, визначається роль дронів у доставці і транспортуванні товарів, робота над оптимізацією ланцюга поставок і зниженням витрат, зокрема, як приклад, використано розподіл ймовірностей, що може бути застосовано до систем з великим числом можливих подій, кожне з яких рідко зустрічається. Використання такого розподіл ймовірностей для вирішення транспортних проблем, а також алгоритми, що застосовуються для вирішення складних завдань оцінки ефективності обгрунтовується тим, що транспортні задачі практично не можуть бути вирішені традиційними методами, особливо в динамічному і невизначеному середовищі, враховуючи дотримання необхідного рівня безпеки польотів.

Доведено, що розв’язання багатовимірних задач, пов’язаних з оцінкою ефетивності, за допомогою простого методу перебору на рівномірній сітці вимагає значної кількості ітерацій і, фактично, можливо лише при невеликих значеннях N та низькій точності рішення. Застосування економних послідовних методів, які створюють нерівномірну сітку, вимагає розв’язання на кожній ітерації додаткової багатоекстремальної задачі, яку також потрібно розв’язувати шляхом методів пошуку (наприклад, метод перебору), що різко збільшує обчислювальну складність ітерації.

Тут аналізується вплив дронів на логістику і транспорт, висвітлюється їхня роль у зміні динаміки ланцюгів поставок. Задача формулюється як двоетапна з умовами стохастичної невизначеності. На першому етапі, до того, як будуть відомі заявки на спеціальні рейси, БПЛА (наприклад, мультироторні або з фіксованим крилом) кожного типу розподіляються між маршрутами й визначається кількість польотів кожного типу по кожному маршруту. На другому етапі після встановлення реалізації випадкових параметрів умов задачі здійснюється перепризначення літальних апаратів (ЛА) з маршруту на маршрут.

В даному розділі зроблено наголос на операційну ефективність, яку забезпечують безпілотники, особливо з погляду скорочення витрат і часу на доставку «останньої милі». Тематичні дослідження різних компаній, показують, що інтеграція дронів у логістичні системи може знизити витрати на доставку до 50% і скоротити час доставки в середньому на 25%. У цьому розділі також досліджується вплив доставки дронами на навколишнє середовище і наводяться дані про те, як дрони можуть допомогти скоротити викиди вуглекислого газу при доставці в містах на 40%, зменшивши залежність від традиційних транспортних засобів доставки.

У третьому розділі розглядаються методи і математичні моделі, які використовуються для оцінки і підвищення ефективності вантажних перевезень за допомогою БПЛА, особливо в ситуаціях, коли інформація є неповною. У ньому досліджуються статистичні методи кількісної оцінки ефективності безпілотників з акцентом на таких ключових показниках, як надійність доставки, економічна ефективність та операційна гнучкість.

Концепція оцінки ефективності UAS базується на врахуванні соціального, економічного та функціонального видів ефекту. Запропоновано та розроблено два підходи до оцінки ефективності UAS: при неявних та явних системних зв'язках засобів з системою більш високого порядку. Оцінка ефективності при неявних зв'язках засобів UAS базується на формуванні результуючого показника якості та зведенні багатокритеріальної задачі до скалярної. Розроблений алгоритм вибору пріоритетного варіанта засобу.

Систематизовано підпроблеми, які виникають при формулюванні цілей, критеріїв та оцінки ефективності при явних системних зв'язках. Доведено, що оцінка ефективності системи UAS пов’язана з проблемою управління ефективністю, яка залежить, в свою чергу, від керованості ситуацій. Сформульовано принципи визначення функціонального ефекту при управлінні динамічними об’єктами. Розроблено основи теорії ситуаційного аналізу повітряної обстановки.

Удосконалені статистичні моделі використовуються для імітації операційних сценаріїв, допомагаючи в подальшому компаніям зрозуміти потенційні можливі результати і підготуватися до них більш ефективно. Наприклад, моделювання за методом Монте-Карло спрогнозувало вплив різних погодних умов на роботу безпілотників, показавши, що належне планування може пом'якшити до 30 відсотків негативних наслідків.

У цьому розділі також пропонується інтеграція алгоритма машинного навчання в операції БПЛА з використанням дерев рішень і байєсівських мереж для прийняття оперативних рішень в режимі реального часу. Ці моделі допомагають впоратися зі складністю динамічних середовищ, надаючи ймовірнісні результати різних рішень, що є важливим для підтримки високого рівня надійності послуг в умовах невизначеності. Представлено приклад, в якій байєсовській мережі були використані для динамічного коригування маршрутів і корисного навантаження безпілотників, що дозволило підвищити загальну операційну ефективність на 35%. Реальний приклад показує, як ці прогнозні моделі можуть підвищити експлуатаційну надійність БПЛА в комерційних службах доставки, зменшуючи час простою і підвищуючи швидкість реагування на зміни навколишнього середовища.

<u>У четвертому розділі</u> визначені математичні методи розв’язання сформульованих задач навігаційного забезпечення вантажних дронів. Створено модифікацію цих методів з урахуванням специфічної особливості задач великої розмірності з суттєвою нелінійністю змінних та складним характером обмежень на фазові координати. Розроблено обчислювальні алгоритми розв’язання задач:

– розрахунку системних обмежень системи посадки, які вносяться літаком як керованим динамічним об’єктом (пошук глобального екстремуму з врахуванням обмежень на змінні у вигляді рівностей та нерівностей);

– прогнозуючої оцінки стохастичної послідовності результатів (ймовірнісний аналіз дерева секвенції множини предикатів польотної ситуації та її оцінки);

– побудови областей допустимих значень параметрів навігаційного забезпечення (відслідковування меж замкнених множин методом прогноз-корекції, з коригуванням за градієнтом порушення межі);

– комбінованого дослідження характеристик навігаційного забезпечення (спільне використання результатів аналітичного розв’язання спрощених задач навігації та моделювання за методом імітаційного моделювання).

Доведена необхідність забезпечення надійного прямого зв’язку між дронами, які літають автономно, щоб запобігти зіткненням і забезпечити взаємодію всіх компонентів Інтегрованої Мережі Космос-Повітря-Земля (ІМКПЗ). Недостатня швидкість передачі даних в будь-якому з каналів може істотно погіршити продуктивність всієї інтегрованої мережі і негативно вплинути на ефективність БАС.

Промодельована система штучного інтелекту AI з хмарною структурою та можливістю змінювати затримку та ймовірність втрати пакетів даних. Отримані залежності втрат від розміру повідомлень і швидкості передачі даних, залежності середнього навантаження для висхідного каналу та часу проходження пакета від розміру транзакцій, а також залежності BER від середнього навантаження дозволяють зробити практичні рекомендації щодо вибору необхідних режимів передачі даних в каналах зв’язку вантажних БАС.

Проведено детальне дослідження використання алгоритмів для оптимізації складних логістичних задач, таких як управління авіапарком і планування маршрутів. Ці алгоритми допомагають знаходити оптимальні рішення, імітуючи природний еволюційний процес, що особливо ефективно в умовах, коли операційні параметри часто змінюються. Доведено, що застосування таких алгоритмів збільшує швидкість доставки на 20% і зменшує операційні витрати на 15%.

Також досліджується застосування динамічного програмування для оптимізації послідовного процесу прийняття рішень в операціях БПЛА. Метод використовується для визначення найкращого способу дій для кожного етапу маршруту доставки, враховуючи поточний стан і приймаючи рішення, які призведуть до найкращого загального результату. Такий підхід дає можливість компанії збільшити пропускну спроможність на 25% при збереженні високого рівня безпеки польотів.

Наукова новизна результатів, отриманих у ході дослідження, полягає у наступному:

1. Запропонована модель управління та планування польоту

Розроблено інноваційну модель управління та планування польоту, особливо в контексті інтеграції пілотованих та безпілотних літальних апаратів, що працюють разом в єдиному повітряному просторі, на відміну від гнучкого та сегрегованого повітряного простору (в термінах ICAO) . Модель враховує численні випадкові величини, які впливають на якість польоту, такі як час перебування літального апарату в конкретній розрахунковій точці та помилки у виконанні команд, на які впливають зовнішні збурення. В результаті модель здатна більш точно прогнозувати маршрути і час польоту. Для оптимізації затримок польотів і забезпечення безпеки в моделі використовується підхід лінійного програмування, який вирішує задачу оптимізації випадкових затримок і інтервалів безпеки. У цій моделі час посадки (або зльоту) кожного повітряного судна прогнозується як випадкова величина з відомою функцією розподілу, яка, в свою чергу, розраховує час затримки кожного повітряного судна в контрольованій зоні для забезпечення ймовірності дотримання безпечного інтервалу.

2. Розвинуті концептуальні засади і запропонована методи оцінки ефективності БАС

В частині вимірювання ефективності в дисертації запропоновано нові методи оцінки ефективності БАС в умовах неповноти інформації та наявності неявних і явних зв'язків системи. Це передбачає побудову узагальненої метрики ефективності, яка поєднує в собі множину факторів, та враховує стан повітряної обстановки, якість експлуатації та ефективність, з метою всебічної оцінки ефективності БПЛА. Зокрема, в роботі розроблено методику оцінки ефективності БАС в аеронавігаційних системах, яка не тільки охоплює оцінку показників ефективності, але й включає порівняльний аналіз змодельованих і виміряних даних. Крім того, автор пропонує новий підхід до оцінки неявних та явних зв'язків системи, яка здатна забезпечити достовірне вимірювання ефективності в різних умовах експлуатації. Розроблений метод оцінки ефективності БАС представлений категорією дії при діяльності системи на певному інтервалі часу, яка відображає відповідність отриманого результату вкладеним ресурсам.

Запропоновано та розроблено два підходи до оцінки ефективності UAS: при неявних та явних системних зв'язках засобів з системою більш високого порядку. Оцінка ефективності при неявних зв'язках засобів UAS базується на формуванні результуючого показника якості та зведенні багатокритеріальної задачі до скалярної. Розроблено оригінальний алгоритм вибору пріоритетного варіанта засобу.

Систематизовано підпроблеми, які виникають при формулюванні цілей, критеріїв та оцінки ефективності при явних системних зв'язках. Доведено, що оцінка ефективності системи UAS пов'язана з проблемою управління ефективністю, яка залежить, в свою чергу, від керованості ситуацій. Концепція оцінки ефективності UAS базується на врахуванні соціального, економічного та функціонального видів ефекту. Так, наприклад, дрони можуть допомогти скоротити викиди вуглекислого газу при доставці в містах на 40%, зменшивши залежність від традиційних транспортних засобів доставки.

3. Розробка оптимізаційної моделі БАС в ланцюгу поставок

З метою оптимізації операцій ланцюга поставок та зменшення витрат у статті детально проаналізовано роль дронів у транспортуванні вантажів на «останній милі». Пропонується модель оптимізації ланцюга поставок, яка враховує такі фактори, як швидкість транспортування, вибір маршруту і транспортні витрати дронів для досягнення загальної оптимізації ланцюга поставок. Завдяки оптимізаційній моделі БАС можуть значно скоротити час і вартість транспортування та підвищити ефективність перевезень вантажів. Використано аналіз витрат і вигод для оцінки економічної ефективності БАС в різних транспортних сценаріях. Цей аналіз допомагає визначити оптимальну стратегію використання БПЛА, яка максимізує економічні вигоди, а також забезпечує ефективне виконання транспортних завдань при дотримані допустимого рівня безпеки польотів.

4. Адаптована модель стохастичного планування польотів БАС

Запропонована в дисертації двоетапна модель стохастичного планування спрямована на вирішення проблеми перерозподілу повітряних суден в умовах невизначеності та реального часу для спеціальних потреб використання БАС. На першому етапі модель визначає кількість льотних годин, виділених для кожного типу літаків на кожному маршруті, і ці розподіли базуються на відомому попиті та льотних ресурсах. На другому етапі, коли фактично виникає особливий попит на перевезення, модель перерозподіляє БПЛА з одного маршруту на інший на основі реалізації стохастичних параметрів, щоб задовольнити новий попит на перевезення. Адаптована модель використовує підхід цілочисельного лінійного програмування, щоб гарантувати, що час польоту і потреба у перевезенні вантажу задовольняються на кожному маршруті, мінімізуючи при цьому загальні транспортні витрати. Таким чином, модель здатна гнучко реагувати на зміни попиту на перевезення та підтримувати ефективну роботу транспортної системи.

5. Алгоритмізація задач інформаційної підтримки

В роботі також досягнуто важливих нововведень в алгоритмізації задач інформаційного забезпечення. Запропоновано алгоритм оцінювання послідовностей результатів подій у динамічній системі керування об'єктом, який дозволяє кількісно оцінити вплив різних послідовностей подій на продуктивність системи, і, таким чином, допомагає оптимізувати рішення системи керування. Крім того, в роботі запропоновано кількісний метод побудови областей допустимих значень параметрів інформаційного забезпечення.

Розроблено обчислювальні алгоритми розв'язання задач:

– розрахунку системних обмежень системи посадки, які вносяться літаком як керованим динамічним об'єктом (пошук глобального екстремуму з врахуванням обмежень на змінні у вигляді рівностей та нерівностей);

– прогнозуючої оцінки стохастичної послідовності результатів (ймовірнісний аналіз дерева секвенції множини предикатів польотної ситуації та її оцінки);

– побудови областей допустимих значень параметрів навігаційного забезпечення (відслідковування меж замкнених множин методом прогноз-корекції, з коригуванням за градієнтом порушення межі);

– комбінованого дослідження характеристик навігаційного забезпечення (спільне використання результатів аналітичного розв'язання спрощених задач навігації та моделювання за методом імітаційного моделювання).

Такий підхід підвищує експлуатаційну стійкість та адаптивність БПЛА в умовах невизначеності за рахунок визначення області допустимих значень параметрів інформаційного забезпечення за різних умов експлуатації. Ці алгоритми та методи не лише покращують транспортні можливості БПЛА, але й підвищують його адаптивність у складних умовах виконання завдань.

Практична цінність результатів, отриманих у дисертації, полягає у наступному:

1. Підвищення операційної ефективності в логістиці з використанням БАС:

Дослідження показало, що розроблені передові алгоритми маршрутизації, значно підвищують операційну ефективність БПЛА в логістиці.

Завдяки адаптації маршрутів польоту в режимі реального часу у відповідь на зміни навколишнього середовища, ці алгоритми скорочують час доставки та підвищують точність поставок. Практичні випробування, проведені в рамках дослідження, продемонстрували скорочення середнього часу доставки до 30% в міських умовах, що доводить ефективність алгоритмів у підвищенні оперативності систем доставки дронів.

2. Управління ризиками при експлуатації БПЛА:

Практичне застосування методу статистичного моделювання для оцінки ризиків в операціях БАС пропонує значні переваги з точки зору безпеки та надійності. Дослідження підтвердило ефективність такого моделювання для прогнозування і пом'якшення потенційних збоїв або операційних затримок. Для логістичних компаній це означає підвищення надійності та зниження операційних ризиків: дослідження показало, що затримки, пов'язані з інцидентами, зменшилися на 25% порівняно з традиційними методами управління ризиками.

3. Дотримання нормативних вимог та інтеграція в системи управління повітряним рухом:

У дисертації запропоновано нові межі для інтеграції БПЛА в існуючі системи управління повітряним рухом, які мають вирішальне значення для більш широкого впровадження технології БАС в комерційному просторі. Ці межі покликані забезпечити відповідність міжнародним авіаційним стандартам і місцевим нормам, сприяючи безперебійному функціонуванню та прискоренню процесів отримання дозволів від регуляторних органів. Практичне застосування цих рамок кількома логістичними компаніями Китаю призвело до прискорення отримання дозволів на польоти БПЛА в обмеженому повітряному просторі на 20%.

4. Екологічна стійкість:

Дослідження, присвячене впливу доставки дронами на навколишнє середовище, підкреслює значне скорочення викидів вуглекислого газу, пропонуючи стійку альтернативу традиційним методам доставки. Емпіричні дані, представлені в дисертації, вказують на те, що доставка дронами може скоротити викиди вуглецю до 50% на кожному маршруті доставки в порівнянні зі звичайним наземним транспортом. Ця екологічна вигода є переконливим аргументом на користь використання дронів компаніями, які прагнуть зменшити свій вуглецевий слід та покращити свою практику сталого розвитку.

5. Зниження витрат в управлінні ланцюгами поставок:

Впровадження моделей прийняття рішень і методів динамічного програмування, розроблених у дослідженні, дозволило знизити загальні операційні витрати в управлінні ланцюгами поставок. Ці моделі оптимізують розподіл корисного навантаження та планування маршрутів, що призводить до більш ефективного використання ресурсів, зменшення споживання палива та експлуатаційного зносу. Практика впровадили ці стратегії, призводить до скорочення логістичних витрат приблизно на 15%, а також підвищує ефективність використання корисного навантаження і пропускної спроможності.

Ці практичні застосування демонструють відчутні переваги дослідження і є вагомим аргументом на користь більш широкого впровадження технології БПЛА та БАС в логістиці та інших секторах. Отримані результати не лише підтримують операційні покращення, але й відповідають ширшим цілям, таким як дотримання нормативних вимог, екологічна стійкість і економічна ефективність.

Ключові слова: Безпілотний літальний апарат (БПЛА), безпілотна авіаційна система (БАС), неповна інформація, набір обмежень, планування польотів, оптимізація ланцюга поставок , стохастичне та лінійне програмування, оцінка ефективності, умови експлуатації, експлуатаційна ефективність, алгоритми моделювання, моделювання даних, інформаційна підтримка, інформаційні технології, системні зв'язки, управління польотами, логістика останньої милі, аналіз витрат і вигод, управління повітряним рухом, оптимізація перевезень, динамічне управління об'єктами, прийняття рішень в реальному часі, безпека польотів, автономний політ, неявні та явні системні зв'язки, узагальнений показник ефективності, оцінка повітряної обстановки, розподіл польотного часу, оцінка послідовності подій, ситуаційний аналіз, діапазони допустимих значень параметрів, оптимізаційні моделі.

ABSTRACTS

Li Haoyang. The effectiveness of drone use under conditions of incomplete information and multiconnectivity of constraints set for flights.

Dissertation for the degree of PhD in specialty J6 - Air Transport, specialization - Air Transport - Kyiv Aviation Institute State University of the Ministry of Education and Science of Ukraine, Kyiv, 2026.

This thesis presents a comprehensive study of hierarchically related tasks of evaluating the efficiency of unmanned aerial systems (UAS). The centerpiece of the thesis is the study of the role that drones play in improving the efficiency of cargo transportation. In particular, how drones can solve logistical problems in the delivery of goods under conditions of incomplete information due to both regulatory and system constraints. Through a detailed analysis and application of the developed algorithms, the study demonstrates how route optimization and fleet management can be significantly improved, thereby reducing operating costs and environmental impact.

In addition, the thesis thoroughly explores the methodological aspects of evaluating drone performance using statistical models, machine learning algorithms, and Monte Carlo simulations. These tools help to understand and predict drone performance in diverse and uncertain environments, contributing to better planning and decision-making.

The ultimate goal of this study is to highlight the transformative potential of UAV technology in modern logistics and provide effective solutions to address the challenges associated with the use of drones in commercial operations. By offering detailed case studies and empirical data, the thesis not only emphasizes the practical benefits of drones, but also contributes to the ongoing debate on their regulatory and operational framework, paving the way for future advances in drone technology.

The introduction substantiates the relevance of the thesis, formulates the purpose and main objectives of the research, and provides information on the relationship of the research to scientific programs and topics. In addition, the scientific novelty and

practical significance of the research are highlighted, the applicant's contribution to joint publications is noted, the approbation of the results of the dissertation is described, and the structure and scope of the dissertation are presented.

The first chapter presents an analysis of the development and application of unmanned aerial vehicles (UAVs or drones), highlighting the need for high mobility and autonomy. It also emphasizes the importance of understanding and complying with the regulatory framework for UAVs of organizations such as ICAO, FAA, EASA, and CAAC, and examines in detail the differences in the criteria for classifying UAVs in different aviation organizations.

One significant difference is the FAA's approach, which primarily focuses on classifying drones based on their weight, with a clear division between small drones weighing up to 55 pounds and larger drones weighing more than 55 pounds. In addition, the FAA considers the purpose of drone use, distinguishing between commercial, research, and recreational applications. In contrast, EASA, ICAO, and CAAC take a more comprehensive approach, considering operational elements in addition to weight. They consider altitude, speed limits, non-line-of-sight operations, level of human supervision, and geographic restrictions to determine the appropriate classifications.

This discrepancy is largely a reflection of regional differences, the densely populated and complex airspace over Europe and Asia compared to the wider and less congested airspace of the United States. Factors such as population density, conflicting air traffic, and complex traffic flows require special rules for drone operations in Europe and Asia to mitigate collision risks that are less prevalent in the more open spaces of the Americas.

As a result, EASA's classification system is the most complex, covering seven specific categories that provide precise specifications, functions, and operational requirements tailored to different drone weight classes. These categories allow for individualized type certification in accordance with safe drone integration standards covering flights over people, beyond line-of-sight operations, heavy payload transportation, and high-altitude missions.

The second chapter explores in detail the transformational impact of drones on logistics and delivery systems, with a particular focus on algorithms and technologies that complement these operations, defining the role of drones in the delivery and transportation of goods, work on supply chain optimization and cost reduction, in particular, as an example, using a probability distribution that can be applied to systems with a large number of possible events, each of which is rarely encountered. The use of such a probability distribution for solving transportation problems, as well as algorithms used to solve complex performance evaluation problems, is justified by the fact that transportation problems cannot be solved by traditional methods, especially in a dynamic and uncertain environment, given the required level of flight safety.

It is proved that solving multidimensional problems related to performance evaluation using a simple search method on a uniform grid requires a significant number of iterations and, in fact, is possible only with small values of N and low solution accuracy. The use of parsimonious sequential methods that create a non-uniform grid requires solving an additional multi-extreme problem at each iteration, which also needs to be solved by search methods (e.g., brute force), which dramatically increases the computational complexity of the iteration.

This paper analyzes the impact of drones on logistics and transportation, highlighting their role in changing the dynamics of supply chains. The problem is formulated as a two-stage problem with stochastic uncertainty. At the first stage, before the requests for special flights are known, UAVs (e.g., multi-rotor or fixed-wing) of each type are distributed among the routes and the number of flights of each type along each route is determined. At the second stage, after establishing the realization of the random parameters of the problem conditions, the aircraft are reassigned from route to route.

This section emphasizes the operational efficiency provided by drones, especially in terms of reducing costs and time for last-mile delivery. Case studies from various companies show that integrating drones into logistics systems can reduce delivery costs by up to 50 % and shorten delivery times by an average of 25 %. This section also explores the environmental impact of drone delivery and provides data on how drones can help reduce carbon dioxide emissions from urban delivery by 40%, reducing reliance on traditional delivery vehicles.

The third chapter discusses the methods and mathematical models used to evaluate and improve the efficiency of cargo transportation using UAVs, especially in situations where information is incomplete. It explores statistical methods for quantifying drone performance with a focus on key indicators such as delivery reliability, cost-effectiveness, and operational flexibility.

The concept of UAS efficiency assessment is based on the consideration of social, economic and functional types of effect. Two approaches to assessing the effectiveness of UAS are proposed and developed: with implicit and explicit systemic links of the means with a higher-order system. Evaluation of efficiency in the case of implicit links of UAS means is based on the formation of the resulting quality indicator and the reduction of a multicriteria problem to a scalar one. An algorithm for selecting the priority option of the means is developed.

The subproblems that arise when formulating goals, criteria, and performance evaluation with explicit systemic links are systematized. It is proved that the evaluation of the effectiveness of the UAS system is associated with the problem of performance management, which depends, in turn, on the controllability of situations. The principles of determining the functional effect in the management of dynamic objects are formulated. The basics of the theory of situational analysis of the air situation are developed.

Advanced statistical models are used to simulate operational scenarios, helping companies to understand potential outcomes and prepare for them more effectively. For example, Monte Carlo simulations predicted the impact of different weather conditions on drone operations, showing that proper planning can mitigate up to 30% of the negative effects.

This section also discusses the integration of machine learning algorithms into UAV operations, using decision trees and Bayesian networks to make real-time operational decisions. These models help to cope with the complexity of dynamic environments by providing probabilistic outcomes of different decisions, which is important for maintaining a high level of service reliability under uncertainty. The paper presents an example in which Bayesian networks were used to dynamically adjust the routes and payloads of drones, which increased overall operational efficiency by 35%. A real-world example shows how these predictive models can improve the operational reliability of UAVs in commercial delivery services by reducing downtime and increasing the speed of response to environmental changes.

The fourth chapter defines mathematical methods for solving the formulated problems of navigation support for cargo drones. A modification of these methods was created to consider the specific features of large-dimensional problems with significant nonlinearity of variables and the complex nature of constraints on phase coordinates. The computational algorithms for solving the problems were developed:

- Calculation of system constraints of the landing system introduced by the aircraft as a controlled dynamic object (search for a global extremum, considering the constraints on variables in the form of equations and inequalities);
- predictive evaluation of a stochastic sequence of results (probabilistic analysis of the sequence tree of the set of flight situation predicates and its evaluation);
- construction of areas of permissible values of navigation support parameters (tracking the boundaries of closed sets by the method of forecast-correction, with correction by the gradient of boundary violation);
- combined study of the characteristics of navigation support (joint use of the results of analytical solution of simplified navigation problems and modeling by the method of simulation modeling).

The need to ensure reliable direct communication between drones flying autonomously to prevent collisions and ensure the interaction of all components of the Integrated Space-Air-Ground Network (ISGN) is proved. Insufficient data transmission rate in any of the channels can significantly degrade the performance of the entire integrated network and negatively affect the efficiency of the UAS.

We modeled an AI artificial intelligence system with a cloud structure and the ability to change the delay and probability of data packet loss. The obtained dependencies of losses on message size and data rate, the dependence of the average load for the uplink and the packet transit time on the size of transactions, as well as the dependence of BER on the average load allow us to make practical recommendations for choosing the necessary data transmission modes in the communication channels of freight UAS.

A detailed study of the use of algorithms to optimize complex logistics tasks, such as fleet management and route planning, was conducted. These algorithms help to find optimal solutions by imitating a natural evolutionary process, which is especially effective in conditions where operational parameters change frequently. It has been proven that the use of such algorithms increases delivery speed by 20% and reduces operating costs by 15%.

The application of dynamic programming to optimize the sequential decision-making process in UAV operations is also discussed. The method is used to determine the best course of action for each stage of the delivery route, considering the current state and making decisions that will lead to the best overall result. This approach allowed the company to increase throughput by 25% while maintaining a high level of customer satisfaction.

The scientific novelty of the primary results obtained during the study is as follows:

1. The proposed model of flight control and planning

An innovative model of flight control and planning has been developed, especially in the context of integration of manned and unmanned aircraft operating together in a single airspace, as opposed to flexible and segregated airspace (in ICAO terms). The model considers numerous random variables that affect flight quality, such as the time spent by the aircraft at a particular calculation point and errors in command execution affected by external disturbances. As a result, the model can more accurately predict flight routes and times. To optimize flight delays and ensure safety, the model uses a linear programming approach that solves the problem of optimizing random delays and safety intervals. In this model, the landing (or take-off) time of each aircraft is predicted as a random variable with a known distribution function, which in turn calculates the delay time of each aircraft in the controlled area to ensure the probability of maintaining a safe interval.

2. The conceptual foundations are developed and methods for assessing the effectiveness of the UAS are proposed

In terms of efficiency measurement, the thesis proposes new methods for assessing the efficiency of UAS in conditions of incomplete information and the presence of implicit and explicit system links. This involves the construction of a generalized performance metric that combines several factors and considers the air situation, quality of operation and efficiency, to comprehensively assess the effectiveness of UAS. In particular, the paper develops a methodology for assessing the effectiveness of UAS in air navigation systems, which not only covers the assessment of performance indicators, but also includes a comparative analysis of modelled and measured data. In addition, the author proposes a new approach to assessing the implicit and explicit links of the system, which can provide a reliable measurement of efficiency in different operating conditions. The developed method for assessing the efficiency of the UAS is represented by the category of action during the system's operation at a certain time interval, which reflects the correspondence of the result obtained to the invested resources.

Two approaches to assessing the effectiveness of UAS are proposed and developed: with implicit and explicit system links of the means with a higher-order system. Evaluation of efficiency in the case of implicit links of UAS means is based on the formation of the resulting quality indicator and reduction of a multi-criteria problem to a scalar one. An original algorithm for selecting the priority option of a vehicle has been developed.

The subproblems that arise in the formulation of goals, criteria and performance evaluation with explicit systemic links are systematized. It is proved that evaluating the effectiveness of the UAS system is associated with the problem of performance management, which depends, in turn, on the controllability of situations. The concept of evaluating the effectiveness of UAS is based on considering social, economic and functional types of effect. For example, drones can help reduce carbon dioxide emissions from urban deliveries by 40%, reducing dependence on traditional delivery vehicles.

3. Development of an optimization model of UAS in the supply chain

With the aim of optimizing supply chain operations and reducing costs, the article analyses in detail the role of drones in the last mile transport of goods. The article proposes a supply chain optimization model that considers factors such as transport speed, route selection and transport costs of drones to achieve overall supply chain optimization. Thanks to the optimization model, UAVs can significantly reduce the time and cost of transportation and increase the efficiency of cargo transportation. A cost-benefit analysis is used to assess the cost-effectiveness of UAS in various transport scenarios. This analysis helps to determine the optimal strategy for using UAVs, which maximizes economic benefits and ensures the efficient performance of transport tasks while maintaining an acceptable level of flight safety.

4. Adapted model of stochastic flight planning for UAVs

The two-stage stochastic scheduling model proposed in this thesis is aimed at solving the problem of redistributing aircraft under conditions of uncertainty and real-time for special needs of the use of the UAS. At the first stage, the model determines the number of flight hours allocated to each type of aircraft on each route, and these allocations are based on known demand and flight resources. In the second stage, when a special demand for transportation arises, the model reallocates UAVs from one route to another based on the implementation of stochastic parameters to meet the new demand for transportation. The adapted model uses an integer linear programming approach to ensure that flight time and cargo demand are met on each route while minimizing overall transportation costs. Thus, the model can flexibly respond to changes in transportation demand and maintain an efficient transportation system.

5. Algorithmizing of information support tasks

The work also achieves important innovations in the algorithmizing of information support tasks. An algorithm for evaluating sequences of event outcomes in a dynamic object control system is proposed, which allows quantifying the impact of different sequences of events on system performance, and thus helps to optimize the control system solution. In addition, the paper proposes a quantitative method for constructing regions of acceptable values of information support parameters.

The computational algorithms for solving the problems were developed:

- calculation of system constraints of the landing system, which are introduced by the aircraft as a controlled dynamic object (search for a global extremum, considering the constraints on variables in the form of equations and inequalities)
- predictive evaluation of a stochastic sequence of results (probabilistic analysis of the sequence tree of the set of flight situation predicates and its evaluation);
- construction of areas of permissible values of navigation support parameters (tracking the boundaries of closed sets by the method of forecast-correction, with correction by the gradient of boundary violation);
- combined study of navigation support characteristics (joint use of the results of analytical solution of simplified navigation problems and simulation modeling).

This approach increases the operational stability and adaptability of UAVs under conditions of uncertainty by determining the range of acceptable values of information support parameters under different operating conditions. These algorithms and methods not only improve the transportation capabilities of the UAV, but also increase its adaptability in difficult task conditions.

The practical value of the results obtained in this thesis is as follows:

1. Improving operational efficiency in logistics using UAS:

The study showed that the developed advanced routing algorithms significantly increase the operational efficiency of UAVs in logistics.

By adapting flight routes in real time in response to environmental changes, these algorithms reduce delivery times and improve delivery accuracy. Practical tests conducted as part of the study demonstrated a reduction in average delivery time of up to 30% in urban environments, which proves the effectiveness of the algorithms in improving the efficiency of drone delivery systems.

2. Risk management in the operation of UAVs:

The practical application of statistical modeling for risk assessment in UAS operations offers significant safety and reliability benefits. The study confirmed the effectiveness of such modeling in predicting and mitigating potential disruptions or operational delays. For logistics companies, this means increased reliability and reduced operational risks: the study showed that incident-related delays were reduced by 25% compared to traditional risk management methods.

3. Regulatory compliance and integration into air traffic control systems:

This thesis proposes new boundaries for the integration of UAVs into existing air traffic control systems, which are crucial for the wider adoption of UAS technology in the commercial space. These boundaries are designed to ensure compliance with international aviation standards and local regulations, facilitating smooth operation and accelerating regulatory approval processes. The practical application of this framework by several logistics companies in China has resulted in a 20% speed-up in obtaining permits for UAV flights in restricted airspace.

4. Environmental sustainability:

A study on the environmental impact of drone delivery highlights the significant reduction in carbon dioxide emissions, offering a sustainable alternative to traditional delivery methods. The empirical data presented in the thesis indicates that drone delivery can reduce carbon emissions by up to 50% on each delivery route compared to conventional ground transportation. This environmental benefit is a compelling argument in favor of the use of drones by companies looking to reduce their carbon footprint and improve their sustainability practices.

5. Reduced costs in supply chain management:

The implementation of decision-making models and dynamic programming methods developed in the study has reduced overall operating costs in supply chain management. These models optimize payload distribution and route planning, leading to more efficient use of resources, reduced fuel consumption, and operational wear and tear. Companies that have implemented these strategies have reported a reduction in logistics costs of approximately 15%, as well as increased payload utilization and throughput.

These practical applications demonstrate the tangible benefits of the research and provide a strong argument in favor of wider adoption of UAV technology in

logistics and other sectors. The findings not only support operational improvements, but also meet broader goals such as regulatory compliance, environmental sustainability, and cost-effectiveness.

Keywords: Unmanned aerial vehicle (UAV), unmanned aerial system (UAS), incomplete information, set of constraints, flight planning, supply chain optimization, stochastic and linear programming, performance evaluation, operating conditions, operational efficiency, modeling algorithms, data modeling, information support, information technology, system communications, flight management, last mile logistics, cost-benefit analysis, air traffic control, transportation optimization, dynamic object management, real-time decision making, flight safety, autonomous flight, implicit and explicit system links, generalized performance indicator, air situation assessment, flight time allocation, event sequence assessment, situational analysis, ranges of acceptable parameter values, optimization models.

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CONTENTS

LIST OF ABBREVIATIONS

UAV	Unmanned aerial vehicle
UAS	Unmanned aerial system
ISR	Intelligence, surveillance and reconnaissance
ICAO	International Civil Aviation Organization
UN	United Nations Organization
VFR	Visual Flight Rules
IFR	Instrument Flight Rules
VMU	Visual meteorological conditions
IMC	Instrumental meteorological conditions
NRZ	Above ground level
LF	Level of flight
MSL	Mean sea level
ATC	Air traffic control
EUROCONTROL	European Organization for the Safety of Air Navigation
RPAS	Remotely Piloted Aircraft System
EASA	European Aviation Safety Agency
VLOS	Line of sight
BVLOS	Beyond line of sight
DSA	Dependable Systems of Application
FAA USA	Federal Aviation Administration of the United States
CAAC	Civil Aviation Administration of China

INTRODUCTION

Relevance of the thesis topic. In recent years, the range of applications of drones in various fields has significantly expanded and their advantages have been realized, especially in the logistics sector. Drones can provide effective services in agriculture, entertainment, tourism and other areas, and have demonstrated great advantages in cargo transportation. The emergence of cargo drones/UAVs is expected to revolutionize the logistics industry, especially in last-mile delivery, where drones can effectively reduce transportation time and costs and improve service quality.

Cargo drones/UAVs operate under conditions of incomplete information, including weather conditions, airspace congestion, and potential hazards along the flight path. UAV operators must face difficulties in navigation, communication, and decision-making in the absence of reliable information, which creates new challenges for research and practical applications. Therefore, the research is aimed at developing methods and strategies for adapting to these uncertain conditions to improve the autonomous decision-making capabilities and increase the operational efficiency of UAVs.

UAVs are subject to numerous restrictions. UAVs are subject to various rules and regulations, and have performance limitations that are intended to ensure safe operation. For example, many countries have strict rules on the altitude at which UAVs can fly, while certain missions require permission from aviation authorities. Numerous restrictions add to the complexity of UAV operations, requiring researchers to carefully evaluate and plan flights to meet regulatory requirements while still achieving scientific goals.

Research goal and objectives. The purpose of this thesis is to evaluate and improve the operational efficiency of cargo UAVs under conditions of incomplete information and multiple constraints. The research focuses on the architecture and functionality of UAVs, exploring their unique advantages over traditional manned aircraft, particularly their potential for use in complex environments. By analyzing the various constraints affecting cargo UAV flights, including regulations, weather conditions, and geographical obstacles, the research aims to identify and address these issues, thereby improving UAV autonomous decision-making and adaptability in challenging environments.

To achieve this goal, the thesis begins by addressing several key challenges. The study delves into the navigation, communication, and decision-making difficulties faced by UAV operations in an incomplete information environment. Due to the lack of reliable information, operators often encounter unpredictable obstacles during UAV flights, which poses a serious threat to the safety and efficiency of flights. By collecting and analyzing relevant data, research has led to the development of new methods and strategies that allow UAVs to make informed decisions under uncertainty, thus improving their autonomous operational capabilities.

Object of research: The object of research is cargo drones, in particular, their operational efficiency under conditions of incomplete information and numerous constraints.

Subject of research: The research topic focuses on the use of cargo UAVs in complex environments, including their architecture, functionality, benefits, and challenges they face. By analyzing these factors, the thesis aims to improve the autonomous decision-making capabilities and operational efficiency of UAVs in difficult environments.

Research methods. Using predictive analytics, the task is solved with the help of regression models, probability distribution, which can be applied to systems with many possible events, each of which is rare, mathematical reliability theory, probability theory, machine learning, numerical analysis, and statistical simulation modeling.

Scientific novelty of the results.

Scientific novelty includes the originality of the development of the following areas:

1. Model of flight control and planning

An innovative model of flight control and planning has been developed, especially in the context of the integration of manned and unmanned aircraft working together. The model considers numerous random variables that affect flight quality, such as the time spent by the aircraft at a particular design point and errors in command execution affected by external disturbances. As a result, the model can more accurately predict flight routes and times. To optimize flight delays and ensure safety, the model uses a linear programming approach that solves the problem of optimizing random delays and safety intervals. In this model, the landing (or takeoff) time of each cargo UAV is predicted as a random variable with a known distribution function, which, in turn, calculates the delay time of each aircraft in the controlled area to ensure the probability of maintaining a safe interval.

2. Methods of efficiency evaluation

In terms of performance evaluation, the thesis proposes a new methodology for determining the effectiveness of UAVs in conditions of incomplete information and the presence of implicit and explicit system links. This involves the construction of a generalized performance metric that combines a set of factors that considers the air situation, quality of operation, and efficiency to comprehensively assess the effectiveness of UAVs. In particular, the paper develops a methodology for evaluating the effectiveness of UAVs in air navigation systems, which not only covers the evaluation of performance indicators, but also includes a comparative analysis of modeled and measured data. In addition, the author proposes a new methodology for assessing implicit and explicit system links, which can provide a reliable measurement of efficiency in different operating conditions.

3. Optimization methods

To optimize supply chain operations and reduce costs, the article analyzes in detail the role of drones in the transportation of goods at the “last mile”. The author proposes a UAV supply chain optimization model that considers factors such as transportation speed, route selection, and drone transportation costs to achieve overall supply chain optimization. Thanks to the optimization model, UAVs can significantly reduce transportation time and cost and improve logistics efficiency. The thesis also uses a cost-benefit analysis to evaluate the cost-effectiveness of UAVs in various transportation scenarios. This analysis helps to determine the optimal strategy for using

UAVs that maximizes economic benefits and ensures the efficient fulfillment of transportation tasks.

4. Stochastic planning model

The two-stage stochastic scheduling model proposed in this thesis is aimed at solving the problem of redistributing aircraft under conditions of uncertainty and real time for special transportation needs. At the first stage, the model determines the number of flight hours allocated to each type of aircraft on each route, and these allocations are based on known demand and flight resources. In the second stage, when special transportation demand occurs, the model reallocates aircraft from one route to another based on the implementation of stochastic parameters to meet the new transportation demand. The model uses an integer linear programming approach to ensure that flight time and cargo demand are met on each route while minimizing overall transportation costs. Thus, the model can flexibly respond to changes in transportation demand and support the efficient operation of the transport logistics system.

5. Algorithmizing of information support tasks

The work also achieves important innovations in the algorithmizing of information support tasks. The author proposes an algorithm for evaluating sequences of event outcomes in a dynamic object control system, which allows quantifying the impact of different sequences of events on system performance and thus helps to optimize the control system solution. In addition, the paper proposes a quantitative method for constructing regions of acceptable values of information support parameters. This approach increases the operational stability and adaptability of UAVs under uncertainty by determining the range of acceptable values of information support parameters under different operating conditions. These algorithms and methods not only improve the development of UAVs, but also increase their adaptability in difficult task conditions.

The validity and reliability of the research results are confirmed by the full and correct application of mathematical tools, such as regression models, law of rare phenomena (Poisson), mathematical reliability theory, probability theory, machine learning, numerical analysis, and statistical simulation modeling.

Practical significance of the results.

1. Improving operational efficiency in logistics using UAVs:

The research showed that the developed advanced routing algorithms significantly increase the operational efficiency of UAVs in logistics. By adapting flight routes in real time in response to environmental changes, these algorithms reduce delivery times and improve delivery accuracy. Practical tests conducted as part of the study demonstrated, for example, a reduction in the average delivery time of up to 30% in urban areas, which proves the effectiveness of algorithms in improving the efficiency of drone delivery systems.

2. Risk management in the operation of UAVs:

The practical application of Monte Carlo simulation for risk assessment in UAV operations offers significant benefits in terms of safety and reliability. The study confirmed the effectiveness of such modeling in predicting and mitigating potential failures or operational delays. For logistics companies, this means increased reliability and reduced operational risks: the study showed that incident-related delays were reduced by 25% compared to traditional risk management methods.

3. Regulatory compliance and integration into air traffic control systems:

This thesis proposes new boundaries for the integration of UAVs into existing air traffic management (ATM) systems, which are crucial for the wider adoption of UAV technology in the commercial space. These boundaries are designed to ensure compliance with international aviation standards and local regulations, facilitating smooth operation and speeding up regulatory approval processes. The practical application of these boundaries by several logistics companies has resulted in a 20% speed-up in obtaining permits for UAV flights in restricted airspace.

4. Environmental sustainability:

The research on the environmental impact of drone delivery highlights the significant reduction in carbon dioxide emissions, offering a sustainable alternative to traditional delivery methods. The empirical evidence presented in the thesis indicates that drone delivery can reduce carbon emissions by up to 50% on each delivery route compared to conventional ground transportation. This environmental benefit is a compelling argument in favor of the use of drones by companies looking to reduce their carbon footprint and improve their sustainability practices.

5. Reduced costs in supply chain management:

The implementation of decision-making models and dynamic programming methods developed in this study can reduce overall operating costs in supply chain management. These models optimize payload distribution and route planning, resulting in more efficient use of resources, reduced fuel consumption, and reduced operational wear and tear. Companies that have implemented these strategies have reported a reduction in logistics costs of approximately 15%, as well as increased payload utilization and throughput.

Personal contribution of the candidate:

Testing the results of the dissertation. Research results were discussed at 14 international congresses, symposia and conferences: 1) “XV International Scientific and Technical Conference “AVIA-2021” of the National Aviation University. (Kyiv, Ukraine, 2021); 2) “Aviation in the XXI century - Aviation safety and space technologies”, (Kyiv, Ukraine, 2022); 3) “Sustainable Development of the Global Communication, Navigation, Surveillance and Air Traffic Management System CNS/ATM - 2021”. (Kyiv, Ukraine, 2021); 4) “XVI International Scientific and Technical Conference ABIA-2023” (Kyiv, Ukraine, 2023); 5) “2023 IEEE International Conference on Information and Telecommunication Technologies and Radio Electronics (UkrMiCo)”, (Kyiv, Ukraine, 2023); 6) “Science-Based Technologies”, No. 3 (59), (Kyiv, Ukraine, 2023); 7) “Science-Based Technologies”, No. 4 (60), (Kyiv, Ukraine, 2023); 8) “2023 IEEE 7th International Conference on Methods and Systems of Navigation and Motion Control (MSNMC) (Kyiv, Ukraine, 2023); 9) “Sustainable Development of the Global Communication, Navigation, Surveillance and Air Traffic Management System CNS/ATM— 2023” (Kyiv, Ukraine, 2023); 10) “Proceedings of the 2nd International Workshop on Advances in Civil Aviation Systems Development,” Lecture Notes in Networks and Systems”, (Kyiv, Ukraine, 2024); 11) “Electronics and Control Systems” № 4(78) (Kyiv, Ukraine, 2023);

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Publications. The main findings and results of the dissertation research are presented in 15 scientific publications, including 5 publications in Ukrainian academic journals, 1 publication in a scientific journal indexed in the Scopus database, and 9 publications in proceedings of international and national scientific and technical conferences.

Structure and content of the dissertation. The thesis consists of an introduction, four chapters, conclusions, list of used references represented after each chapter, and three appendices. The total number of pages is 212. In the thesis, there are 34 figures, 19 tables, 208 references on 33 pages and 7 pages of appendices.

CHAPTER 1. SCOPE OF APPLICATION OF UNMANNED AERIAL VEHICLES (UAVS)

1.1. Mission objectives of unmanned air transport. Advantages of using unmanned aircraft compared to manned aircraft

Unmanned aerial vehicle, abbreviated as "UAV". A UAV is an unmanned aerial vehicle that is controlled by remotely piloted equipment and autonomous software devices, or fully or intermittently autonomously controlled by an on-board computer.

UAVs are widely used in the military, primarily for tactical and strategic aerial reconnaissance. Micro" and "small" UAVs are increasingly used in platoon and detachment combat operations, i.e. to address military intelligence missions. UAVs can also be used to coordinate fires and strikes against ground targets.

In addition, non-military drones are used for a variety of tasks, but their performance is not feasible for manned aircraft for various reasons. diagram shown Fig 1.1.

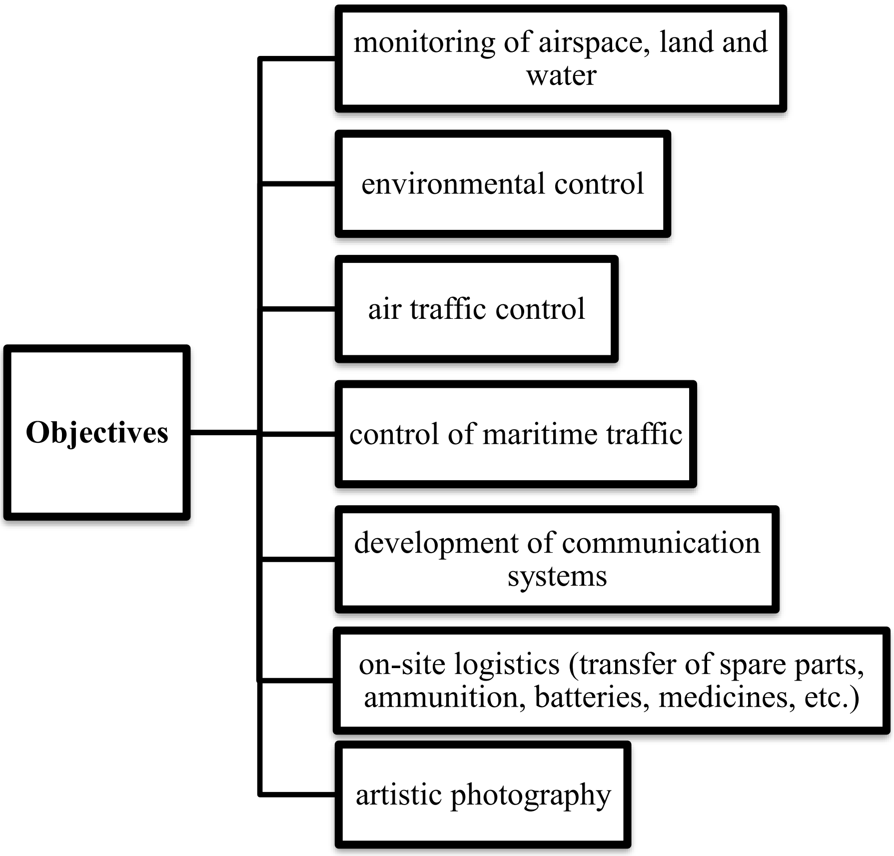


Fig 1.1 - non-military drones are used for a variety of tasks

Compared to manned aircraft, it has advantages such as small size, low cost, ease of use, low requirements for the combat environment, and high survivability on the battlefield. Drones are now widely used to capture footage that can do the same job as very expensive helicopters and cranes [1,6,7]. Large e-commerce giants such as Amazon, Alibaba, DHL, and some other major e-commerce companies are advocating the use of drones [2, 36]. UAVs can save a lot of time and are not affected by any traffic conditions. In addition, they can also be used for short distances [3]. UAV technologies are now also enabling farmers and are radically changing the agriculture industry Agriculture with modern farming technologies [8, 9].

Compared to conventional manned aircraft, unmanned aerial systems (UAS) offer a number of performance and capability advantages. It can perform tasks that are too dangerous or complex for manned aircraft. UAVs can also fly at lower altitudes and slower speeds, allowing for more accurate data collection and processing. In addition, UAVs can be equipped with a variety of sensors and cameras, allowing for more accurate and detailed data collection. UAVs can also be used for search and rescue missions, as they are able to fly slowly and at low altitudes, which increases the effectiveness of search efforts. To summarize, UAVs are a vital tool in a variety of industries due to their performance and capabilities [19].

1.2. The challenges of the unmanned aerial vehicle (UAV) market

The global market for unmanned aerial vehicles by type (fixed-wing and multicopter), components (airframe, payload, navigation, control system and propulsion system), and application (military and commercial UAVs), as shown in Fig. 1.2.

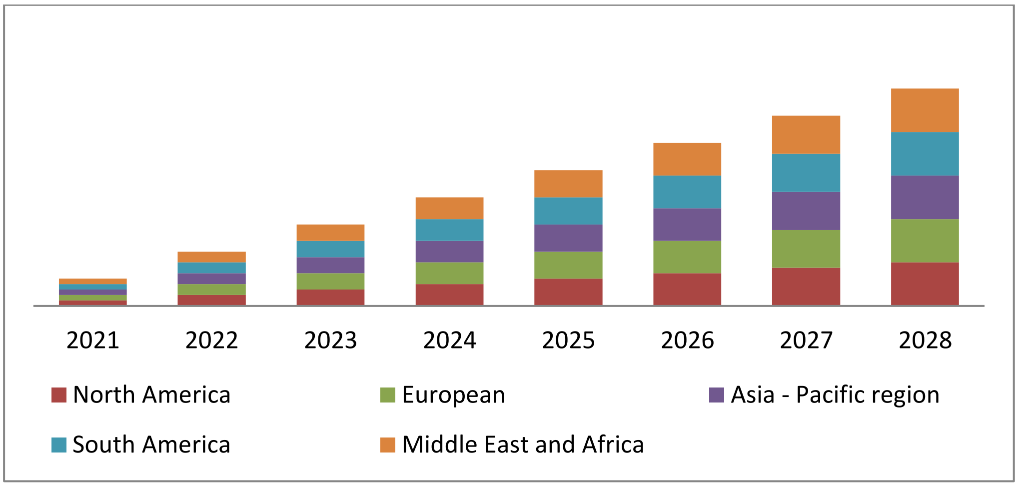


Fig 1.2 - Diagram of the global UAV market in 2021-2028

The Unmanned Aerial Vehicles Market is expected to grow at a CAGR of 30.76% during the forecast period of 2021 to 2028. Various industries are currently exploring the use of UAVs for commercial and military purposes. Increasing adoption of drones in various industries such as mining, oil & gas, telecommunication, and retail is expected to drive the growth of the drone market size.

The drone market is segmented on the basis of type, component, and application. The growth among the segments helps in analyzing the growth niches and market strategies and identifying the key applications and target market differentiators:

- On the basis of type, the unmanned aerial vehicle market is segmented into fixed-wing and multi-engine rotary-wing versions;

- on the basis of components, the unmanned aerial vehicle market is segmented into airframe, payload, navigation guidance system, control system, and propulsion system;

- on the basis of application, the unmanned aerial vehicle market is divided into military and commercial UAVs.

The competitive landscape of the UAV market provides detailed information on competitors, which includes company overview, company financials, revenue generation, market potential, R&D investments, new market initiatives, regional distribution, company strengths and weaknesses, product launches, product breadth and depth, and application benefits. This data only covers the company's focus on the unmanned aerial vehicle market.

1.3. A general approach to the classification of unmanned aircraft

An unmanned aerial system (UAS) should be understood as a complex of unmanned aerial vehicle (UAV) systems with remote control points on the ground and managers to ensure its proper operation, as well as control and communication channels to transmit the results of UAS operation to consumers.

The functional purpose, organizational and technical parameters of UAVs and are UAS classified in Table 1.1 [21-29].

Table 1.1

General classification of unmanned aircraft

Classification	Purpose
Scope of UAS application	- tactical - operational; - strategic.
UAV takeoff weight	- UAS with micro-UAV ($m_o < 1.0$ kg); - UAS with a small UAV ($1.0 < m_o \leq 100$ kg); - UAS with light UAV ($100 < m_o \leq 500$ kg); - UAS with medium UAV ($500 < m_o \leq 5000$ kg); - UAS with heavy UAV ($5000 < m_o \leq 15000$kg); - UAS with super-heavy UAV ($m_o > 15000$kg).
Flight duration	- UAS with UAV of short flight duration ($t < 1$ hour); - UAS with UAV of medium flight duration ($1 < t \leq 6$ hours); - UAS with UAV of long flight duration ($t > 6$ hours).
Execution UAV	- UAS with UAVs of non-airfield launch (catapult type as a variant), which are launched by hand; - UAS with UAVs of airfield launch from a runway (platform).
Landing	- UAVs with "airplane-like" landing (with a run); - UAVs with a point landing of the UAV (parachute descent, catching by various devices).
Functional purposes of UAS	- supervisory - intelligence; and - transportation; - multi-purpose.
Dimensions and weight characteristics	- miniature - ultra-small - small - medium - large.
Range for reusable UAVs	- short-range with a range of less than 80 km and a flight duration of 1 to 6 hours - short-range with a range of 300-700 km and barrage time from 2 to 8 hours; - medium-range with a range of 300-700 km and a barrage time of 2 to 8 hours; - long-range with an unlimited range and a duration of more than 24 hours.

Продовження таблиці 1.1

Height of application	- ultra-low-altitude

	- low-altitude - medium-height; - used at high altitudes.
Basing of the UAV	- airfield - mobile - stationary.
Flight control	- radio-controlled (controlled by the operator via control lines (channels)); - automatic (controlled automatically by a program); - combined (with a combined control system).
Application of intelligence	- photo and video reconnaissance in the visible part of the spectrum; - radar reconnaissance; - thermal imaging reconnaissance; - radio and radio engineering intelligence; - radiation, chemical and biological intelligence; - weather intelligence (meteorological intelligence).
Time of receiving the collected information	- in real time; - periodically during communication sessions; - after landing.
Launcher basing	- ground-based - airborne - sea-based.

1.4. Classification by ICAO, EUROCONTROL, FAA USA, CHINA

1.4.1. ICAO classification of drones

The ICAO classification system is used to classify aviation incidents based on their severity and potential impact on aviation safety. This system determines the organizational sequence of work to prevent aviation incidents, the tasks and functions of management agencies, management agencies, management objects and subjects.

ICAO's Model UAS Regulations provide a framework that member states can adopt or use to supplement their existing drone regulations. The regulations are divided into multiple parts, with highlights including:

Part 101: Focusing on unmanned aircraft weighing 25 kg or less and operating in standard conditions, emphasizing registration requirements and inspections for heavier drones.

Part 102: Addressing operations using drones that weigh more than 25 kg or those not adhering to Part 101 requirements, and facilitating ongoing operations through certification.

Part 149: Promoting the use of Approved Aviation Organizations to assist with tasks like remote pilot licensing and drone inspection.

This framework allows for a level of flexibility and adaptability for ICAO member states, accommodating the evolving landscape of drone technology and usage. As shown in Table 1.2.

Table 1.2

ICAO classification of drones

Category	**Maximum Takeoff Weight**	**Flight Rules**	**Altitude Range**	**Primary Purpose**	**Remarks**
Unmanned Aircraft	< 25 kilograms	General Aviation Rules	Low to Medium Altitudes	Recreational and Small Commercial Use	Basic small unmanned aircraft
Small Unmanned Aircraft	< 25 kilograms	General Aviation Rules	Low to Medium Altitudes	Various Applications	Small unmanned aircraft categorized based on specific rules
Large Unmanned Aircraft	> 25 kilograms	Special Aviation Rules	Medium to High Altitudes	Commercial and Professional Use	Typically require specialized permits
Unmanned Aircraft System	N/A	N/A	N/A	Various, including Research and Military	Includes drones, ground stations, and other equipment
UAS Operator	N/A	N/A	N/A	Drone Operation and Management	Individual or entity responsible for flight compliance

1.4.2. EUROCONTROL classification of drones

EUROCONTROL is a pan-European organization that supports European aviation. Its mission is to provide safe and efficient air traffic management services to its member states and to ensure the smooth flow of air traffic in Europe. As a result, EUROCONTROL plays a vital role in the aviation industry, working closely with various stakeholders to ensure the safety and efficiency of air travel in Europe.

One of EUROCONTROL's key initiatives is its classification system, which is designed to standardize the classification of airspace and air traffic services in Europe. The aim of this system is to provide a consistent and comprehensible classification of all airspace and air traffic services, making it easier for pilots, air traffic controllers and other aviation stakeholders to understand and navigate the complex European airspace.

Standardization is critical in aviation as it helps reduce the risk of error and improve safety.

Remotely piloted aircraft (RPAS) are difficult to classify due to their wide variety of shapes, sizes, and characteristics. Category m traffic is a set of flight rules, operating procedures and system functions applicable to RPAS and operators operating RPAS in selected airspace. EUROCONTROL's RPAS traffic classification consists of four categories for very low altitudes (less than 500 feet) and three categories for flights above FL600, as summarized in Table 1.3.

Table 1.3

EUROCONTROL classification of drones

Class	Description	EASA Category	VLOS or BVLOS	Operational Requirements
I	Buy and Fly	Open	VLOS	Low-risk environments; 3D self-separation; avoidance of geo-zones without drone areas; mandatory declarations
II	Free Flight	Specific or Certified	VLOS and BVLOS	Free flight trajectory; up to 500 feet above sea level; 3D self-separation; observation possibility; barometric equipment for BVLOS; mandatory authorization
III	Free Flight or Route Structure for Medium/Long Distance	Specific or Certified	BVLOS	Free flight or within route structure; up to 500 feet; observation possibility; barometric equipment; mandatory authorization; mainly for medium/long-haul transport
IV	Special Operation	Specific or Certified	VLOS and BVLOS	Designed for specialized operations; up to 500 feet; tracking capability might be required; special permit for each case; could be civil, state, or military operations
V	Development outside ATS network under IFR/VFR	-	VLOS and BVLOS	Beyond route network of air traffic control; up to 600 feet; no additional performance requirements compared to manned aircraft; two-way RPAS communication with ATC if needed; DSA; flight plan required
VI	Operation under IFR including in the network	-	BVLOS	Includes ATS route network, terminals, and airports; up to 600 feet or unmanned aircraft capable of piloted flight; two-way RPAS communication with ATC; DSA; flight plan required
VII	IFR at Very High Altitude	-	VLOS and BVLOS	Above 600 feet, mostly uncontrolled airspace; transition through separated or unseparated airspace; prior agreement; special procedures; flight plan required

1.4.3. FAA classification of drones

Recent drone legislation in the U.S. reflects this: a distinction is made between small drones, model airplanes, and micro aerial vehicles, and different rules apply.In

2016, the FAA established rules specific to small drones as part of Federal Rule 107. Under Part 107, a "small drone" is defined as a drone that weighs less than 55 pounds (25 kg) including all cargo. Part 107 also provides more detailed regulations on registration, pilot control, and operational restrictions for small UAVs. This is shown in Table 1.4.

Overall, U.S. drone legislation imposes relatively few legal restrictions on small, model, and microbial drones and is decreasing, primarily because these types of drones are generally lighter and slower. The security threat is relatively low. In addition, on top of the distribution of drones primarily by weight, different rules have been considered based on the use of the drones, reflecting a further refinement of the rules governing the categorization of drones in the United States.

Table 1.4

FAA classification of drones

Purpose Classification	Size Classification	Flight Altitude	Activity Radius
Commercial	Small (< 55 lbs)	Below 400 feet (Low)	Local
	Medium	400 - 1200 feet	Regional
	Large (> 55 lbs)	Above 1200 feet (High)	National
Research	Small (< 55 lbs)	Below 400 feet (Low)	Local
	Medium	400 - 1200 feet	Regional
	Large (> 55 lbs)	Above 1200 feet (High)	National
Recreational	Small (< 55 lbs)	Below 400 feet (Low)	Local
	Medium	400 - 1200 feet	Regional
	Large (> 55 lbs)	Above 1200 feet (High)	National

1.4.4. CAAC (China) classification of drones

The Civil Aviation Administration of China (CAAC) is the governing body responsible for regulating civil aviation in China. The CAAC was formed in 1949 after the founding of the People's Republic of China and is headquartered in Beijing. CAAC is responsible for overseeing all aspects of civil aviation, including air traffic control, airport management and airline security.

The Civil Aviation Administration of China (CAAC) Provisional Regulations for the Operation of Light and Small Unmanned Aircraft and the Piloting Regulations for

Civil Unmanned Aircraft provide a classification of unmanned aircraft as summarized in Table 1.5 This classification takes into account the weight of the aircraft and operational characteristics. It provides a relatively simple framework for defining operating and pilot license requirements. The CAAC regulations for temporary light and small unmanned aerial vehicles apply to the categories of unmanned aerial vehicles listed in Table 1.5, but they do not apply to model aircraft unless they are equipped with an autopilot, command and control data links or autonomous flight equipment, and also do not apply to indoor operations [48-50].

Table 1.5

CAAC (China) classification of drones

Category	Empty weight (kg)	Takeoff weight (kg)	Requirements for operation		Remote pilot
I	≤ 1.5		VLOS; CAS $\leq 100 \frac{км}{h}$; < 120 м AGL < 500 м from the pilot/observer	Pilot safety	No license required
II	$> 1.5 \leq 4$	$> 1.5 \leq 7$		Geofencing and ground station. Cloud connection at 60 seconds if over or around important facilities or airports	
III	$> 4 \leq 15$	$> 7 \leq 25$		Flight data is stored for 3 months, geo-zoning; UAS cloud connection with a reporting speed of 1 second (densely populated areas) or 30 seconds.	A remote pilot license administered by a national professional organization. No license is required for indoor operation. No license is required for experimental operation in rural areas.
IV	$> 15 \leq 116$	$> 25 \leq 150$		Passive surveillance.	
V	Agriculture, $W \leq 5700$			Geofencing and ground station Cloud connection with a speed of 60 seconds if over or around important facilities or airports.	
VI	The volume of the airship $\leq$ 4600 $м^3$		BVLOS ≤ 15 м	Flight data is stored for 3 months; geo-zoning; UAS cloud	

VII	BVLOS categories I та II	BVLOS	connection at 1 s (densely populated areas) Speed reporting at 30 s.	

1.4.5. Differences in drone classification methods among FAA, EASA, ICAO and CAAC

Aviation regulators globally, including the United States' Federal Aviation Administration (FAA), the European Union Aviation Safety Agency (EASA), the International Civil Aviation Organization (ICAO), and China's Civil Aviation Administration (CAAC), have developed distinct drone classifications that mirror their unique regional conditions and priorities. A notable distinction is the FAA's methodology, which primarily categorizes drones by their weight, drawing a line between small drones under 55 pounds and larger ones above this threshold. Moreover, the FAA differentiates based on the purpose of drone use, such as commercial, research, and recreational activities. In contrast, EASA, ICAO, and CAAC adopt a more nuanced approach that includes operational aspects alongside weight, considering factors like altitude, speed restrictions, operations beyond the visual line of sight, levels of human supervision, and geographic limitations to determine their classifications.

This variation largely reflects the regional differences, particularly the dense population and complex airspace in Europe and Asia versus the more open and less congested airspace in the United States. The higher population density, conflicting air traffic, and intricate traffic flows in Europe and Asia necessitate more detailed drone regulations to minimize collision risks, which are less of a concern in the expansive spaces of America.

EASA's classification system is notably detailed, introducing seven specific categories that define precise performance, features, and operational requirements for various drone weight classes. This system facilitates customized type certifications to ensure safe drone integration, accommodating flights over people, beyond visual line of sight operations, heavy payload transport, and high-altitude missions.

ICAO provides a robust yet flexible framework, encouraging member countries to adapt and enhance it according to their specific needs. Meanwhile, CAAC integrates additional considerations unique to China's market, which encompasses both extensive urbanization and vast rural areas with differing agricultural needs, distinct from those in Western regions.

While the United States has been at the forefront of implementing simpler and more entrepreneur-friendly drone regulations with nationwide consistency, it faces challenges related to effectively enforcing safety limits as drone usage increases. Conversely, the stricter classifications in Europe and Asia are designed to proactively address potential risks.

In summary, the FAA's drone classification significantly differs from the more complex approaches of EASA, ICAO, and CAAC. These differences stem from technical characteristics, intended drone roles, and geographic complexities, setting the stage for potential global harmonization in the commercial drone industry. While the FAA focuses on industry growth, other regulators prioritize localized risk mitigation and constraints. Over time, the identification and incorporation of best practices from various conditions may unify and refine drone classifications worldwide.

1.5. Regulatory framework

1.5.1. ICAO’s laws, regulations and regulatory framework for drones

The International Civil Aviation Organization (ICAO) plays a pivotal role in shaping the regulatory framework for drones and unmanned aircraft systems (UAS) globally. ICAO's approach to drone regulations focuses on the harmonization and standardization of rules and procedures to ensure safe, secure, and sustainable development in the field of unmanned aviation. ICAO's involvement in drone regulation can be highlighted in several key areas. As shown in table 1.6.

Table 1.6

ICAO regulations and supervision on drones

Aspect	Details
DRONE ENABLE Symposiums	Organizing international symposiums (like DRONE ENABLE 2023) for stakeholders to discuss innovation and developments in unmanned aviation.
Harmonization of Regulations	Developing a comprehensive, harmonized regulatory framework in collaboration with civil aviation authorities and industry stakeholders.
Safety and Security Standards	Setting safety and security standards, including guidelines and best practices for drone operations.
International Collaboration	Facilitating international collaboration for the development of UAS regulations, sharing research, best practices, and lessons learned.
Education and Awareness	Raising awareness and educating stakeholders through webinars, reports, and knowledge exchange platforms.

In summary, ICAO's role in drone regulation is centered around creating a unified global framework that addresses the complexities and challenges of integrating unmanned aircraft systems into the existing aviation infrastructure. Through symposiums, standardization efforts, and international collaboration, ICAO aims to foster an environment where drones can be used safely and efficiently for a variety of purposes, contributing positively to the global aviation ecosystem.

1.5.2. EUROCONTROL and EASA's legal, regulatory and regulatory framework for drones

EUROCONTROL, as an intergovernmental organization dedicated to ensuring efficient and safe air traffic management across Europe, contributes to the regulatory framework, particularly with regard to Unmanned Aerial Vehicle Traffic Management (UTM). Key aspects include:

1) Network Manager Role: EUROCONTROL plays a role in the management and coordination of the European airspace network, including the integration of drone operations.
2) UTM Development: EUROCONTROL is involved in the development and

implementation of UTM systems necessary to manage drone flights, especially in controlled airspace.

3) Research and Innovation: EUROCONTROL participates in research programs exploring new technologies and procedures for the safe integration of drones into the airspace.
4) Stakeholder Engagement: Work with various stakeholders including air navigation service providers, drone operators and regulators to develop comprehensive UTM solutions.

The European Commission has adopted a series of U-space regulations that introduce new services for drone operators, allowing them to perform more complex and longer-range operations, especially in congested low-altitude airspace (below 120 meters) and beyond visual range flight. The development route is divided into four stages, as shown in Table 1.7.

Table 1.7

U-Space development route

U-Space development route	
U1 Foundation Services	Possess the capabilities of e-Registration, e-Identification, and Pre-tactical Geofencing.
U2 Initial Services	Possess the capabilities of Procedural Interface with ATC, Monitoring, Tactical Geofencing, Flight-Planning Management and Tracking, and Weather Information.
U3 Advanced Services	The initial service capability improvement stage.
U4 Full Services	The stage of improvement of advanced service capabilities.

In the DREAMS project serving U-Space, the designed U-Space data interaction platform needs to collect, process and distribute meteorological data, airspace data, air navigation notification data, terrain obstacle data, population density data and communication, navigation and monitoring facilities data. , aircraft flight data and various dynamic and static data, as shown in Figure 1.3.

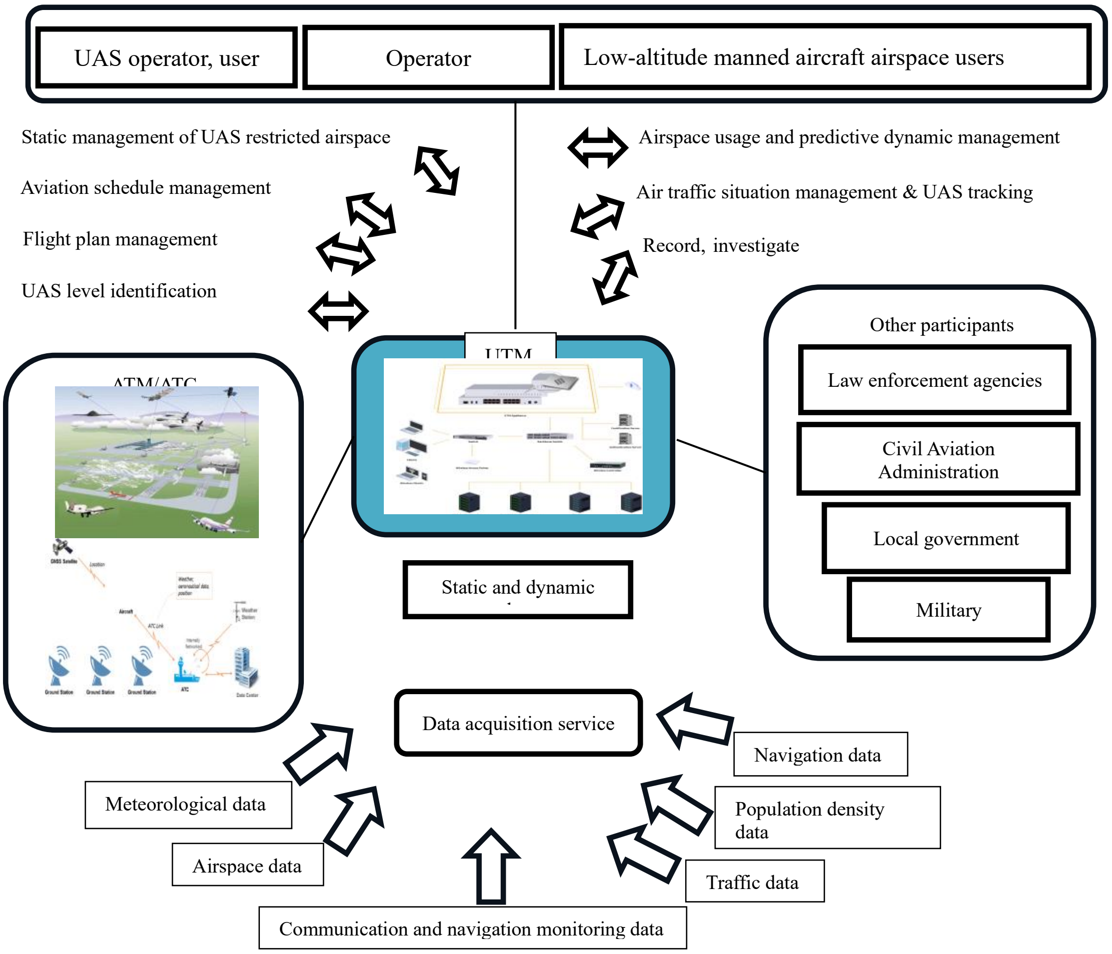


Fig.1.3 DREAMS diagram

The European Union Aviation Safety Agency’s (EASA) “Proposed Revision Notice 2017-05(A)” puts forth a regulatory framework for unmanned aerial vehicle (UAV) operations -- operation of open and specific UAV systems, targets the operation of open UAV systems (low-altitude, VLOS, one-person only). capable of controlling a UA at the same time), and put forward traffic management regulations focusing on three aspects: operational restrictions, remote pilot qualification requirements, and aircraft system technical requirements. See Table 1.8 for details; For charter drone operations, traffic management regulations based on risk assessment and risk mitigation are proposed. It is recommended that the Joint Agency for Unmanned Systems Rulemaking (JARUS) SORA approach be used to develop management regulations, risk assessment methods and risk mitigation measures. See Figure 1.4 for details. For charter drone operations, operators can conduct risk assessments using standard scenarios endorsed by EASA. If the assessment is low risk, the operator can submit a "declaration" to the regulator to obtain a license. If the assessment results in a high risk, the operator can obtain a license by submitting a "declaration" to the regulatory authority. Obtain a charter from a regulatory agency in the form of an "authorization"; holders of a Light UAV Operator Certificate (LUC) can also obtain self-"authorization" on preferential terms.

Table 1.8

EASA Open Class UAS Traffic Management Regulations

EASA Open Class UAS Traffic Management Regulations									
UAS category	UAS level	Maximum takeoff weight/Joule	Crowd distance	Maximum flight altitude	Remote control pilot capabilities	Remote control driver age	Main technical requirements (CE mark)	UAS registration	Electronic Identification, EI and Geofencing, G
A1 Flying over the crowd	Private manufacturing	<250g	Flying over unrelated crowds (not over gatherings of people)	<50m	User's Guide	Unlimited	Unnecessary	Unnecessary	Unnecessary
	C0						Toy regulatory requirements, no sharp edges, instructions for use		
	C1	<80J or 900g		<120m，or no higher than 50 meters above the building at the request of the owner	Instructions for use and online training and testing	Aged 14 or above or with supervision	Kinetic energy requirements, no sharp edges, optional height restrictions, instruction manual	Operator	If it is equipped with a lens or audio sensor larger than 5MP, EI is required; if the operating airspace is required, EI and G are require

A2 Flying close to people	C2	<4kg	Intention to approach unrelated people but keep a safe distance (rotor drone is greater than 20 meters; fixed-wing drone is greater than 50 meters)	<120m，or no higher than 50 m above the building at the request of the owner	Instructions for use and certificate of conformity (with theoretical qualifications and passed testing by an approved center)	Over 16 years old or with supervision	Mechanical strength, loss of connection management, optional height limit, instruction manual	Operators and drones	Requirement
A3 Fly away from crowds	C3	<25kg	Fly to an area where irrelevant people are generally not present	<120m，or no higher than 50 m above the building at the request of the owner	Instructions for use and online training and testing	Over 16 years old or with supervision	Lost connection management, optional height limit, instruction manual	Operators and drones	If required for operational airspace, EI and G
	C4		In addition to the above requirements, you must also maintain a safe distance from cities, crowded areas and airport borders				Instructions for Use		
	Private manufacturing						Unnecessary		

Fig 1.4 SORA diagram

1.5.3. FAA's laws, regulations and regulatory framework regarding drones

The FAA in the United States has established a comprehensive set of laws, regulations, and a regulatory framework for the operation of drones, officially known as unmanned aircraft systems (UAS). Here's an overview:

1) Laws & Regulations

- The current regulations and rules governing drones/unmanned aircraft systems (UAS) are contained in the Federal Aviation Regulations (FAR) Part 107 which covers operational limitations, remote pilot certification, aircraft requirements, etc.
- Part 107 builds on the FAA Modernization and Reform Act of 2012 which mandated the FAA to integrate UAS operations safely into national airspace.
- Key categories defined in FAA rules are Model Aircraft (recreational users operating under community guidelines), Recreational Flyers, and Commercial Operators.

2) Regulatory System：

- At the federal level, the FAA has primary regulatory authority over drones in

US airspace. State and local governments have limited regulatory powers.

- Commercial users must obtain Remote Pilot Airman Certificate by passing an aeronautical exam from FAA. Recreational users simply need to register drones and follow community standards.
- The FAA approvals required include aircraft registration, airworthiness certification, remote pilot licensing, obtaining operational waivers, facilities maps filing, night operation, external load approval etc.
- FAA rules cover restrictions pertaining to altitude, airspace, time of day, visual line of sight operations, critical infrastructure, flying over people, carriage of hazardous materials etc. to ensure safety and public interest.

In summary, EASA's framework enables scaled regulations, assessments, and certifications depending on the scope and risk profiles of UAV operations - open category low-risk versus specialized commercial activities. The focus is on pragmatically easing adoption of routine drones while ensuring adequate oversight for advanced operations through centralized as well as operator-driven evaluations.

1.5.4. CAAC's laws, regulations and regulatory framework regarding drones

In recent years, China's drones have frequently flown illegally and interfered with navigation. The supervision of civilian drone flight activities has been put on the agenda by the Civil Aviation Administration of China (CAAC), and has been in the air traffic management, airworthiness management, pilot A series of normative documents have been promulgated in terms of management and operation management. In 2015, the Civil Aviation Administration of China issued an advisory notice on the operation and management of civilian UAVs, "Regulations on the Operation and Management of Light and Small UAVs (Trial)", which proposed seven categories of UAVs suitable for operation management and stipulated operational requirements. The "Management Regulations for Trial Operation of Specific Categories of UAVs (Interim)" released in 2019 combines China's national conditions with SORA and proposes the application and approval process and requirements for the qualification review of specific categories of UAVs. It is a step forward in the supervision of civilian UAV operations. This is an important step, and it can be seen that China has adopted the classification management supervision idea based on operational risks. Refer Table 1.9 for specifics.

Table 1.9

CAAC Drone Regulations in China

Regulation Category	Details
Drone Registration	Drones over 250 grams must be registered with the CAAC. Requires personal information, drone details, and possibly a Chinese mobile phone number.
Commercial Use Licensing	License required for drones between 7 and 116 kg. Drones over 116 kg require a pilot's license and UAV certification.
General Flying Rules	Maintain visual line of sight, avoid flying above 120 meters and in densely populated areas. No flying near airports, military installations, and sensitive areas. Adhere to No-Fly Zones.
Travel Considerations	Drones are allowed on airplanes, trains, buses. Batteries must be in carry-on luggage.
Local Awareness	Be cautious and respectful of local sentiments, especially outside major cities.
No-Fly Zones	Beijing and other specified areas are no-fly zones. Check specific maps for details.

1.5.5. The differences between the laws, regulations and regulatory frameworks of FAA, EASA, EUROCONTROL,ICAO and CAAC regarding drones

The differences in legal regulations and regulatory frameworks for drones between the Civil Aviation Administration of China (CAAC) and four international organizations, the Federal Aviation Administration (FAA), the European Union Aviation Safety Agency (EASA), EUROCONTROL, and the International Civil Aviation Organization (ICAO), can be analyzed as follows:

1) Geographic Scope:

- CAAC: The regulatory authority of the CAAC is limited to drone operations within China, and its regulations and standards apply exclusively to operations within China's borders.

- FAA: The FAA's regulations apply within the United States, but it also has some international influence and requires compliance with certain globally recognized safety standards for commercial drone operators registered in the United States.
- EASA: EASA's regulations cover drone operations within Europe.
- EUROCONTROL: EUROCONTROL primarily focuses on air traffic management coordination and support, regarding drones, especially concerning airspace management and integration in Europe.

2) Regulatory Development:

- CAAC, FAA, and EASA each develop their own drone regulations and standards tailored to their respective countries or regions.
- EUROCONTROL does not develop regulations but assists in coordinating safety and management aspects of drones in European countries.
- ICAO, as an international organization, sets some global drone safety standards, but specific regulations are usually developed by individual countries.

3) Registration and Licensing:

- CAAC, FAA, and EASA all require drone operators to register and issue specific levels of licenses or certificates, with requirements varying based on the type and purpose of the drone.
- EUROCONTROL does not issue licenses but aids in the coordination of safety and operations regarding air traffic management.
- ICAO encourages countries to establish registration and licensing procedures, but it does not directly issue licenses.

4) Flight Rules and Airspace Management:

- CAAC, FAA, EASA, and EUROCONTROL have all established relevant flight rules, including altitude restrictions, no-fly zones, and operational regulations.
- ICAO provides global guidance on drone flight principles, but individual countries have the flexibility to adjust and implement them according to

their specific needs.

In summary, these organizations differ in their drone laws, regulations and regulatory frameworks, depending primarily on their respective geographical scope, legal systems, flight safety needs and regulatory approaches. Drone operators are required to comply with regulations specific to their region.

Conclusions of chapter 1

The chapter provides a detailed overview of the development and application of unmanned aerial vehicles (UAVs/drones) in academia and industry, with a focus on the growing concern of researchers and the need for high mobility and autonomy. It also emphasizes the importance of understanding and complying with the regulatory frameworks for drones from organizations such as ICAO, FAA, EASA, Eurocontrol and CAAC, and analyzes the differences in the way these organizations approach drones. The drone taxonomy is used to more fully understand how drones are used in real life to ensure aviation and human safety. It also presents the regulatory framework for the use of airspace as a key step towards the safe integration of drones into the airspace. Finally, this section emphasizes the importance of regulation, safety, and ongoing research in the field of drones in accordance with international norms.

CHAPTER 2. THE ROLE OF DRONES IN THE DELIVERY AND TRANSPORTATION OF GOODS TO IMPROVE THE EFFICIENCY OF SUPPLY CHAINS

2.1. Air traffic control and flight planning for cargo UAVs in a single airspace

Consider the important management and planning tasks that occur in the practice of civil aviation. Some of the first publications in this area are articles [1] and [2]. Thus, one of the first works was an individual model of automation of air traffic control at the controller level [1], which is still relevant today, but with significant complications in the organization of air traffic at the current level and the development of GATM (Global Air Traffic Management). Such complications are caused primarily by the need to allow UAVs with large payloads to enter the single airspace. Today, drones can transport small loads without any problems, but a problem arises in the case of large and heavy cargo.

Cargo drones can fly in the same airspace as manned aircraft in accordance with the requirements of the EASA Certified category. Then the flight phases of cargo drones can be presented as shown in Fig 2.1.

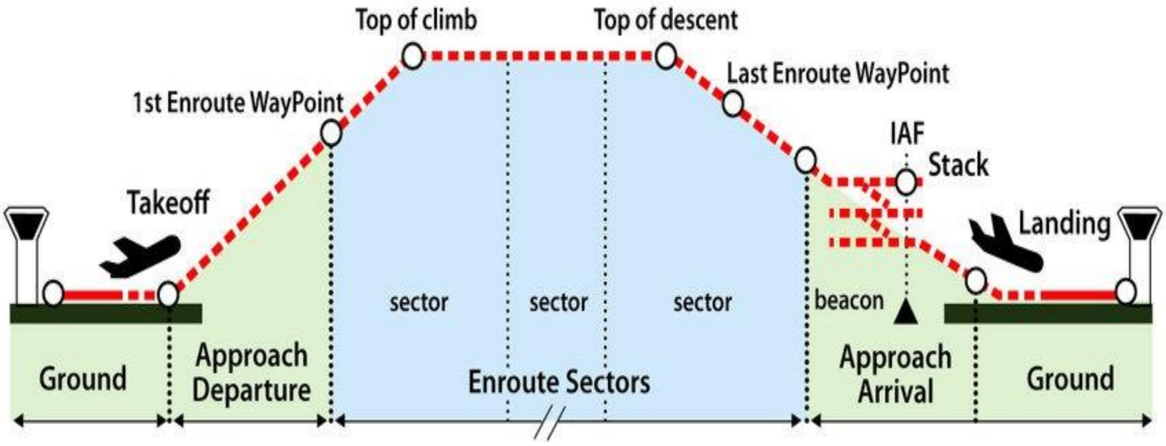


Figure 2.1. Phases of flight

Let's consider a modified model of flight control and planning, when both the air traffic controller and the remote pilot, who control a set of aircraft taking off or landing, must take into account the random nature of a number of parameters that determine the quality of the task. These include, in particular, the moment when the aircraft appears at the calculated point and the errors in the execution of commands by individual aircraft, which are also affected by external disturbances.

Suppose that there is a certain set of aircraft in the control area. For each i-th aircraft from this set, the moment of landing (take off) $\boldsymbol{\tau_i}$ is predicted. The moments of two consecutive landings (take offs) τ_{i+1} and τ_i ($\tau_{i+1} > \tau_i$) must be separated in time by at least $\Delta S_i -$ the safety interval, which is limited by the echeloning standards. If the safety conditions are not met, it is necessary to change the trajectory or flight mode and delay the aircraft in the control area for a certain time interval t_i. The delay is performed in buffer zones and is also regulated by ATFM (Air Traffic Flow Management). The choice of the interval t_i must guarantee a given probability of compliance with the safety interval:

$$P\{\tau_{i+1} + t_{i+1} - \tau_i - t_i \geq \Delta S_i\} \geq \alpha_i,\ i = 1, \dots, n. \qquad (2.1)$$

Here τ_i is a random variable whose distribution is known.

The pilot, as a rule, cannot realize the delay exactly. Therefore, in inequalities (1), the variables should be considered random variables whose mathematical expectations coincide with the aircraft delay intervals in the control area, which are subject to determination and transmission to the board. It is assumed that the distribution function is known to the exact value of that is sought.

Of course, the random variables τ_i, τ_{i+1}, t_i, t_{i+1} are independent of each other. In this case, knowing the distribution functions of τ_i and t_i, it is easy to calculate the distribution functions of the random variable:

$$\xi_i = (\tau_{i+1} + t_{i+1} - \bar{\tau}_{i+1} - \bar{t}_{i+1}) - (\tau_i + t_i - \bar{\tau}_i - \bar{t}_i).$$

We denote it by $\boldsymbol{F_i(z) = P(\xi_i < z)}$.

The quality of management will be evaluated by the average value of the weighted sum of delays:

$$M\sum_{i=1}^{n}\beta_i\xi_i=\sum_{i=1}^{n}\beta_i\xi_i\,,$$

where the weighting coefficients $\boldsymbol{\beta_i}$ are assumed to be given. The control conditions and technical constraints on the choice of$t_i$are specified by inequalities:

$$\underline{\boldsymbol{\gamma_i}}\le\bar{\boldsymbol{t}}_{\boldsymbol{i}}\le\bar{\boldsymbol{\gamma}}_{\boldsymbol{i}}\,,\qquad \boldsymbol{i}=1,\dots,n.$$

Thus, the individual task of automating takeoff and landing control under consideration is reduced to the following stochastic model.

It is necessary to calculate the value of $\bar{\boldsymbol{t}}_{\boldsymbol{i}}$ delays that are transferred to the of the $\boldsymbol{i}$-th aircraft, for which:

$$\sum_{i=1}^{n}\beta_i\bar{t}_i\to min$$

under the conditions:

$$P\{\tau_{i+1}+t_{i+1}-\tau_i-t_i\ge\Delta_i\}\ge\alpha_i,\ \ i=1,\dots,n. \qquad (2.2)$$

$$\underline{\gamma_i}\le\bar{t}_i\le\bar{\gamma}_i\,,\ i=1,\dots,n. \qquad (2.3)$$

To get the deterministic equivalent of the problem, let's rewrite the conditions (2.1) in the form:

$$P\{\xi_i<\Delta_i-\bar{\tau}_{i+1}-\bar{t}_{i+1}+\bar{\tau}_i+\bar{t}_i\}\le 1-\alpha_i,\ \ i=1,\dots,n,$$

or the same thing,

$$\Delta_i-\bar{\tau}_{i+1}-\bar{t}_{i+1}+\bar{\tau}_i+\bar{t}_i\le F_i^{-1}(1-\alpha_i),\ \ i=1,\dots,n).$$

We have come to the next linear programming problem:

$$\sum_{i=1}^{n}\beta_i\bar{t}_i\to min, \qquad (2.4)$$

$$\bar{t}_i-\bar{t}_{i+1}\le F_i^{-1}(1-\alpha_i)+\bar{\tau}_{i+1}-\bar{\tau}_i-\Delta_i, \qquad (2.5)$$

$$\underline{\gamma_i}\le\bar{t}_i\le\bar{\gamma}_i\,,\ i=1,\dots,n. \qquad (2.6)$$

Model (2.4)-(2.6) is simpler than the model presented in [1] and, unlike it, does not require assumptions about the nature of the distribution of random parameters of the problem conditions, which allows the use of machine learning technologies.

In the process of air cargo transportation, it is necessary to consider a flight planning system [2] that serves two types of flights: regular and special. Scheduled flights are operated between fixed points and are planned in advance. However, plans can be changed within a certain period of time. Special flights occur irregularly, and the time and points of transportation are not fixed in advance. Special flights can be carried out by UAVs operating on regular routes, thereby diverting them from those routes.

Different types of aircraft, both manned and unmanned, differ in payload, flight time, and costs on different routes. Flights are planned with incomplete information. The demand for special transportation is not known in advance. The amount of cargo that arrives over time is based on uncertain parameters of the task conditions. There is a need to reassign aircraft from routes that serve transportation for which the demand is higher than expected. Reassignment may, in particular, be made at intermediate stops. The objective is to minimize the average expected costs over the entire planning period.

The problem is formulated as a two-stage problem with stochastic uncertainty. At the first stage, before the requests for special flights are known, aircraft of each type are allocated to routes and the number of flights of each type on each line is determined. At the second stage, after establishing the realization of the random parameters of the problem conditions, aircraft are reassigned from route to route.

Fixed conditions (conditions of the first stage) limit the total number of flight hours for each type of aircraft distributed over all routes. The restrictions are also related to the existing flight resources for the planned period.

The second stage constraints can be divided into two groups. The restrictions of the first group record the fact that for each type of aircraft, the total number of flight hours transferred from a given route to other lines does not exceed the number of flight hours originally assigned to that route and the ratio of payload to UAV flight range.

The development of the latest technologies optimizes the payload to range ratio of UAVs. The payload-to-range ratio (PRR) for UAS is a metric used to evaluate the efficiency and capabilities of a drone in terms of how much payload it can carry in relation to the distance it can travel. It provides an indication of a drone's ability to transport a specific payload over a certain distance, which is especially important for applications such as cargo delivery, surveillance, scientific research, etc.

The formula for calculating the **PRR** as follows:

$$\mathbf{PRR} = \frac{\boldsymbol{Payload\ Capacity}}{\boldsymbol{Range}} \tag{2.7}$$

$\boldsymbol{Payload\ Capacity}$ - is the maximum weight of the payload that a drone can carry.

$\boldsymbol{Range}$ - is the maximum distance a drone can cover on a single battery charge or fuel tank.

A higher **PRR** value indicates that the drone can carry more payload over a given distance, which can be useful for applications where payload capacity is a critical factor. However, it is important to note that maximizing PRR is not always the primary goal, as other factors such as endurance, maneuverability, or specific payload requirements may be prioritized for different applications.

When considering payload to range ratios, it is also important to consider factors such as wind conditions, operating altitude, battery life, and propulsion efficiency. These factors can affect the actual performance of the drone and its ability to achieve the specified payload and range.

Therefore, the constraints of the second group, which are common in two-stage problems, such as stochastic programming, are balancing ratios for each route.

We introduce the following notation:

$\boldsymbol{x_{ij}}$ – is the number of flights during a certain period of time of aircraft of type $\boldsymbol{i}$, initially assigned to route $\boldsymbol{j}$;

$\boldsymbol{x_{ijk}}$ – is the number of flights of aircraft type $\boldsymbol{i}$ withdrawn from route $\boldsymbol{j}$ and reassigned to route $\boldsymbol{k}$;

$\boldsymbol{y_j^+}$ – is the unrealized requests (in tons of cargo) for transportation on route $\boldsymbol{j}$;

$\boldsymbol{y_j^-}$ – is the unloaded capacity of aircraft (in tons of cargo) on the $\boldsymbol{j}$-th route;

$\boldsymbol{a_{ij}}$ – is the number of hours required for an aircraft of type $\boldsymbol{i}$ to cover route $\boldsymbol{j}$ if the aircraft was originally assigned to this route;

$\boldsymbol{a_{ijk}}$ – is the number of hours required for an aircraft of type $\boldsymbol{i}$, originally assigned to route $\boldsymbol{j}$, to cover route $\boldsymbol{k}$. Obviously, $\boldsymbol{a_{ijk}} \geq \boldsymbol{a_{ik}}$;

$\boldsymbol{b_{ij}}$ – is the number of tons of cargo transported per flight by an aircraft of type $\boldsymbol{i}$ on route $\boldsymbol{j}$;

$\boldsymbol{a_i}$ – is the permissible number of flight hours of an aircraft of type $\boldsymbol{i}$ during a month;

$\boldsymbol{d_j}$ – is the requests for transportation (in tons of cargo) on route $\boldsymbol{j}$;

$\boldsymbol{c_{ij}}$ – is the cost of a flight of an aircraft of type $\boldsymbol{i}$ on route $\boldsymbol{j}$, provided that the aircraft was originally assigned to this route;

$\boldsymbol{c_{ijk}}$ – is the cost of a flight of an aircraft of type i on route $\boldsymbol{k}$ if it was withdrawn from route $\boldsymbol{j}$. Obviously,, $\boldsymbol{c_{ijk}} \geq \boldsymbol{c_{ik}}$;

$\boldsymbol{q_j^{(+)}}$ – is a penalty for failure to fulfill an application for the transportation of a ton of cargo on route $\boldsymbol{j}$;

$\boldsymbol{q_j^{(-)}}$ – is the penalty for underloading by one ton of aircraft on route $\boldsymbol{j}$.

Let's write the formal model of the problem in the above notation.

The conditions of the first stage, which constrain the total number of flight hours on all routes for each type of aircraft, are as follows:

$$\sum_j a_{ij} x_{ij} \leq a_i, \ \forall_i. \qquad (2.8)$$

To formalize the constraints of the second stage, the following remark should be taken into account. The flight time of an aircraft of type $\boldsymbol{i}$ assigned to route $\boldsymbol{j}$ is $\boldsymbol{a_{ij}}$ hours. If this aircraft is reassigned to rout*e* $\boldsymbol{k}$**,** then it will take $\boldsymbol{a_{ijk}}$ hours to overcome this route. Thus, this flight on route $\boldsymbol{k}$ causes the cancellation of $\boldsymbol{a_{ijk}/a_{ij}}$ flights on route $\boldsymbol{j}$.

The conditions of the second stage of the first group, which mean that it is impossible to cancel more flights of aircraft type $\boldsymbol{i}$ on route $\boldsymbol{j}$ than were originally scheduled for this route, are written in the form:

$$\sum_{k \neq j} \frac{a_{ijk}}{a_{ij}} x_{ijk} \leq x_{ij}, \ \forall_{i,j}. \qquad (2.9)$$

The conditions of the second group of the second stage are as follows:

$$\sum_i b_{ij} x_{ij} + \sum_i \sum_{k \neq j} b_{ik} x_{ikj} - \sum_i \sum_{k \neq j} \left(b_{ij} \frac{a_{ijk}}{a_{ij}} \right) x_{ijk} + y_j^+ - y_j^- = d_j, \ \forall_j. \quad (2.10)$$

These are the balance conditions that determine transportation requests and their fulfillment.

The target functionality of the two-stage flight planning problem is expressed as follows:

$$\sum_{i,j} c_{ij} x_{ij} + M \left\{ \min_{x_{i,j,k}, y_j^+, y_j^-} \left[\sum_i \sum_{k \neq j} \left(c_{ijk} - c_{ij} \frac{a_{ijk}}{a_{ij}} \right) x_{ijk} + \sum_j (q_j^+ y_j^+ + q_j^{(-)} y_j^-) \right] \right\}.$$

(2.11)

Thus, the flight planning problem is reduced to a two-stage stochastic programming model, in which it is necessary to calculate the nonnegative parameters $\boldsymbol{x_{ij}}, \boldsymbol{x_{ijk}}, \boldsymbol{y_j^+}, \boldsymbol{y_j^-}$ that minimize the objective function (2.11) under the conditions (2.8) - (2.10). The variables $\boldsymbol{x_{ij}}$ and $\boldsymbol{x_{ijk}}$ are also subject to an additional requirement of integer integrity.

Representing flight planning as a two-stage model is a certain idealization of the problem. A more natural description of the situation can be presented by means of a multi-stage stochastic programming problem, which would consistently take into account daily changes in transportation requests. However, solving a multi-stage flight planning problem is associated with significant computational difficulties. We propose the following way to simplify the problem.

We divide the planning horizon into $\boldsymbol{n}$ periods and represent the situation as a sequence of two-stage stochastic programming models. The solution obtained for a sequence of two-stage problems can be considered as an approximate solution to a multi-stage flight planning problem.

The optimal plan of the problem for period $\boldsymbol{t}$ determines the initial information for the next period:

$$x_{ij}(t+1) = x_{ij}(t) - \sum_{k \neq j} \frac{a_{ijk}}{a_{ij}} x_{ijk}(t) + \sum_{k \neq j} x_{ikj}(t). \quad (2.12)$$

To the uncertain transportation requests to be received in period t are added requests for cargoes that were received but not transported in previous periods. A penalty is introduced for the delay of cargo by $\boldsymbol{l}$ periods.

The problem of the t-th period minimizes the total costs associated with reassigning flights, losses due to late cargo, fines for unfulfilled transportation requests, and underutilization of aircraft.

The problem domain is described by constraints on the available aircraft fleet and on the cargo capacity of each type of aircraft on each route. In addition, the model conditions include the usual balance relations for a two-stage problem and inequalities of the form (2.9) typical for reassignment problems.

It can be assumed that the outlined sequence of two-stage problems allows us to obtain a fairly good approximation to optimal flight planning with significantly less computational complexity than a multi-stage stochastic programming problem.

Consider how drones affect the efficiency of «last-mile logistics». While first-mile delivery is the beginning of the supply chain, last-mile delivery is the end of the supply chain. The introduction of drones into the last-mile logistics industry has revolutionized the process of delivering goods to customers. First-mile operations ensure the delivery of goods from the manufacturer through the courier to the carrier. Last mile operations are completed when the order is delivered.

In the context of transportation, supply chain, manufacturing, and retail, the last mile is used to describe the delivery of products as the last stage of transportation, the performance of which is determined:

a) Faster delivery and greater convenience attract consumers.

в) Increased sales and revenues: deliveries to remote and rural areas, their sales and profits can increase due to better access to new customers.

c) Increased efficiency: Last-mile delivery can help businesses optimize their operations by reducing the time and resources required for delivery. Using automation and digital technology, manual labor and administrative tasks can be eliminated, leading to more efficient and profitable delivery operations.

In this case, drones can reduce the time and costs associated with last-mile delivery, as well as improve the quality of customer service and thus increase the efficiency of goods logistics. This means maximizing the ratio of the beneficial effect to the cost of obtaining it. In this respect, drones have become a powerful asset in the last-mile logistics industry, allowing for shorter delivery times and, as a result, increased efficiency in this industry. This is due to the fact that:

1) Drones can travel faster than traditional delivery vehicles because they don't need roads or traffic;

2) They can deliver goods directly to the customer's location;

3) Drones can be programmed to fly autonomously, which reduces the need for manual labor and shortens delivery times;

4) Drones can be used to access previously inaccessible areas. For example, drones can be used in rural areas that are difficult to reach by road. This makes it easier for companies to deliver goods to these areas and provides customers with a more efficient delivery service;

5) The ability to track and control the delivery process in real time. Companies can use drones to track the location of a parcel as well as to determine the status of delivery. This provides customers with greater visibility into the delivery process and helps companies better manage their operations;

6) Due to the ability to cover large areas regardless of terrain, drones can approach dangerous areas, such as high voltage zones, without endangering people and allowing for more informed decisions during adverse incidents;

7) Drones are used to improve the safety of last-mile logistics. Drones can be used to monitor the areas around a delivery location, ensuring that the delivery is made safely and the customer's property is protected. In addition, drones can be used to detect intruders and, if necessary, alert the appropriate personnel.

All of this enables companies to reduce delivery costs and increase customer satisfaction by providing faster delivery services. Therefore, the problem of urgent delivery of goods can be viewed as an automated system with queuing objects with events that occur at random moments in time. Such events form a stochastic sequence, usually called an event stream.

2.2. Drones as objects of mass service with events occurring at random moments in time

We will assume that the flow of events associated with a request for delivery of goods by a service object satisfies the following conditions:

1) for any two non-intersecting time intervals, the probability of occurrence of any given number of events during one of them does not depend on the number of events that appear during the other;

2) the probability of occurrence of one event during an infinitesimal time interval $(t, t + \Delta t)$ is an infinitesimal value of order Δt;

3) the probability of occurrence of more than one event during the time interval $(t, t + \Delta t)$ is infinitesimal of the highest order compared to Δt.

Let P_m (t_1, t_2) denote the probability of occurrence of m events in the time interval (t_1, t_2). Then conditions 2) and 3) will be written in the form:

$$P_1 (t, t + \Delta t) = \lambda (t) + o (\Delta t), \qquad (2.13)$$

$$\sum_{k=2}^{\infty} P_k(t + \Delta t) = o(\Delta t), \qquad (2.14)$$

where $\lambda(t)$ is some nonnegative function.

The equation that the event will not happen.

The task is to find the probabilities that m events $(m = 0, 1, 2, ...)$ will appear in a given time interval (t_0, t) for a stream of events that satisfies the conditions (2.13, 2.14, and 2.15).

Considering the moment t0 fixed, we denote the probabilities $P_m (t)$ $(m = 0, 1, 2, ...)$.

To calculate $P_0 (t)$, we note that $P_0 (t+\Delta t)$ is the probability of intersection of two events: no event in the interval (t_0, t) and no event in the interval $(t, t + \Delta t)$. According to condition 1), these events are independent. Therefore:

$$P_0 (t + \Delta t) = P_0 (t) P_0 (t, t + \Delta t). \qquad (2.15)$$

Based on (2.13) and (2.14):

$$P_0(t, t + \Delta t) = 1 - \sum_{k=1}^{\infty} p_k (t, t + \Delta t) = 1 - \lambda(t) \Delta t + o(\Delta t). \qquad (2.16)$$

Substituting this into expression (2.15), we obtain:

$$P_0(t+\Delta t) = P_0(t) - P_0(t)\,\lambda(t)\,\Delta t + o(\Delta t),$$

Whence

$$\frac{p_0(t+\Delta t)-p_0(t)}{\Delta t} = -\lambda(t)p_0(t) + \frac{o(\Delta t)}{\Delta t}.$$

As $\Delta t \to 0$, the right-hand side of this equality tends to a certain limit, $\lambda(t)\,P_0(t)$. Consequently, there is a limit to the left-hand side. Thus, the probability $P_0(t)$ is differentiable for any t, and in the limit at $\Delta t \to 0$ we obtain the differential equation:

$$P`_0(t) = -\lambda(t)\,P_0(t). \qquad (2.17)$$

To find the initial value of the probability $P_0(t)$, it is enough to set $t = t_0$ in (2.16) and move to the limit when $\Delta t \to 0$. Then we get $P_0(t_0) = 1$.

Equations for the probabilities of different numbers of events.

To derive the equations for the probabilities $P_1(t)$, $P_2(t)$, ...note that m events can appear in the time interval $(t_0,\ t+\Delta t)$ in one of the following m+1 incompatible ways: all m events appear in the interval $(t_0,\ t)$ and none in the interval $(t,\ t+\Delta t)$, m-1 events appear in the interval $(t_0,\ t)$ and one in the interval $(t,\ t+\Delta t)$, etc., all m events appear in the interval $(t,\ t+\Delta t)$. Therefore, based on the axiom of probability addition and the theorem of multiplication of probabilities of independent events $P(A_1A_2...A_n) = P(A_1)\,P(A_2)\,...\,P(An)$, we have:

$$P_m(t+\Delta t) = P_m(t)\,P_0(t,t+\Delta t) + P_{m-1}(t)\,P_1(t,t+\Delta t) + \ldots + P_0(t)\,P_m(t,t+\Delta t).$$

Hence, in accordance with (1), (2), (4), we obtain:

$$P_m(t+\Delta t) = P_m(t) + [P_{m-1}(t) - P_m(t)]\,\lambda(t)\,\Delta t + o(\Delta t).$$

Отже,

$$\frac{P_m(t+\Delta t)-p_m(t)}{\Delta t} = \lambda(t)[P_{m-1}(t) - P_m(t)] + \frac{o(\Delta t)}{\Delta t}.$$

Reasoning further in the same way as in the derivation of equation (2.17), we obtain the differential equation:

$$P_m(t) = \lambda(t)\,[P_{m-1}(t) - P_m(t)] \qquad (m = 1, 2, \ldots). \qquad (2.17)$$

The initial probability values $P_1(t)$, $P_2(t)$, … are all zero because, $P_0(t_0) = 1$, $P_m(t_0) = 0$ $(m = 1, 2, \ldots)$.

Solving equations

Taking the following as the independent variable

$$\mu = \int_{t_0}^{t} \lambda\,(\tau) d\tau\,, \qquad (2.18)$$

Let's rewrite equations (2.16) and (2.17) as follows

$$\frac{dP_0}{d_\mu} = -P_0, \ \frac{dP_m}{d_\mu} = -P_m + P_{m-1}\ (m = 1, 2, \ldots) \qquad (2.19)$$

The initial conditions will be $P_0 = 1$, $P_m = 0$, (m = 1, 2, ...) with μ=0. It is easy to verify by direct substitution that the integrals of equations (8) satisfying the initial conditions are defined by the formula:

$$P_m = \frac{\mu^m}{m!} e^{-\mu} \qquad (m = 0, 1, 2, \ldots) \qquad (2.20)$$

Thus, for a given time interval (t_0, t), we have an even set of elementary events: no event in this interval, one, two, etc., and the probabilities of these events are determined by formula (2.20). Thus, formula (2.20) defines the probability distribution. Therefore, a stream of events satisfying conditions 2.13), 2.14) and 2.15) is called a Poisson stream. The parameter μ of the Poisson distribution represents the average number of events occurring in each time interval (t_0, t). The function $\mu(t)$ is called the intensity of the Poisson flow.

EXAMPLE. Estimating the probability of receiving requests for delivery of goods

There are m = 100 control UAVs of service points (SPs) in the service area that can request service. The probability that within t - minutes the service point will contact is equal to P_z = 0.01.

It is necessary to estimate the probability that within t - minutes they will contact you:

1) three software programs;
2) less than three LAs;
3) more than three LAs;
4) at least one LA.

According to the condition m = 100, P_z= 0.01 and considering that the occurrence of software is independent with a large number of them and a low probability of this event (P_z = 0.01), we can use the Poisson formula (2.20):

$$P_m = \frac{\mu^m}{m!} e^{-\mu} \qquad (m = 0, 1, 2, \ldots),$$

where μ is the parameter of Poisson's law.

In this case, the value of X is distributed according to the Poisson law and its probability takes the value m.

1) Find the value of the parameter μ:

$\mu = m \cdot P_z = 100 \cdot 0{,}01 = 1.$

The probability that three software programs will communicate simultaneously ($m = 3$):

$$P_m(3) = \frac{e^{-1}}{3!} = \frac{0{,}367879}{6} = 0{,}0613.$$

2) Find the probability that less than three software programs will communicate:

$P(<3) = P_{100}(0) + P_{100}(1) + P_m(2) = e^{-1} + e^{-1} + \frac{e^{-1}}{2} = \frac{5}{2}e^{-1} = \frac{5}{2} \cdot 0{,}367879 = 0{,}9197.$

3) The probability that more than three software will communicate (P (> 3)) will have the following value.

Since the events "more than 3 software will communicate" and "no more than 3-LAs" P = P (> 3), and Q = P (< 3) - are opposite events, so P + Q = 1

i.e:

$P(> 3) = 1 - P(<3) = 1 - [P_{100}(0) + P_{100}(1) + P_{100}(2) + P_{100}(3)].$

Then $P(> 3) = 1 - [0{,}9197 + 0{,}0613] = 0{,}019.$

4) The probability that at least one PO (we denote the probability of this event by P).

The events "at least one aircraft will communicate" and "no aircraft will communicate" (denoted by the probability of this event by Q) are opposite. Therefore, $P + Q = 1$.

Hence, the probability that at least one UA will get in touch is equal to:

$P = 1 - Q = 1 - P_{100}(0) = 1 - e^{-1} = 1 - 0{,}36788 = 0{,}632.$

Other transportation problems are solved in a similar way if the flow of events can be described by Poisson's law.

2.3. Advantages and disadvantages of drones for last-mile cargo transportation

Drones offer a number of advantages for last-mile transportation, especially in the context of logistics and delivery. The key advantages of using cargo drones are shown in Fig. 2.2.

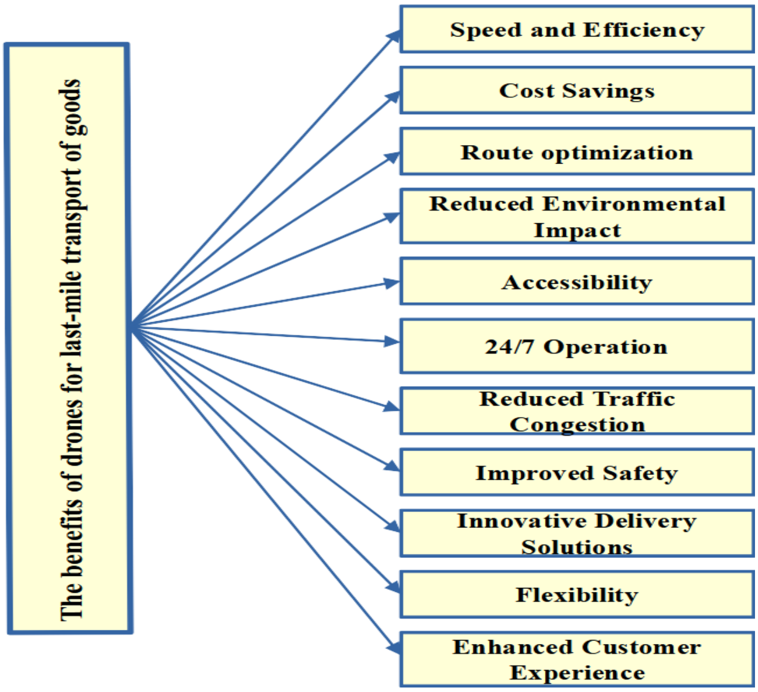


Fig 2.2 Advantages of cargo drones for last-mile freight transport

Despite these advantages, challenges such as regulatory frameworks, airspace management, safety issues, and public perception must be considered and addressed to ensure the successful integration of drones into last-mile delivery systems.

Disadvantages of drones for last-mile cargo transportation.

While drones have several advantages for last-mile cargo transportation, they also currently face several significant disadvantages and challenges (Fig. 2.3). Nevertheless, given the rapid development of UAV technology, most of them will be overcome.

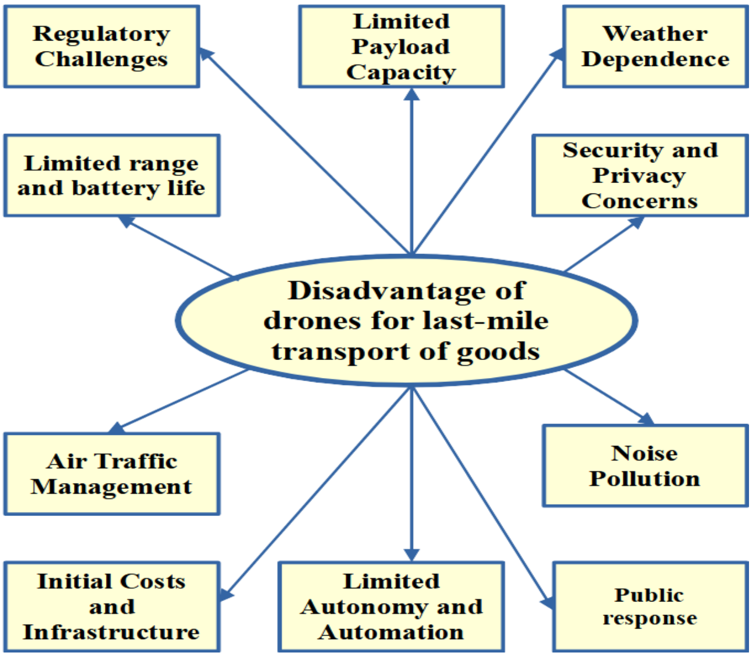


Fig 2.3. Disadvantage of drones for last-mile transport of goods

Balancing the advantages and disadvantages of drone technology requires careful consideration of these challenges and the development of effective strategies to overcome them. Of course, with the development of technology and legislation, some of these limitations may be eliminated or mitigated over time.

Drones have effectively revolutionized the last-mile logistics industry by enabling faster delivery, increased efficiency, and improved safety and security. The use of drones in this industry is expected to continue to grow as companies look to capitalize on their many benefits. Thus, it is clear that drones are transforming the delivery process and making last-mile logistics more efficient.

2.4. Optimization of supply chain operations and cost reduction

Companies are looking to optimize their supply chains and reduce costs. Drone delivery has a number of advantages over traditional delivery methods, including shorter delivery times, greater efficiency, and lower overhead costs.

In terms of speed, drones have the potential to significantly reduce delivery times. Drones can fly directly from point A to point B without the need to navigate traffic or stop at different locations. This not only reduces delivery times, but also increases efficiency as it eliminates the need for multiple drivers. In addition, drones require less energy than traditional vehicles, resulting in lower fuel costs and reduced emissions.

Optimizing supply chain operations and reducing costs depends on fuel efficiency . The fuel efficiency of an aircraft is determined by the amount of fuel it uses to cover a certain distance under certain conditions. This indicator is a fuel efficiency metric (FEM). Fuel efficiency is the distance traveled per unit of fuel used; for example, kilometers per liter (km/l) or miles per gallon (MPG), where 1 MPG (imperial) $\approx$ 0.354006 km/l. J= kg·m2·s−2. The higher the value, the more fuel-efficient the vehicle is (the greater the distance it can travel on a given amount of fuel). Energy efficiency is similar to fuel efficiency, but consumption is usually measured in units of energy such as mega joules (MJ), kilowatt hours (kWh), kilocalories (kcal), or British thermal units (BTU). The inverse of "energy efficiency" is "energy intensity," or the amount of input energy required to produce a unit of output, such as MJ/passenger-kilometer (for passenger transport), BTU/ton-mile or kJ/t-km (for freight transport), GJ/t (for steel and other materials), Btu/(kWh) (for electricity), or liters/100 km. Liters per 100 km is also a measure of "energy intensity," where the input is measured by the amount of fuel and the output by the distance traveled.

The results show that to achieve the best fuel efficiency, a cargo drone based on the very light class of general aviation aircraft (VLA) with a traditional aircraft layout should have a composite structure and a wing aspect ratio of about 10-12. Assessment of fuel efficiency at distances from 500 to 2500 km shows that such a UAV will be competitive with the current generation of large manned commercial cargo aircraft, achieving energy efficiency of about 7-8 MJ/(t.km). This is much better than the 14-24 MJ/(t.km) of utility turboprops. To a certain extent and in some cases, such a UCA will be competitive with road transport, whose energy intensity is estimated at 4-5 MJ/(t.km). This study should be considered as a preliminary step towards a comprehensive assessment and optimization of the transport systems of the UAS, including the aircraft itself, ground infrastructure, operation, etc.

The use of drones also provides cost savings. By optimizing the supply chain, companies can reduce inventory costs as well as labor costs. Drones can also transport goods directly from the supplier to the customer, eliminating the need for intermediaries. This results in lower costs for the customer as well as increased profits for the business. In addition to cost savings, drone delivery also provides greater accuracy and improved customer service. By using GPS tracking technology, companies can ensure that the package arrives on time and in the right place. This helps reduce customer complaints and increase customer satisfaction. In addition, drones can be used to monitor inventory levels, allowing companies to better manage inventory and reduce wastage.

The task of optimizing deliveries by drones can be solved in different ways. The author believes that the following approach is a rational way.

Problems of minimizing (or maximizing) functions under various additional conditions are typical mathematical models of decision-making processes in the computer-aided design of technical devices and systems, in vehicle control, in updating dependencies based on the analysis of experimental data and evaluating the efficiency of complex systems, including unmanned systems and complexes.

The simplest type of such a problem assumes that the choice of a variant of the unmanned object being designed (i.e., the optimization problem will be interpreted as the choice of a solution in design) is characterized by the choice of the value of the vector of design parameters $\boldsymbol{y} = (\boldsymbol{y_1}, \dots, \boldsymbol{y_N})$. At the same time, the conditions for the creation and operation of the vehicle impose some restrictions on the permissible values of the vector y. These are formally described as the requirement that the vector y belongs to some valid region $\boldsymbol{Q}$ in the $\boldsymbol{N}$ -dimensional parameter space $\boldsymbol{R^N}$.The effectiveness of an object variant that corresponds to a given value of the vector $\boldsymbol{y}$ is described by the indicator $\boldsymbol{\varphi(y)}$, which can be calculated based on the analysis of the mathematical model of this object. Such calculations will be called experiments. If we assume that a decrease in $\boldsymbol{\varphi(y)}$ corresponds to an improvement of the project, then the choice of the value of $\boldsymbol{y}^*$, which determines the best option, is reduced to an approximate solution of the minimization problem:

$$y^* = arg\ min \{\varphi(y): y \in Q\} \tag{2.21}$$

Based on the results $\boldsymbol{Z^i} = \boldsymbol{\varphi}(\boldsymbol{y^i}),\ \boldsymbol{1} \leq \boldsymbol{i} \leq \boldsymbol{k}$ of a finite number of experiments at points $\boldsymbol{y^i} \in \boldsymbol{Q}$.

The selection of experimental points can be carried out sequentially, i.e., when selecting the next point $\boldsymbol{y^{i+1}}$, the already known results $\boldsymbol{Z^1}, \dots, \boldsymbol{Z^i}$of the experiments at the previous points $\boldsymbol{y^1}, \dots, \boldsymbol{y^i}$ can be used. It is assumed that some selected points may not belong to the region $\boldsymbol{Q}$**.** The mathematical model of the object should contain a test to detect such cases (with a negative test result taken as the result of the experiment). Thus, the procedure for selecting points from region $\boldsymbol{Q}$ can be determined indirectly - through the test for belonging to this region. It is also possible that the admissible region is empty, which corresponds to the incompatibility of the requirements for the object. Establishing this fact is also considered a solution to problem (2.21).

The accuracy of the approximate solution of problem (2.21), which has coordinate $\boldsymbol{y}_*$ and value $\boldsymbol{\varphi}_* = \boldsymbol{\varphi}(\boldsymbol{y}_*)$,can be characterized by some accepted (for meaningful reasons) notion of proximity to the exact solution, for example, by the estimate $||\boldsymbol{y}^* - \boldsymbol{y}_*||\ or\ the\ estimate\ |\boldsymbol{\varphi}^* - \boldsymbol{\varphi}_*|$, where $\boldsymbol{\varphi}^* = (\boldsymbol{\varphi})\boldsymbol{y}^*$.

Limited Differences in the Estimation of the Optimum. Any possibility of a reliable estimate of the global optimum in a multi-extreme problem is fundamentally based on the availability of certain a priori information that allows us to relate possible values of the minimization function to known values at points where measurements have already been made.

Let's assume that the admissible region $\boldsymbol{Q}$ in problem (1) coincides with the search region $\boldsymbol{D}$ (i.e., there are no restrictions).

We will use the fact that in many applied problems, a change in the parameter vector $\boldsymbol{y}$ leads to a change in the characteristics of the object, limited to a certain degree of change in $\boldsymbol{y}$. This fact can be interpreted as a reflection of the capacity constraint that generates changes. Of course, there are situations when opposite phenomena occur (shock effects, resonance phenomena, etc.), which should be modeled as discontinuities in characteristics.

A formal model that describes the above property of boundedness of changes for the considered problem with one characteristic $\boldsymbol{\varphi(y)}$ can be, for example, the following system of inequalities:

$$|\varphi(y') - \varphi(y'')| \leq K\rho(y', y''), y', y'' \in D, \qquad (2.22)$$

Where $\boldsymbol{\rho(y', y'')}$ is some distance function in the parameter space, and $\boldsymbol{K}$ is a given constant. In the case when in (2.21).

$$\rho(y', y'') = (||y' - y''||)^{1/N}\ , \qquad (2.23)$$

Where the function $||\cdot||$ corresponds to the Euclidean metric, we say that the function φ satisfies the uniform condition with exponent $\boldsymbol{1/N}$ and coefficient $\boldsymbol{K}$.

When $\boldsymbol{N = 1}$, this condition is called the Lipschitz condition with constant $\boldsymbol{K}$. We will consider this case to explain the main ideas, and for the sake of clarity, we assume that the problem is one-dimensional, and, therefore, the search domain $\boldsymbol{D}$ is some segment $[\boldsymbol{a}, \boldsymbol{b}]$ of the real $\boldsymbol{y}$-axis.

So, let the function $\boldsymbol{\varphi(y), y} \in [\boldsymbol{a}, \boldsymbol{b}]$ satisfy the condition with a given constant $\boldsymbol{K}$, i.e:

$$|\ \varphi(y') - \varphi(y'')| \leq K|y' - y''|, y', y'' \in [a, b], \qquad (2.24)$$

And, let the experiments be carried out at points $\boldsymbol{y^1, \ldots, y^k}$ in the interval $[\boldsymbol{a}, \boldsymbol{b}]$. Renumber the points $\boldsymbol{y^1}$ using the lower indices in ascending order of coordinate values, i.e:

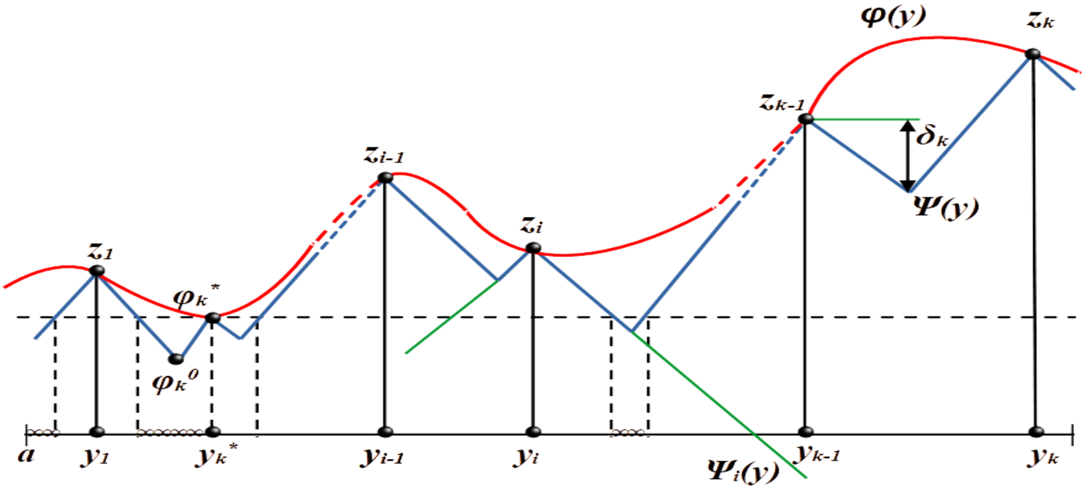


Fig. 2.4. Search For the Global Optimum

$$\boldsymbol{a \le y_1 < \dots < y_i < \dots < y_k \le b,}$$

And denote the function values calculated in them as $\boldsymbol{z_i = \varphi(y_i), 1 \le i \le k.}$ Fig.1 illustrates the above. Let's introduce the functions:

$$\varphi_i(\mathrm{y}) = z_i - K|y - y_i|, y \in D, 1 \le i \le k, \quad (2.25)$$

for which, in accordance with (2.24), the following applies:

$$\varphi(y) \ge \psi_i(y), y \in D, 1 \le i \le k$$

or

$$\varphi(y) \ge \psi(y) = max\{\psi_i(y) : 1 \le i \le k\}, \;\; y \in D, \qquad (2.26)$$

that is, the experimental results and condition (2.24) allow us to construct the minorant $\boldsymbol{\psi(y)}$ from (2.26) of the minimized function $\boldsymbol{\varphi(y)}$ in the search domain. At the same time, the desired minimum value of $\boldsymbol{\varphi(y^*)}$ is estimated:

$$\overset{\circ}{\varphi}_k \le \varphi(y^*) \le \varphi_k^* , \qquad (2.27)$$

де

$$\overset{\circ}{\varphi}_k = min\{\psi(y) : y \in D\},$$

$$\varphi_k^* = min\,\{z_i : 1 \le i \le k\}, \qquad (2.28)$$

and the upper estimate of $\boldsymbol{\varphi_k^*}$ corresponds to the point $\boldsymbol{y_k^*}$ at which it is reached, i.e., $\boldsymbol{\varphi_k^* = \varphi(y_k^*)}$. The lower bound $\boldsymbol{\overset{\circ}{\varphi}_k}$ can be calculated quite simply. If we denote:

$$\overset{\circ}{\varphi}_{ki} = min\{\psi(y) : y \in [y_{i-1}, y_i]\}, 1 \le i \le k+1, \quad (2.29)$$

where $y_0 = a$ and $y_{k+1} = b$, then according to (2.28),

$$\overset{\circ}{\varphi}_k = \overset{\circ}{\varphi}_{kt} = min\{\overset{\circ}{\varphi}_{ki} : 1 \le i \le k+1\}, \qquad (2.30)$$

in accordance with (2.24), (2.25), (2.29):

$$\overset{\circ}{\varphi}_{ki} = (z_i + z_{i-1} - K\delta_i)/2, \;\; 1 < i \le k, \qquad (2.31)$$

$$\overset{\circ}{\varphi}_{k1} = z_1 - K\delta_1, \overset{\circ}{\varphi}_{k,k+1} = z_k - K\delta_{k+1}, \qquad (2.32)$$

where $\delta_i = y_i - y_{i-1}, 1 \le i \le k+1.$

The search method. It follows from (2.29), (2.31), (2.32) that:

$$\delta_i = min(z_{i-1}, z_i) - \overset{\circ}{\varphi}_{ki} \le K\delta_i)/2, \;\; 1 < i \le k, \qquad (2.33)$$

$$\delta_i = z_1 - \overset{\circ}{\varphi}_{k1} = K\delta_1, \;\; \delta_{k+1} = z_k - \overset{\circ}{\varphi}_{k,k+1} = K\delta_{k+1}. \qquad (2.34)$$

Since, at the same time:

$$\varphi_k^* - \overset{\circ}{\varphi}_k min\{\delta_i \,:\, 1 \le i \le k+1\},$$

Then the uniform location of the test points $\boldsymbol{y_i}, \boldsymbol{1} \leq \boldsymbol{i} \leq \boldsymbol{k}$, at which $\Delta_i = \boldsymbol{2\delta/K}, \boldsymbol{1} \leq \boldsymbol{i} \leq \boldsymbol{k}, \boldsymbol{\delta_1} = \boldsymbol{\delta_{k+1}} = \boldsymbol{\delta/K}$, provides an estimate of (2.27) with an accuracy of δ, since, according to (2.33) - (2.34):

$$\varphi_k^* - \overset{\circ}{\varphi}_k \leq \delta. \qquad (2.35)$$

This method of finding an optimal solution is called the uniform grid search method.

Search on an Uneven Grid. To obtain an estimate of (2.35) To obtain an estimate of by the brute force method, we need to perform $\boldsymbol{k} = \boldsymbol{K}(\boldsymbol{b} - \boldsymbol{a})/\boldsymbol{2\delta}$ experiments. This estimate can be achieved with a much smaller number of experiments, given that the desired solution $\boldsymbol{y}^*$ can only belong to a set:

$$D_k = \{y \in D: \psi(y)\} \leq \varphi_k^* \qquad (2.36)$$

(In Fig. 2.4 the corresponding set $\boldsymbol{D_k}$ is indicated by shading). Thus, it is possible to perform the search on a coarse grid, which corresponds to an accuracy of $\boldsymbol{\delta'} > \boldsymbol{\delta}$ and requires a small number of experiments $\boldsymbol{k'}$. At the next stage of the search, the search is performed only in a subset of $\boldsymbol{D}_k$ for a higher accuracy $\boldsymbol{\delta''} < \boldsymbol{\delta'}$, and so on (until the required accuracy $\boldsymbol{\delta}$ is reached). By increasing the number of stages and decreasing the number of experiments at each stage, it is possible to build a fully sequential method in which exactly one experiment is performed at each stage.

One such method, which consistently generates a non-uniform mesh, is that each subsequent $\boldsymbol{k} + \boldsymbol{1}$ iteration (next experiment) is performed at a point:

$$y^{k+1} = (y_t + y_{t-1})/2 - (z_t + z_{t-1})/2K,$$

In which the minimum of the minorant $\boldsymbol{\psi}(\boldsymbol{y})$ is achieved, i.e., the lower estimate of $\overset{\circ}{\boldsymbol{\varphi}}_{\boldsymbol{k}}$ from (2.28), (2.30) is achieved.

Expediency of conducting the next experiment at the point of minimum of the minorant $\boldsymbol{\psi}$ can be (informally) motivated by the fact that obtaining a small value of the minimized function $\boldsymbol{\varphi}$ at this point will lead to an improvement in the upper estimate $(\boldsymbol{\varphi}_{\boldsymbol{k+1}}^* < \boldsymbol{\varphi}_{\boldsymbol{k}}^*)$, and obtaining a large value will lead to an improvement in the lower estimate $\left(\overset{\circ}{\boldsymbol{\varphi}}_{\boldsymbol{k+1}} > \overset{\circ}{\boldsymbol{\varphi}}_{\boldsymbol{k}}\right)$, if the latter was achieved at a single point. In this case, each experiment improves the estimate (2.27). The starting points for the experiments can be, for example, $\boldsymbol{y^1} = \boldsymbol{a},\ \boldsymbol{y^2} = \boldsymbol{b}$.

Estimation of the constant and stochastic model. The previous discussion was based on the assumption that the constant $\boldsymbol{K}$ in conditions (2.22) or (2.24) is given. A rough upper estimate that can be obtained in applied problems leads, as can be seen from (2.35), to the need to use significantly denser networks (uniform or non-uniform), the nodes of which are used for experiments. With an underestimation of the value of the constant, inequalities (2.24) and the entire scheme for estimating the optimum based on them lose their validity.

A possible solution is as follows. Instead of condition (2.24), which implies reliable boundedness of the differences of the function, we assume that the differences $\boldsymbol{\varphi}(\boldsymbol{y}') - \boldsymbol{\varphi}(\boldsymbol{y}'')$ are interpreted as random variables with an absolute value of the mathematical expected value equal to $\boldsymbol{L}/\boldsymbol{y}' - \boldsymbol{y}''/$, if the minimum point y^* does not lie between the points $\boldsymbol{y}', \boldsymbol{y}''$. In this case, it is possible to build current estimates of the unknown constant $\boldsymbol{L}$ based on the results of the experiments, i.e., based on the observed values of the relative differences of the function.

This approach leads to the fact that the estimates of the desired optimum based on the results of experiments are also stochastic in nature. At the same time, both estimates using probability distributions and precise estimates, such as maximum likelihood estimates for the global minimum point, can be entered, which allows you to build a sequential search method, according to which each subsequent experiment is carried out at the current point of maximum likelihood.

Maximum likelihood algorithm. The first experiment is performed at an arbitrary point $\boldsymbol{y^1} \in (\boldsymbol{a}, \boldsymbol{b})$. The point of any subsequent $\boldsymbol{k+1}$ experiment is determined by the expression:

$$y^{k+1} = \frac{y_t + y_{t-1}}{2} - \begin{cases} (z_t - z_{t-1})/2r\mu, & 1 < t \le k, \\ 0, t = 1, & t = k+1, \end{cases} \qquad (2.37)$$

where the number t is determined from the condition:

$$R(t) = \max\{R(i): 1 \le i \le k+1\}, \qquad (2.38)$$

where for $\boldsymbol{1 < i \le k}$

$$R(i) = \delta_i + (z_i - z_{i-1})^2/\mu^2\delta_i - 2(z_i + z_{i-1})/r\mu, \qquad (2.39)$$

$$R(1) = 2\delta_1 - 4z_1/r\mu, R(k+1) = 2\delta_{k+1} - 4z_k/r\mu \quad (2.40)$$

$$\mu = max\{|z_i - z_{i-1}| \;/\; \delta_i : \; 1 < \; i \; \leq \; k \}. \qquad (2.41)$$

If expression (2.41) s equal to zero, as well as when $k = 1$, it is assumed that $\mu = \mathbf{1}$. The number r from (2.37), (2.39), (2.40) is a parameter of the method, and the inequality $\boldsymbol{r} > \mathbf{1}$ must be satisfied.

Convergence conditions. Methods (2.37) - (2.41), as already mentioned, sequentially perform iterations at the points that are most likely to contain the global minimum, estimating their location by means of an appropriate interpretation of the experimental results within a certain stochastic model. However, the rules (2.37) – (2.41) for selecting iterations can be investigated beyond the initial assumptions. If this algorithm is used to minimize (with a constant $\boldsymbol{k}$) the function $\boldsymbol{\varphi}$, then for any boundary point y^', the sequence $\{\boldsymbol{y}^{\boldsymbol{k}}\}$ generated by it is valid:

1) the point $\boldsymbol{y}'$ is at least a locally optimal point of the function $\boldsymbol{\varphi}$ if this function has a finite number of local minima;

2) if there is another boundary point $\boldsymbol{y}''$ of the sequence $\{\boldsymbol{y}^{\boldsymbol{k}}\}$, then $\boldsymbol{\varphi}(\boldsymbol{y}'') = \boldsymbol{\varphi}(\boldsymbol{y}')$, which means that simultaneous convergence to different values of the function is impossible, and, therefore, the method generates an uneven mesh when minimizing functions other than a constan;

3) $\boldsymbol{z}^{\boldsymbol{k}} = \boldsymbol{\varphi}(\boldsymbol{y}^{\boldsymbol{k}}) \geq \boldsymbol{\varphi}(y'), \boldsymbol{k} = \mathbf{1}, \mathbf{2}, \dots$, i.e., the algorithm cannot generate convergence to points where the function value exceeds the result of any experiment;

4) if at some stage the condition.

$$r\mu > 2K, \qquad (2.42)$$

then $\boldsymbol{y}'$ is the point of global minimum of the function $\boldsymbol{\varphi}$, and, moreover, the set of all boundary points of the sequence $\{\boldsymbol{y}^{\boldsymbol{k}}\}$ coincides with the set of points of global minimum of the function $\boldsymbol{\varphi}$.

It is important to note that this algorithm, which does not require an a priori setting of the Lipschitz constant, has proven to be effective in solving many specific applied problems.

The influence of dimensionality. The considered scheme for estimating the global optimum based on the test results and the a priori assumption (2.22), which characterizes the limitation of the differences in the values of the minimized function to a certain extent of the differences in the corresponding argument values, remains true in multidimensional problems, i.e., when $\boldsymbol{N > 1}$. However, the computational complexity of the evaluation increases significantly.

Exponential growth of the search complexity. Let us assume that the minimized function φ satisfies the condition (with constant $\boldsymbol{K}$) in the admissible domain $\boldsymbol{Q = D}$ of (2.25). Similarly, to (2.25), we introduce a family of minorants $\boldsymbol{\psi_i}$, i.e:

$$\varphi(y) \geq \psi_i(y) z^i - K||y - y^i|, y \in D,$$

$$1 \leq i \leq k, \qquad (2.43)$$

where $\boldsymbol{y^i}$ and $\boldsymbol{z^i = \varphi(y^i)}$ denote the points and experimental results, respectively. It follows from (2.43) that in the closed ε -neighborhood $\boldsymbol{U(y^i)}$ of the point $\boldsymbol{y^i}$, there is an estimate:

$$z^i - min\,\{\varphi(y) : y \in D \cap U(y^i)\} \leq \delta,$$

If $\boldsymbol{\varepsilon = \delta / K}$. By selecting the test points so that they form an $\boldsymbol{\varepsilon}$ -network in the search area $\boldsymbol{D}$, we obtain an estimate of the desired solution:

$$\varphi_k^* - \varphi(y^*) \leq \delta, \qquad (2.44)$$

where

$$\varphi_k^* = min\,\{z^i : 1 \leq i \leq k\}, \qquad (2.45)$$

since, for the solution point $y^*$and the coverage of the domain $\boldsymbol{D}$ by the neighborhoods of $\boldsymbol{U(y^i)}$, it is true that:

$$\varphi(y^*) = \min_{1 \leq i \leq k}(min\,\{\varphi(y) : y \in D \cap U(y')\}). \qquad (2.46)$$

the way in which the admissible region $\boldsymbol{Q}$ is set determines the search area for the global extremum $\boldsymbol{D = \{y \in R^N : a_i \leq y_i \leq b_i,\ 1 \leq i \leq N\}}$, which describes the range of possible parameter changes, and additional constraints such as inequalities describing the conditions for the normal functioning of the object, which can be reduced to a single form $\boldsymbol{g_i(y) \leq 0,\ 1 \leq i \leq m}$:

$$Q = \{y \in D : g_i(y) \leq 0,\ 1 \leq i \leq m\}. \qquad (2.47)$$

A uniform $\boldsymbol{\varepsilon}$ -network in a multidimensional domain $\boldsymbol{D}$ from Equation (2.47) can be effectively constructed in various ways. In this case, the total number of nodes in such a uniform network exceeds $(\boldsymbol{b_1} - \boldsymbol{a_1} \cdot \ldots \cdot (\boldsymbol{b_N} - \boldsymbol{a_N})/\boldsymbol{\varepsilon^N}$, i.e., grows exponentially with increasing dimension N.

Difficulty in consistently constructing non-uniform grids. Similarly to the one-dimensional case, it is possible to reduce the number of measurements required to obtain an estimate of (2.44) using the brute force method by first performing a low-fidelity search on a coarse mesh containing k nodes and, based on the measurement results, constructing the set $\boldsymbol{D_k}$ from (2.36), where $\boldsymbol{\psi}(\boldsymbol{y})$ is the upper bending (2.26) minor of $\boldsymbol{\psi_i}$ from (2.43) and $\boldsymbol{\varphi_k^*}$ from (2.25). The set $\boldsymbol{D_k}$ should contain the desired solution $\boldsymbol{y}^*$, and further search (with greater accuracy) should be performed in this set, and so on.

When $\boldsymbol{N} = \mathbf{1},$ the set (2.36) is a set of segments on the real number axis (see shading in Fig. 2.5). When $\boldsymbol{N} > \mathbf{1}$, the constructive task of this set becomes much more complicated. To illustrate the difficulties, let us consider a specific example for the case of $\boldsymbol{N} = \mathbf{2}$ and $\boldsymbol{k} = \mathbf{4}$ shown in Fig. 2.5, where in the rectangular region $\boldsymbol{D}$ the points of the four measurements are marked (by small black circles) and the values of the minimized function at these points are indicated, as well as the lines of a constant level of the minorant $\boldsymbol{\psi}(\mathbf{y})$. The outline of the non-contour region $\boldsymbol{D_k}$ is highlighted (shading).

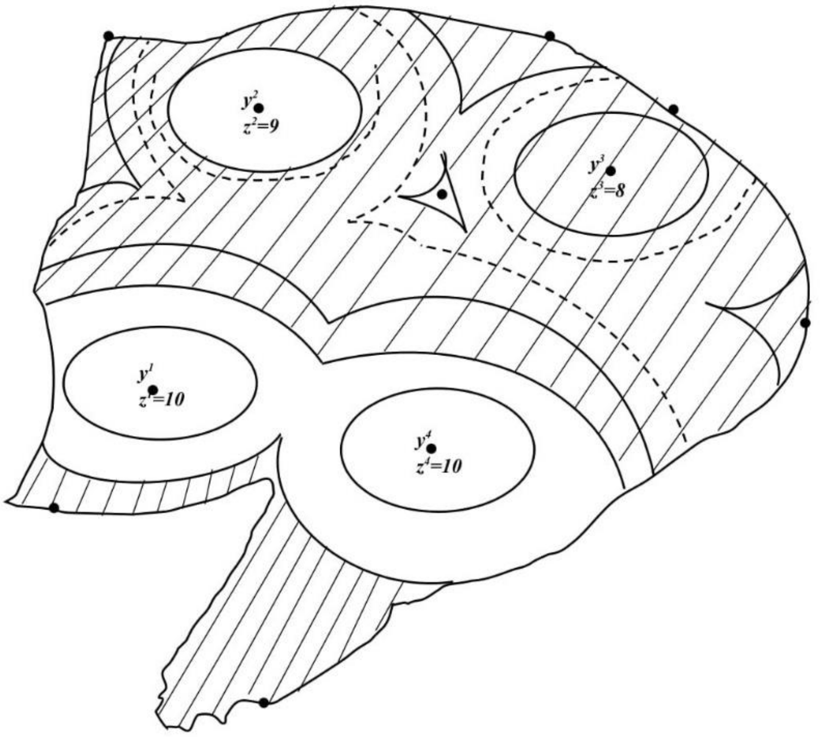


Fig. 2.5. Unlinked search area for parameters

The difficulty of determining the region $\boldsymbol{D_k}$, which should include a uniform grid corresponding to a higher accuracy, is removed if we switch to a fully sequential search scheme, when at each $\boldsymbol{k + 1}$ step in the corresponding region $\boldsymbol{D_k}$ exactly one measurement is performed, as discussed for the one-dimensional case. In this case, the point $\boldsymbol{y^{k+1}}$ of the next measurement that improves the estimate of (2.27), can, for example, be used as the point at which the minorant $\boldsymbol{\psi(y)}$ reaches the absolute minimum of (2.28). This point, of course, belongs to the domain $\boldsymbol{D_k}$, but it can be determined by minimizing $\boldsymbol{\psi}$ in a simpler domain $\boldsymbol{D}$.

In the one-dimensional case, according to (2.29) - (2.32) minimizing $\boldsymbol{\psi}$ is quite simple and reduces to choosing the minimum of $\boldsymbol{k + 1}$ values (2.30), each of which is the minimum value of (2.29) of the minor of ψ in the corresponding subinterval $\boldsymbol{[y_{i-1,} y_i]}$, $\boldsymbol{1 \leq i \leq k + 1}$. This simplicity follows from the fact that for $\boldsymbol{N = 1}$, each measurement point y_i falls into at most two intervals $\boldsymbol{[y_{i-1,} y_i]}$, $\boldsymbol{[y_i, y_{i+1}]}$, and the minimum value of ψ in each such interval does not depend on the results of measurements in other intervals (and can be found analytically as a function of the coordinates of the endpoints of the interval and the values of the minimized function at these endpoints). When $\boldsymbol{N} > \mathbf{1}$, the relationship between the measurement results and the minimum point is minor:

$$y^{k+1} = \arg\min\{\psi\ (y;\ y^1, \dots, y^k;\ z^1, \dots\ ,\ z^k): y\ \in\ D\} \qquad (2.48)$$

Indeed, the rule (2.48) for selecting the next measurement point itself includes a minimization problem similar to the original problem (2.22). The values of the function $\boldsymbol{\psi}$ from (2.26), (2.43) are usually much simpler to calculate than the values of the object characteristic $\boldsymbol{\varphi}$ from (2.22), which must be minimized, obtained by analyzing a complex mathematical model of this optimization object. However, problem (2.46) has to be solved at each iteration of problem (2.22). Note that this difficulty remains unchanged for approaches according to which the next iteration is carried out not at the point of minimum of the minority $\boldsymbol{\psi}$, but at the point of maximum likelihood or at the point of minimum of the expected value of the function $\boldsymbol{\varphi}$ (both of these rules are based on probabilistic analogues of model (2.22), imilar to the model for the case $\boldsymbol{N} = \mathbf{1}$ discussed above), or by using another rule that ensures consistent improvement of the estimates (2.27) at each (or almost each) step by performing iterations at the point (2.46), that provides an extremum to some current estimate $\boldsymbol{\varphi}$ of the desired solution.

Conclusions of chapter 2

Any possibility of a reliable estimate of the global optimum in a multi-extreme problem is fundamentally based on the availability of certain a priori information that allows us to relate possible values of the minimization function to known values at points where measurements have already been made. It is proved that solving multidimensional problems using a simple search method on a uniform grid requires a significant number of iterations and, in fact, is possible only for small values of N and low solution accuracy. The use of economical sequential methods that create an uneven grid requires solving an additional multi-extreme problem of the type (2.46) at each iteration, which also needs to be solved by search methods (for example, the brute force method), which dramatically increases the computational complexity of the iteration.

On the other hand, when $N = 1$, simple sequential search methods can be constructed for a multi-extreme problem based either on a given value of the constant or on estimates calculated during the solution process, which create an economical non-uniform grid whose nodes are used for measurements. In this regard, it is worth considering the possibility of reducing multidimensional, multi-extreme problems to some equivalent one-dimensional problems.

In conclusion, it should be noted that a targeted search for solutions to multi-extreme problems based on a priori assumptions of type (2.22) bout the boundedness of differences generally requires more measurements than a local search for solutions to unimodal problems, since in the first case measurements are made at the nodes of a (non-uniform) grid in the multidimensional search area, and in the second case - at the nodes located on some one-dimensional descent path. This ratio can change under certain conditions, complementing model (2.22).

In general, drone delivery is an effective option for companies seeking to optimize their supply chains and reduce costs. By reducing delivery times, increasing efficiency, and saving costs, drone delivery can help businesses stay competitive in the marketplace.

CHAPTER 3. METHODOLOGY FOR ASSESSING THE EFFICIENCY OF CARGO TRANSPORTATION BY DRONES IN CONDITIONS OF INCOMPLETE INFORMATION

3.1. Methods for evaluating the efficiency of complex systems

Determination of system efficiency by an analytically determined efficiency indicator.

The purpose of determining the efficiency of a system is to optimize the system in the process of development and modernization or to select the closest variant of the system for implementation to the optimal one according to the selected efficiency indicator [11 , 13, 95, 173, 178,184].

The peculiarity of complex systems is the need to evaluate them by many individual quality indicators: accuracy, reliability, cost, etc. In accordance with the principle of unambiguity (3.1), the performance indicator of the system as a whole as a criterion of optimality should be presented in the form of one general indicator that includes all the individual indicators taken into account. In general, the effectiveness of the system implementation or modernization is assessed by means of an indicator:

$$E = D/C, \qquad (3.1)$$

where

$\boldsymbol{D} -$ is the effect, i.e. the value that shows what the application of a new system or modernization of an existing one gives;

$\boldsymbol{C} -$ is the cost of developing, implementing and operating or modernizing the system.

Hereafter, we will assume that the modernization of an existing system is equivalent (in terms of efficiency assessment) to the introduction of a new system.

Theoretically, the efficiency indicator of the new system $\boldsymbol{E}$ takes into account all the costs and benefits of its introduction: the costs of social labor, satisfaction of qualitatively new needs, improvement of product quality, etc. However, not all of these indicators can be directly measured. If the effect of the system implementation can be determined in monetary terms, then the absolute value of economic efficiency, for example, the annual economic effect, is estimated as a difference:

$$\epsilon = \epsilon_{\text{річн}} - \varepsilon_n C, \qquad (3.2)$$

where

$\boldsymbol{\epsilon}_{\text{річн}}$ – is the annual increase in profit as a result of the new system implementation;

$\boldsymbol{\varepsilon_n}$ –is the normative coefficient of capital investments in this industry. In this case, the effectiveness of the system implementation is determined by the economic efficiency indicator:

$$\varepsilon = \epsilon_{\text{річн}}/C. \qquad (3.3)$$

The introduction of a new system (or the modernization of an existing one) will be expedient if the actual indicator of its economic efficiency $\boldsymbol{\varepsilon}$ is higher than the normative coefficient of capital investments in this industry, which is ensured when using capital investments for the introduction of systems already mastered in this industry:

$$\varepsilon > \varepsilon_n. \qquad (3.4)$$

At the same time, the system variant for which the economic efficiency indicator ε is the highest compared to all other developed system variants is preferred for implementation.

If the full effect of the introduction of a new system cannot be presented in monetary terms, then the concept of technical and economic efficiency is used, which, in addition to saving public labor costs, takes into account the measurable technical indicators of the new system:

$$\varepsilon = F(y_1, y_2, \dots, y_l, C), \qquad (3.5)$$

where

$\boldsymbol{y_1, y_2, \dots, y_l}$ – measurable technical indicators, which are called individual quality indicators;

$\boldsymbol{l}$ – the number of individual quality indicators taken into account.

Costs $\boldsymbol{C}$ for the development, implementation and operation of new equipment can be considered as one of the individual quality indicators, so formula (3.5) can be written in a general form::

$$\varepsilon = F(y_1, y_2, \dots, y_n), \qquad (3.6)$$

where

$\boldsymbol{n}$ – is the total number of individual quality indicators taken into account, including costs $\boldsymbol{C = y_n}$.

Individual quality indicators depend on structural and design parameters that can be changed during the development and implementation of the system:

$$y_i = \varphi_i(x_1, x_2, \dots, x_m), \ i = (\overline{1, n}), \quad (3.7)$$

where

$\boldsymbol{x_1, x_2, \dots, x_m}$ – structural and design parameters of the system and its elements.

If the functions $\boldsymbol{\varphi_i}$ and $\boldsymbol{F}$ are known, i.e., expressed analytically, then it is easy to determine the performance indicator $\boldsymbol{\varepsilon}$, since the parameters $\boldsymbol{x_1, x_2, \dots, x_m}$ are known for each system variant.

If the function $\boldsymbol{F}$ is unknown, it is sometimes limited to assessing the system's effectiveness by one of the most important individual indicators (e.g., $\boldsymbol{y_1}$), and imposing restrictions on the others to ensure that they do not exceed certain limits:

$$\varepsilon = y_1,$$

$$y_{\text{H}i} \le y_i \le y_{\text{B}i}, i = 2, 3, \dots, n,$$

where

$\boldsymbol{y_{\text{H}i}}$ and $\boldsymbol{y_{\text{B}i}}$ – are the lower and upper limits of the $\boldsymbol{i}$-th individual quality indicator. Depending on the individual quality indicator, one of the limits (upper or lower) may not be limited.

Evaluating the system efficiency by one individual indicator while limiting other individual indicators has the disadvantage that solving the optimization problem or choosing the practically optimal system variant for implementation will be ambiguous.

Many variants of systems can be obtained with the same or approximately the same main individual quality indicator $\boldsymbol{y_1}$ with other individual indicators (which differ significantly) that satisfy the constraints. In this case, it is impossible to determine with certainty which system variant will be close to the optimal one.

One method of determining the near-optimal variant of a complex system is to replace the performance indicator function (3.6), when its analytical expression is unknown, with a linear function that includes all the main individual quality indicators:

$$\varepsilon = b_1 y_1 + b_2 y_2 + \dots + b_n y_n, \qquad (3.9)$$

where

$\boldsymbol{b_1} + \boldsymbol{b_2} + \dots + \boldsymbol{b_n}$ – weighting coefficients. If there are restrictions.

$$y_{\text{н}i} \le y_i \le y_{\text{в}i}. \qquad (3.10)$$

The linear form of the indicator (criterion) of the effectiveness of complex systems is the simplest function that takes into account all the main individual quality indicators. It is used to identify the practically optimal (from competing) option without any difficulty.

The main individual indicators (criteria) of the quality of autopilot systems of modern UAVs include the following.

1) Quality of the control process. This indicator consists of a number of assessments, such as steady-state error, overshoot, transient time, independence of the controlled variable from disturbances, etc. simultaneously ensuring high control quality indicators for all indicators in practice is often difficult. For example, the desire to ensure high accuracy in the steady-state mode mixes with the implementation of astatic systems, in which the control error tends to zero regardless of the size of the action, if the latter acquires a stable constant value. However, this increases the transient time.

The theory of invariance provides a method for synthesizing systems in which the controlled variable is invariant to disturbing influences and covariant to control influences. As a generalized absolute criterion for assessing the quality of the control process, when determining the effectiveness of UAVs in the automatic flight mode, a certain functional $\boldsymbol{y_1} = \boldsymbol{J}(\boldsymbol{x_1}, \boldsymbol{x_2}, \dots, \boldsymbol{x_n})$ is acquired. The best system will be the one in which the value of the functional is $\boldsymbol{y_1}$ minimal.

2) Reliability $\boldsymbol{y_2}$. Not only UAVs, but any system must be reliable in operation. The reliability of a system can be assessed by the failure rate over a certain period of operation. The best system will be the one with the lowest failure rate $\boldsymbol{y_2}$ and the highest probability of failure-free operation. The maximum permissible failure rate is determined based on the specific operating conditions of the system in question.

3) Mass y_3 and dimensions y_4. They are one of the main indicators of system quality. As a rule, in all cases, they should be minimal. The maximum allowable weight and dimensions are set based on specific conditions. It is known that particularly stringent requirements are imposed on control systems located on unmanned aerial vehicles.

4) Ease of maintenance y_5. The assessment of this indicator is closely related to the assessment of operational reliability. The purpose of maintenance is to bring the system to an operating state where the probability of failure is minimized. Maintenance includes work on preliminary adjustment and adjustment of the system, control inspections, routine maintenance, preflight preparation, etc.

The ease of maintenance of a UAV can be assessed by the average time spent on bringing the system into working order over a certain period of the system's operation. The quality of such a system will be higher, the less time it takes to maintain it.

5) Ergonomics of the system y_6. Human-machine systems belong to the number of organic systems in which a human operator or a group of operators is a necessary link (3.2 - 3.5). In organic systems, a machine is any technical device designed to convert information, energy, or matter. Thus, any technical product, since it is operated by a human, should be considered as a machine of a human-machine system. Automatic systems should also be considered as machines of an organic system, since they are operated by humans, even though humans are not part of their closed loop.

In an ergonomic system, human-machine compatibility must be ensured, i.e., the characteristics of the machine must be consistent with the psychophysiological characteristics of the person. There are five types of compatibility:

- information – matching the characteristics of the Z_1 machine (e.g., the speed of information output, forms of presentation of the original information, etc.) with the characteristics of a person in terms of receiving, storing, processing, and transmitting information;
- energy – matching the strength and power characteristics of the Z_2 machine

(for example, the force on the control handles) with the strength and power characteristics of a person;

- spatial and anthropometric - matching the spatial location of the controls and the $\boldsymbol{Z_3}$ operator's workstation with the anthropometric characteristics of a person;
- biophysical – matching the parameters of the microclimate created by the $\boldsymbol{Z_4}$ with the physiological characteristics of a person;
- technical and aesthetic – providing artistic and aesthetic decoration of the $\boldsymbol{Z_5}$ car and workplace in accordance with the high artistic taste of a person.

Each of the machine characteristics $\boldsymbol{Z_1} - \boldsymbol{Z_5}$ is determined by a set of variables (continuous or discrete parameters). For example, the information characteristic $\boldsymbol{Z_1}$ is determined by the speed of information output $\boldsymbol{z_{11}}$, sound $\boldsymbol{z_{12}}$, type of coding $\boldsymbol{z_{13}}$, method of displaying the original information $\boldsymbol{z_{11}}$, etc.:

$$Z_1 = \psi_1(z_{11}, z_{12}, \dots, z_{1m}), \qquad (3.11)$$

where

$\boldsymbol{m} -$ is the number of parameters to be taken into account.

Machine-human compatibility in an ergonomic system means that the machine's performance parameters must lie within certain limits:

$$z_{\text{н}ki} \leq z_{ki} \leq z_{\text{в}ki}\,, \qquad (3.12)$$

where

$\boldsymbol{k} -$ number of the characteristic by type of compatibility;

$\boldsymbol{i} -$ number of the parameter of the characteristic;

$\boldsymbol{z_{\text{н}ki}}, \boldsymbol{z_{\text{в}ki}} -$ lower and upper limits of change in the parameter $\boldsymbol{z_{ki}}$, which are determined by the permissible values of the parameters of the corresponding human characteristics. In an optimal ergonomic system, the parameters of machine characteristics that are taken into account when ensuring compatibility must be equal to the optimal parameters of the corresponding human characteristics:

$$z_{ki} = z_{ki\text{опт}}, k = (\overline{1,5}), i = (1, m_k), \qquad (3.13)$$

Where

$\boldsymbol{m_k}$ – is the number of parameters considered in the $\boldsymbol{k}$-th characteristic;

$\boldsymbol{z_{ki}}_{\text{опт}}$ – is the optimal value of the $\boldsymbol{i}$-th parameter of the $\boldsymbol{k}$-th human characteristic.

It should be noted that the optimal human parameters $\boldsymbol{z_{ki}}_{\text{опт}}$ re defined as average based on the processing of the results of a study of many operators working with this class of UAVs.

The ergonomics of the machine as the degree of fulfillment of ergonomic requirements is evaluated using the rati:

$$H = W/W_P, \qquad (3.14)$$

where $\boldsymbol{W_P}$ – s the potential ergonomic function that is obtained when the machine's characteristics fully match the optimal human characteristics. The ergonomic function $\boldsymbol{W}$ is quite complex and for most types of machines is not yet sufficiently studied. Therefore, in practice, the ergonomics of a machine is assessed by individual ergonomic characteristics:

$$h_{ki} = z_{ki}/z_{ki\text{опт}}. \qquad (3.15)$$

The standard deviation of the actual parameters of the system or product from the optimal ones is used as an individual quality indicator of an automatic system or technical product in terms of ergonomics, which is used to assess the system efficiency indicator $\boldsymbol{E}$:

$$y_{\text{в}} = \sqrt{\frac{\sum_{i=1}^{n}(\Delta z_{ki})^2}{kn}}\ , k = \overline{1,5}, \qquad (3.16)$$

Where

$$\Delta z_{ki} = \frac{(z_{ki\text{опт}} - z_{ki})}{z_{ki\text{опт}}}.$$

The best system in terms of individual ergonomic quality indicator will be the one for which $\boldsymbol{y}_{\text{в}}$ is minimal.

The issue of ergonomic design of Unmanned Aerial Vehicles (UAVs) has been introduced and discussed in [3.2, 3.3, 3.4, 3.5].

6) Cost $\boldsymbol{y_7}$. It is one of the main indicators that influences the choice of a system option for implementation, since complex technical products such as UAVs are quite expensive. Many of the individual quality indicators $\boldsymbol{y_1} - \boldsymbol{y_7}$ are not very related to each other and can be considered independently of each other with small changes, but none of them can be considered independently of cost. Therefore, in those cases where it is necessary to emphasize the role of cost as an individual indicator of system quality, we will denote it not by $\boldsymbol{y_7}$, but by $\boldsymbol{C}$, as in formulas (3.1) – (3.3), (3.5).

In addition to the considered individual quality indicators of systems, other indicators specific to a given system and the task at hand may be considered when developing and modernizing them. If these indicators are measurable, then they are considered as the main ones and are included in the linear function of the overall system efficiency $\boldsymbol{E}$ as components with their own weighting coefficients and limitations.

For example, in the serial production of UAVs (especially in the case of multi-series production), the labor intensity of setting up the system's units and channels is of great importance. The labor intensity of the setup is estimated using the setup time of a unit or the entire system after modernization $\boldsymbol{y_8}$. As a limit, you can take the specified maximum setup time $\boldsymbol{y_{8max}}$ or the time that was required for setup before the upgrade. The best system is one for which $\boldsymbol{y_8}$ has a minimum value.

To apply quantitative methods of UAV research, mathematical models are always required. There are no general ways to build mathematical models: in each case, the model is created based on the targeted focus of operations and research objectives, taking into account the required solution accuracy and the reliability of the source data used. Building a model is a crucial part of operations research.

In work (3.1), the efficiency of self-tuning automatic control systems is considered by single criteria and then by a general (complex) indicator that takes into account their totality.

For example, single criteria are taken into account: $\boldsymbol{E_1 = r_c/r} -$ is the system's sustainability performance indicator.

where $\boldsymbol{r} -$ is the radius of a circle characterizing the stability margin for a system without self-tuning;

$\boldsymbol{r_c} -$ for a self-adjusting system

and $\boldsymbol{E_2 = \lambda_c/\lambda} -$ is the system efficiency indicator in terms of reliability, etc

The complex performance indicator $\boldsymbol{E_K}$ is a linear combination of the individual criteria $\boldsymbol{E_i}$:

$$E_K = \sum_{i=1}^{n} b_i E_i\,, \qquad (3.17)$$

Where $\boldsymbol{n}$ – is the number of individual criteria taken into account.

However, the paper does not provide data on the determination of the $\boldsymbol{b_i}$ coefficients, which makes it impossible to use formula (3.17) for a practical assessment of system efficiency. In addition, the complex performance indicator $\boldsymbol{E_K}$ does not take into account the purpose of the system and therefore cannot serve to confidently select the best option for self-tuning, since the self-tuning system itself is part of a larger system. Therefore, obtaining optimal results from self-adjustment may not mean obtaining optimal results for the entire system. For example, self-adjustment will require the introduction of a number of structural elements that will affect the weight, size, reliability, ease of maintenance, etc. of the entire complex, which may ultimately reduce efficiency.

It is possible to determine the efficiency of an automatic control system using the equation:

$$P = Q + \lambda R, \qquad (3.18)$$

where

$\boldsymbol{Q}$ – is a function that is an indicator of system quality;

$\boldsymbol{R}$ – is a reliability indicator (probability of system failure);

$\boldsymbol{\lambda}$ – is a weighting factor.

The function $\boldsymbol{Q}$ depends on the measure of control quality, which is determined using the extremum of a certain functional - an indicator of the control goal:

$$E(X, Y, F, t) = extr. \qquad (3.19)$$

The main task of control is to ensure that the control system approximates as closely as possible to the conditions corresponding to (3.19). This implies that the entire system consists of the control object and the control part of the system itself. All available information about the control object's behavior over time is contained in $\boldsymbol{n}$ variables $\boldsymbol{x_i(t), i = 1, 2, \ldots, n}$, where $\boldsymbol{x_i}$ – are the components of an $\boldsymbol{n}$- dimensional vector $\boldsymbol{X}$

called thestate vector of the controlled object:

$$X(t) = \begin{vmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{vmatrix}. \qquad (3.20)$$

The change of $\boldsymbol{X}$ (and its derivatives) is usually subject to certain restrictions.

The state of the object described by the vector $\boldsymbol{X}$ changes under the influence of external conditions and signals from the control system. The external conditions are exhaustively described by the external influence vector:

$$F(t) = \begin{vmatrix} f_1 \\ f_2 \\ \vdots \\ f_m \end{vmatrix}. \qquad (3.21)$$

The effect of the control system signals on the object is described using the object control vector:

$$Y(t) = \begin{vmatrix} y_1 \\ y_2 \\ \vdots \\ y_k \end{vmatrix}. \qquad (3.22)$$

The control of an object is always purposeful and subject to certain constraints. To ensure optimal control, it is necessary to form such a functional dependence of the control vector $\boldsymbol{Y(t)}$ on the vector $\boldsymbol{X(t)}$ and the vector of external influences $\boldsymbol{F(t)}$ that achieves the best approximation of the system to the requirements defined by condition (3.19). This should take into account both the constraints imposed on the vectors $\boldsymbol{X, Y}$ and $\boldsymbol{F}$, and the real possibilities of obtaining the necessary information. Suppose that the dependence that realizes the optimal control vector $\boldsymbol{Y_0(t)}$ is as follows:

$$Y_0(t) = Y_0(X, F, t). \qquad (3.23)$$

The system that implements the optimal control algorithm (3.22) has the optimal value of the control objective $\boldsymbol{E_0(t)}$, which is determined in accordance with (3.19). In a real system, taking into account the constraints imposed on the technical means, we can only talk about the approximation of the control vector $\boldsymbol{Y(t)}$ o the optimal control vector $\boldsymbol{Y_0(t)}$. Therefore, the real system corresponds to the control metric $\boldsymbol{E_p}$, which differs from the optimal $\boldsymbol{E_0(t)}$. (3.24)

The difference between $\boldsymbol{E_0(t)}$ is an indicator of control accuracy (a measure of control quality) $\Delta = \boldsymbol{E_0(t) - E_p(t)}$ or more generally:

$$Q = \varphi(\Delta) = \varphi[E_0(t) - E_p(t)]. \qquad (3.25)$$

To improve the quality of control, it is necessary to minimize the functionality (3.25). The technical measures associated with meeting this requirement lead to a change in the reliability index $\boldsymbol{R}$. The task is to find a reasonable compromise between the values of $\boldsymbol{Q}$ and $\boldsymbol{R}$, which ensures the highest system efficiency, i.e., at which the value of $\boldsymbol{P}$, determined in accordance with (3.18), would be minimal, taking into account all the constraints.

The advantage of the proposed criterion is that it takes into account the quality of control and reliability of the entire system. It is used to evaluate automatic control systems that do not have special requirements in terms of weight, size, cost, etc. The disadvantage of this criterion is that it requires knowledge of the weighting factor $\boldsymbol{\lambda}$, which is an independent and rather complicated task. In addition, it should be recalled that the control system is usually part of a complex technical product, and the choice of a system variant with the minimum $\boldsymbol{P}$ value should provide for an increase in the efficiency of the entire product.

Therefore, this criterion should be considered as a certain total individual indicator of the quality of a technical product, which, in combination with other indicators, affects the efficiency of a complex technical product.

A number of authors propose to evaluate the efficiency of a system by the efficiency of a benchmark system. In this case, the comparison criterion is the quality indicator or management goal, which depends on the state of the management object, external influences, and other parameters.

Since the system operates under the influence of random variables, the mathematical expectation of the criterion functional $\boldsymbol{Q}$, which has the form:

$$Q = \int_0^T G[x(t), u(t)]\, dt + \varphi_1[x(T)], \qquad (3.26)$$

where

$\boldsymbol{x(t)}$ – coordinates of the control object;

$\boldsymbol{u(t)}$ – a certain sequence of controls minimizing the value of $\boldsymbol{Q}$;

$\boldsymbol{T}$ – fixed time;

$\boldsymbol{\varphi_1}[\boldsymbol{x}(\boldsymbol{T})]$ – is a function that characterizes the movement of the object.

The proposed criterion applies mainly to automatic control systems and evaluates a modernized or newly designed system in comparison with a system already tested in practice, which is currently the best.

The disadvantage of this criterion is that it is not related to the design, operational and economic characteristics of the system, as well as to the indicator characterizing the purpose of the product of which the system under consideration is an integral part. It should be noted that the selection of a reference system, i.e. the best of the functioning systems, is often a difficult task.

In cases where the objective function is difficult to define or exists, but the large dimensionality of the parameter space requires more computational work, an effective solution is considered to be a satisfactory (from a practical point of view) one found using other parameters and a design reference that has been tested in practice. In this case, the optimal design problem may consist in achieving an extremum of the objective function (e.g., minimum mass, dimensions, cost, etc.) for the existing set of parameters while imposing constraints on the parameters in the form::

$$B_{i\,min} \leq B_i \leq B_{i\,max}, \qquad (3.27)$$

where

$\boldsymbol{B_i}$ – quantitative value of the parameter;

$\boldsymbol{B_{i\,min}}, \boldsymbol{B_{i\,max}}$ – the constraints on this parameter from below and above, respectively.

However, it is not always possible to find a single, consistent objective function that links the entire set of parameters. The best domestic and foreign models of devices of this type can serve as reference devices. Numerous parameters of these devices are usually related to each other. However, these relationships are not analytical in nature. These are so-called associative relationships, for which only the type of relationship and an approximate qualitative assessment of the degree of relationship (weak, strong) are known. The only way to determine the coefficients of associative relationships is to use benchmarks. In this case, determining an unknown parameter $\boldsymbol{x_1}$ from a set of $\boldsymbol{n}$ random is equivalent to finding a conditional mathematical expectation:

$$M[(x_1), f(\{x_1\})_{\substack{i=1 \\ j\neq i}}^{n}] = f(x_1, x_2, \dots, x_n), \quad (3.28)$$

where

$\boldsymbol{f}(\{\boldsymbol{x_1}\})_{\substack{\boldsymbol{i=1} \\ \boldsymbol{j\neq i}}}^{\boldsymbol{n}}$ – regression equation for $\boldsymbol{x_1}$ on other parameters.

This problem is successfully solved by sequential training based on the machine learning algorithm proposed in Section 4 of this paper. The advantage of this criterion is that it takes into account the whole variety of individual quality indicators that characterize the design and operational properties of the system and is a criterion of practical optimality. It should be noted that, as in the previous cases, there are not always device standards and not all fields of technology can evaluate the efficiency of devices by standards and other parameters. In addition, the determination $\boldsymbol{x_1}$ itself involves time-consuming computational operations. However, in cases where other methods are unacceptable and where a reference can be found, the method under consideration is sufficiently effective.

The effectiveness of a UAV can be more fully assessed by the probability of accomplishing its task. If $\mathbf{P}_{\boldsymbol{s}}$ is the probability that the system will accomplish its task, provided that the set of its elements is in state $\boldsymbol{s}$ with probability $\boldsymbol{H_s}$, then the function $\boldsymbol{F}$ will characterize the total probability of the system accomplishing its task:

$$F = \sum_{s\in G} \mathrm{P}_s H_s, \quad (3.29)$$

where $\boldsymbol{G}$ – is a set of states.

If $\mathbf{P}_{\boldsymbol{s}}$ has a dimension (e.g., transported cargo), then the function $\boldsymbol{F}$ is a mathematical expectation of the system's output effect. For a system with a number (quantity) of $\boldsymbol{z}$ normally functioning elements, $\boldsymbol{F} = \boldsymbol{M}\{\boldsymbol{P}(\boldsymbol{z})\}$, where $\boldsymbol{P}(\boldsymbol{z})$ – s an indicator that characterizes the effect of the system on the output in the case of normal functioning of exactly $\boldsymbol{z}$ elements.

The effectiveness of automatic and autonomous UAV flights can be assessed by the probability that the system will meet the specified technical task (TT) and control quality criteria under given operating conditions during its service life. Then the following approach is possible.

It should be noted that the technical requirements for UAVs in terms of reliability, accuracy, cost, etc. are contradictory. Therefore, before designing or modernizing a UAV, it is necessary to set a condition in advance to find a compromise solution in which the quality indicators are not clearly optimal and may lie within certain confidence intervals. At the same time, it is necessary to ensure that the values of the system parameters do not exceed the permissible limits defined by the technical specifications.

Mathematically, this criterion is represented as an event probability:

$$P\begin{pmatrix}\eta_i \geq \varepsilon_i \\ t \geq T\end{pmatrix} = \beta, \;\; i = (\overline{1, m}), \qquad (3.30)$$

where

$\boldsymbol{\eta_i}$ – is the criterion of the $\boldsymbol{i}$-th quality;

$\boldsymbol{\varepsilon_i}$ – is the threshold value of the $\boldsymbol{i}$-th quality;

$\boldsymbol{m}$ – number of criteria taken into account;

$\boldsymbol{T}$ – is the time of reliable operation of the system. It is assumed that the quality indicator $\boldsymbol{\eta_i}$ is better the higher its value.

The system at each moment of time can be characterized by an $\boldsymbol{n}$- dimensional vector of parameters $\boldsymbol{a_i}$, i.e. $\boldsymbol{A} = (\boldsymbol{a_1}, \boldsymbol{a_2}, \dots, \boldsymbol{a_n})$. (3.31)

To meet the technical specifications for the system quality criterion $\boldsymbol{\eta_i}$, it is necessary to ensure that the vector $\boldsymbol{A}$ is within a certain region $\boldsymbol{B_n}$. Going beyond this area is considered an unfavorable event. Then the condition (3.31) is written in the form:

$$P\begin{pmatrix}A \in B_n \\ t \geq T\end{pmatrix} = \beta. \qquad (3.32)$$

When parameters are varied, the efficiency of $\boldsymbol{\beta}$ can be determined through probability densities:

$$\beta = \int_0^T \iiint_{B_n} p(a_1, a_2, \dots, a_n, t) da_1 da_2 \dots da_n dt, \qquad (3.33)$$

where

$\boldsymbol{p(a_1, a_2, \dots, a_n, t)}$ – is the probability density of the $\boldsymbol{n}$-dimensional random state vector $\boldsymbol{A}$ of the system.

As can be seen from (3.33), $\boldsymbol{\beta}$ is determined, on the one hand, by integration in the time domain, the result of which characterizes the ability of the system to serve reliably over a certain period of time, and on the other hand, by integration in the domain of system parameters, the result of which determines the ability of the system to ensure a given quality value. When choosing the region $\boldsymbol{B_n}$, it is necessary to proceed from the conditions of the worst combination of impacts on the system, which corresponds to the lower boundary of the quality criterion. The region $\boldsymbol{B_n}$ is obtained by solving the following system of equations:

$$\eta_i = f_i(a_j, x_k), \eta_i \geq \varepsilon_i \,, \tag{3.34}$$

$$i = (\overline{1, m}); a \in A, j = (\overline{1, n});\ x_k \in X, k = (\overline{1, l}), \tag{3.35}$$

where

$\boldsymbol{a_j}$ – value of the $\boldsymbol{j}$-th parameter;

$\boldsymbol{n}$ – number of parameters under consideration;

$\boldsymbol{A}$ – the set of possible values of element parameters;

$\boldsymbol{x_k}$ – $\boldsymbol{k}$-th impact on the system;

$\boldsymbol{l}$ – number of impacts;

$\boldsymbol{X}$ – the set of possible impacts;

$\boldsymbol{\varepsilon_i}$ – limit values of the assessment for the $\boldsymbol{i}$-th quality criterion;

$\boldsymbol{m}$ – number of assessments.

The system of these equations is solved not in a strictly mathematical sense, but as a choice of quantitative values of parameters that satisfy a group of requirements. In general, when $\boldsymbol{n}$ parameters are varied, the region $\boldsymbol{B_n}$ s limited to a complex surface in $\boldsymbol{n}$- dimensional space. 3he task of the designer is to determine this region in which the requirements for the quality of the system specified by the tutor are satisfied. The advantage of this criterion is that it takes into account all the technical requirements of the system. But there is a big problem in assessing the effectiveness of the UAV, given the nature of the $\boldsymbol{B_n}$ domain, since it:

a) it may have a complex shape rather than a simple one, which is not described by simple geometric shapes;

b) it can be not only single-connected, but also multi-connected, which will not allow for orthodromy flights.

These features make it impossible to solve model (3.33) by analytical methods. Great difficulties also arise when trying to apply numerical methods, since it is necessary to divide the region $\boldsymbol{B_n}$ into a set of simple geometric shapes.

The method and algorithm for solving this problem are proposed in chapter 4 of this paper.

The selection of new UAV devices and means is possible when the system efficiency and optimization is assessed on the basis of a generalized criterion - the maximum probability that the system meets all specified technical requirements. In this case, the following criteria are accepted as optimization criteria:

– minimum time of one control cycle $\boldsymbol{\tau}$;

– minimum total weight of the device $\boldsymbol{P}$;

– minimum total weight of the device $\boldsymbol{V}$;

– minimum power consumption $\boldsymbol{W}$;

– maximum reliability $\boldsymbol{H}$;

– maximum cost of development, manufacturing, implementation and operation of the system $\boldsymbol{C}$.

The specific choice of a system is based on a qualitative analysis. Let $\boldsymbol{J_1} -$ denote the amount of information received in time $\boldsymbol{\tau_1}$. he speed of receiving this amount of information is $\boldsymbol{n_1}$. Accordingly, the amount of information transmitted, processed and used to influence the object is denoted by $\boldsymbol{J_2}, \boldsymbol{J_3}, \boldsymbol{J_4}$, time by $\boldsymbol{\tau_2}$, $\boldsymbol{\tau_3}$, $\boldsymbol{\tau_4}$, and the speed of transmission, processing and influence by $\boldsymbol{n_2}$, $\boldsymbol{n_3}$, $\boldsymbol{n_4}$. Then the control cycle time will be equal to:

$$\tau = \tau(\tau_1, \tau_2, \tau_3, \tau_4) = \tau\left(\frac{J_1}{n_1}, \frac{J_2}{n_2}, \frac{J_3}{n_3}, \frac{J_4}{n_4}\right). \qquad (3.36)$$

Let's define::

$$a_{i1} = J_1/\bar{n}_1;\ x_{i1} = n_1/\bar{n}_1, i = 1,2,3,4, \qquad (3.37)$$

where

$\bar{\boldsymbol{n}}_{\mathbf{1}}$ – performance parameters of the old system. Then, based on (3.36) and (3.37), we obtain

$$\tau = \tau\left(\frac{a_{11}}{x_{11}}, \frac{a_{21}}{x_{21}}, \frac{a_{31}}{x_{31}}, \frac{a_{41}}{x_{41}}\right). \qquad (3.38)$$

If there is no information about the intended organization of the functioning (on which the analytical form of expression (3.38) depends), then the form of the function $\boldsymbol{\tau}$ can be determined from the condition of consistent organization of the work of various technical means, which corresponds to the worst case:

$$\tau = \frac{a_{11}}{x_{11}} + \frac{a_{21}}{x_{21}} + \frac{a_{31}}{x_{31}} + \frac{a_{41}}{x_{41}}. \qquad (3.39)$$

We'll get the same result:

$$P = P\left(\frac{a_{12}}{x_{12}}, \frac{a_{22}}{x_{22}}, \frac{a_{32}}{x_{32}}, \frac{a_{42}}{x_{42}},\right) \qquad (3.40)$$

or

$$P = \frac{a_{12}}{x_{12}} + \frac{a_{22}}{x_{22}} + \frac{a_{32}}{x_{32}} + \frac{a_{42}}{x_{42}}, \qquad (3.41)$$

where

$\boldsymbol{a}_{\boldsymbol{i}\mathbf{2}} = \bar{\boldsymbol{P}}_{\boldsymbol{i}}$ mass of old technical means of the $\boldsymbol{i}$-th class;

$$V = V\left(\frac{a_{13}}{x_{13}}, \frac{a_{23}}{x_{23}}, \frac{a_{33}}{x_{33}}, \frac{a_{43}}{x_{43}}\right) \qquad (3.42)$$

or

$$V = \frac{a_{13}}{x_{13}} + \frac{a_{23}}{x_{23}} + \frac{a_{33}}{x_{33}} + \frac{a_{43}}{x_{43}}, \qquad (3.43)$$

where

$\boldsymbol{a}_{\boldsymbol{i}\mathbf{3}} = \bar{\boldsymbol{V}}_{\boldsymbol{i}}$ – the volume of old technical means of the $\boldsymbol{i}$-th class;

$$W = W\left(\frac{a_{14}}{x_{14}}, \frac{a_{24}}{x_{24}}, \frac{a_{34}}{x_{34}}, \frac{a_{44}}{x_{44}}\right) \qquad (3.44)$$

or

$$W = \frac{a_{14}}{x_{14}} + \frac{a_{24}}{x_{24}} + \frac{a_{34}}{x_{34}} + \frac{a_{44}}{x_{44}}, \qquad (3.45)$$

where

$\boldsymbol{a}_{\boldsymbol{i}\mathbf{3}} = \bar{\boldsymbol{V}}_{\boldsymbol{i}}$ – the power consumption of old equipment of the $\boldsymbol{i}$-th class.

If reliability is viewed as the probability of failure-free operation, then:

$$H(\tau) = H[H_1(\tau), H_2(\tau), H_3(\tau), H_4(\tau)], \qquad (3.46)$$

where

$\boldsymbol{H_i(\tau)}$ – probability of failure of technical means of the $\boldsymbol{i}$- th class, $\boldsymbol{i = 1, 2, 3, 4}$.

If there are no studies on the reliability of the old system, then as a simple hypothesis, it is believed that the failures of technical means of a given class ($\boldsymbol{i = 1, 2, 3, 4}$) If there are no studies on the reliability of the old system, then as a simple hypothesis, it is believed that the failures of technical means of a given class $\boldsymbol{\lambda_i}$, these streams are independent and have a Poisson distribution. Then:

$$H(\tau) = e^{-\tau \sum_{i=1}^{4} \frac{1}{\lambda_i}} \text{ or } -\frac{\ln H(\cdot)}{\tau} = \sum_{i=1}^{4} \frac{a_{i5}}{x_{i5}},$$

where $\boldsymbol{a_{i5} = 1/\bar{\lambda}_i;\ x_{i5} = \lambda_i/\bar{\lambda}_i,\ i = 1, 2, 3, 4}$.

The expression $\boldsymbol{\ln H(\tau)\tau}$ – is a monotonically decreasing function of its arguments $\boldsymbol{x_{i5} > 0}$.

If the functions of different technical means are not combined, then:

$$C = \sum_{i=1}^{4} C_i,$$

where $\boldsymbol{C_i}$ – ost of development and implementation of technical means of the $\boldsymbol{i}$- th class.

In general, the cost of $\boldsymbol{C_i}$ is a function of the main parameters:

$$C_i = C_i(x_{i1}, x_{i2}, x_{i3}, x_{i4}, x_{i5}). \qquad (3.48)$$

When defining the structure of a function, the following conditions must be met:

1) $\boldsymbol{C_i = \bar{C}_i,\ i = 1 - 4}$, if $\boldsymbol{x_{i1} = x_{i2} = x_{i3} = x_{i4} = x_{i5} = 1}$;
2) $\boldsymbol{C_i = 0}$ for $\boldsymbol{x_{ij} = 0;\ \ 1 \le j \le 5}$, i.e., the cost is zero if at least one of the parameters reaches zero;
3) $\boldsymbol{C_i(tx_{ij}) = \psi(t) C_i(x_{ij}), i = 1 - 4;\ \ j = 1 - 5}$.

Condition 3 means that if all parameters are increased by t times, the cost increases by $\boldsymbol{\psi(t)}$ times, where $\boldsymbol{\psi(t)}$ – ome differentiated increasing function that takes on the value $\boldsymbol{\psi(t) = 1}$ at $\boldsymbol{t = 1}$;

4) the function $\boldsymbol{C_i}$ is nonnegative and strictly monotonically increasing in all its arguments.

Condition 3 implies that $\boldsymbol{C_i}$ s a solution to a partial differential equation:

$$\sum_{j=1}^{5} \frac{\partial C_i}{\partial x_{ij}} dx_{ij} = \rho C_i \, , \qquad (3.49)$$

where

$\boldsymbol{\rho = \frac{d\psi}{dt}\Big|_{t=1}}$ – growth rate.

The simplest solutions to equation (3.49) that satisfy conditions 1, 2, and 4 will be:

$$C_i = \bar{C}_i x_{i1} x_{i2} x_{i3} x_{i4} x_{i5}$$

for the case of linear function growth and $\boldsymbol{C_i = \bar{C}_i x_{i1}^2 x_{i2}^2 x_{i3}^2 x_{i4}^2 x_{i5}^2}$ – for quadratic growth.

The statistical materials of the conducted studies show that the quadratic growth law has the widest scope. If we take, for example, $\boldsymbol{\tau_{min}}$ as an optimization criterion, assuming $\boldsymbol{P, V, W, H, C}$ are given, then, in addition to (3.38), (3.39), and (3.42), (3.44), (3.46) can be written on the basis of (3.44):

$$\varphi(H) = \varphi\left(\frac{a_{15}}{x_{15}}, \frac{a_{25}}{x_{25}}, \frac{a_{35}}{x_{35}}, \frac{a_{45}}{x_{45}}\right), \qquad (3.50)$$

$$C = \sum_{i=1}^{4} C_i \left(x_{i1}, x_{i2}, x_{i3}, x_{i4}, x_{i5}\right), \quad (3.51)$$

where $\boldsymbol{P, V, W, H, C}$ дare some given constant numbers, and $\boldsymbol{\varphi(H)}$ – some monotonically decreasing function at $\boldsymbol{x_{i5} > 0}$.

The solution to the optimization problem in this case is to find the values of $\boldsymbol{x_{i1}, x_{i2}, x_{i3}, x_{i4}, x_{i5}}$ $\boldsymbol{(i = 1 - 4)}$, hat satisfy the conditions (3.50). By its nature, this is a problem of finding a conditional extremum for a function of many variables, which can be solved using analytical or quantitative methods. We are looking for a similar solution for $\boldsymbol{P = P_{min}}$ when $\boldsymbol{x_{i2} > 0}$, etc. By applying the method of indefinite Lagrange multipliers, after some transformations, we can obtain the optimal values of the parameters $\boldsymbol{x_{ij}}$.

The advantage of the criterion under consideration is the ability to assess the best satisfaction of the technical requirements for the system and to take into account the main individual criteria that characterize its technical and economic properties. The disadvantages of the criterion include the lack of its connection with the main purpose of the system, as well as the complexity of its application, since the optimization problem in this case belongs to the class of variational problems, the solution of which requires more time even when using a computer program.

For industrial systems of continuous or long-term operation, an efficiency criterion has been developed [3.1] that takes into account the quality of system operation $\boldsymbol{Q}$ during time $\boldsymbol{t}$, reliability $\boldsymbol{R}$, cost $\boldsymbol{C}$, ease of maintenance, availability of reserves, losses incurred in case of system failure, etc:

$$\epsilon = f(Q, R, C, t, \dots). \qquad (3.52)$$

The economic efficiency of the system is visually determined by the expression:

$$\epsilon = \frac{B_t - C_p - C_\epsilon - C_y}{B_t}, \qquad (3.53)$$

Where:

$\boldsymbol{B_t}$ – system performance in UAH/hour;

$\boldsymbol{C_p}$ – cost of system development and manufacturing costs;

$\boldsymbol{C_\epsilon}$ – cost of operation and repair;

$\boldsymbol{C_y}$ – cost of damage caused by system failure.

Determining the values on which economic efficiency (3.53) depends is an independent task. As a rule, a certain part of the costs $\boldsymbol{C_p}$ is connected by some functional or statistical dependence with the probability of failure (time between failures).

Tables 3.1 and 3.2 summarize the methods for assessing the effectiveness of complex systems and devices based on selected criteria.

Table 3.1

Criteria for evaluating efficiently sophisticated systems and devices

№. of criteria	**Performance evaluation**
1	Comparing this system with an optimally and perfectly functioning system (a quality criterion or control goal that depends on the state of the object, controls, external influences, and other parameters)
2	The extremum of some functionality, which is called the indicator of the management goal
3	Weapons (weapon control systems) - by the ratio of damage caused (prevented) to the cost of the weapon
4	Weapons - probability of hitting the target
5	Weapon systems are one of the individual criteria: - the average cost of missiles to hit a target; - the average amount of time spent on hitting one target, etc.

6	Enemy defense - by minimizing the function that links the system parameters
7	System performance, reliability, ease of maintenance, availability of reserves, amount of damage caused by system failure
8	Self-adjusting systems - according to single criteria and a comprehensive indicator, whether the effectiveness of introducing self-adjustment (modernization) is determined
9	Systems - the probability of the system performing its task
10	Weapons - a function of the time of its operation, the weight of failure in the formula is introduced as a function of the time when the failure occurred
11	Systems - as an individual case of the most general criterion for the quality of dynamic systems - loss functions (error functions)
12	Integral assessment of the probability of performing a task at the required level in a certain time
13	Probability that the system will meet the specified technical conditions and quality criteria under the given operating conditions for the required period of time
14	When it is difficult to define the objective function or when the large dimensionality of the space requires a lot of computational work, efficiency is considered as a satisfying solution (from a practical point of view) found by other parameters and a design standard that has been tested in practice
15	The effectiveness of the system, its optimality is assessed on the basis of a generalized criterion - the "maximum probability" that the system meets all specified technical requirements
16	The efficiency of the system is calculated on the basis of the practical optimality of the system, which is an integral criterion that takes into account the operational, structural and economic qualities of the system
17	The efficiency of the ACS(Auto Control System) of the individual criteria (root mean square error, speed, etc.), which can be calculated (computed) on the basis of the latest theory of optimal processes
18	The system's efficiency is assessed using a vector indicator - a set of quality indicators.

Table 3. 2

Classification criteria for evaluating the effectiveness of complex systems and devices

№	**Evaluation of efficiency**	**№ of criteria according to Table 3.1(1)**
1	Performance evaluation	1, 14
2	By the extremum of the objective function	2, 10, 11
3	By the probability of completing the task without taking into account economic factors	4, 6, 9, 12
4	The probability of completing the task, taking into account economic factors	3, 7
5	To maximize the likelihood that the system meets all specified technical requirements	13, 15
6	According to individual criteria	5, 8, 17
7	Based on a combination of design, operational and economic factors	16, 18

CONCLUSIONS. The main point of efficiency assessment is the selection of an efficiency criterion for its quantitative assessment and the development of an efficiency model of the system being designed or modernized. In the most general case, the system efficiency model includes the output effect and costs. The output effect of the system is determined using operations research methods that allow analyzing the system's performance and determining the place of each quality indicator in achieving the required result. When developing the efficiency model, the costs at the design, production, and operation stages of the system should be reflected.

Comparison of various performance criteria with implicit system links leads to the conclusion that the most acceptable criteria are those that allow, given known weighting coefficients of individual system quality indicators (such as accuracy, cost, reliability, weight, dimensions, etc.), to determine a practically optimal system. A practically optimal system is defined as a system that has the highest performance among the systems under consideration, even if none of the individual quality indicators (IQIs) of the technical system reaches an extreme value. Knowing the weighting coefficients transforms the optimization problem into an algebraic one, which greatly simplifies its solution.

In order to evaluate the option of creating or modernizing the system under consideration according to the selected criterion, taking into account all quality indicators, it is necessary to have initial objective data and optimization methods that can be used to make an assessment. At the same time, it is obvious that the options under consideration must meet the specified quality criteria.

3.2. Methods for measuring the efficiency of UAVs in an air navigation system

The measurement of inputs and outputs is based on the general principles of evaluating system solutions, as well as on the specific methods for determining the efficiency of various complex systems discussed in the previous section. The category of efficiency is of great theoretical and applied importance.

The concept of efficiency for the implementation of the method of its measurement can be formulated as follows.

Definition 3.1. Efficiency is a category of action or activity of a system at a certain time interval, which reflects the correspondence of the result obtained to the resources invested.

The above definition of efficiency implies the following properties:

1) efficiency has a quantitative measure and is represented by functionality;
2) the efficiency metric is external to the system, i.e., the description of the system does not provide a basis for introducing such a measure;
3) efficiency is characteristic of purposeful systems;
4) efficiency assessment takes into account certain properties and interconnection of the supersystem with the system under evaluation;
5) system efficiency management is associated with the variation of its resources in order to change the result of the subsystem's influence and actions.

The concepts of effect and efficiency are usually distinguished. The effect is usually understood as the result of certain actions, and efficiency is the ability to create an effect and obtain a result..

Different approaches are used to assess efficiency, which to some extent take into account the specifics of the system, as discussed in paragraph 3.1.

The fundamentals of efficiency theory are based on the methodology of operations research and decision-making. They include a wide range of mathematical models built using the methods of probability theory, mathematical statistics, game theory, information theory, schedules, fuzzy sets, machine learning technologies, etc.

The results of the performance measurement allow us to solve the following practical tests of UAVs in general and cargo drones in particular:

1) comparison of similar systems;
2) selection of similar systems from the group of systems;
3) operational evaluation of the systems;
4) checking the system's compliance with its purpose;
5) identifying the presence or absence of targeting;
6) determination of the level of compliance of the system with the purposefulness;
7) determining the technical level, prospects and feasibility of new system developments;
8) optimization of tactical and technical requirements;
9) establishing the conditions for acceptable and most effective use of systems;

10) determining the feasibility of replacing systems in operation with more promising ones.

To solve this kind of problem, a conceptual approach based on different types of effect is required. Technical and economic assessments can be obtained by linking functional and economic assessments. These types of effects are in a certain relationship, which leads to their mutual influence.

The social effect is manifested primarily in ensuring the safety and regularity of aircraft flights. To measure the social effect, methods based on its direct assessment are used. For example, the regularity of flights can be assessed by the average duration of flight delays, the accuracy of flight schedules, economic losses, etc.

Flight safety is characterized by the level of flight security and is a characteristic of the aviation transport system, which is determined by the probability that a catastrophic situation will not occur during the flight. To quantify flight safety, statistical and probabilistic indicators are used, which can be general and specific, absolute and relative. General indicators characterize flight safety in general for all reasons, while specific indicators characterize flight safety for individual reasons or their group.

Common absolute statistical indicators of flight safety include: the number of aviation accidents, the number of fatalities in aviation accidents over a certain period of time. Individual absolute indicators include the number of accidents caused by any i-cause, the number of accidents at the j-th stage of the flight, etc. Absolute statistical indicators allow to identify a general trend in the state of flight safety for a certain period, but they do not reflect the level of flight safety.

More generalized indicators are those that correlate the number of aircraft accidents with the amount of work performed or work in progress. These indicators allow us to assess the level of flight safety and take into account all factors and causes of aviation accidents.

The main advantage of statistical indicators is their objectivity, as they characterize the events that have occurred. At the same time, such indicators also have a number of disadvantages: they cannot be used in long-term planning of the level of flight safety, since they do not take into account the features of new equipment, changes in its operating conditions; they do not allow determining the degree of danger of adverse factors and their impact on flight safety, and, as a result, cannot be used in finding effective ways to prevent aviation accidents before their practical implementation.

The probability of completing a flight without an accident, the probability of a precondition for an accident, and a number of others can serve as an analytical indicator that determines the safety of UAV flights. In the general form of probabilities, the flight safety indicator can be represented as follows.

Let the state of the system be determined by a vector:

$$\vec{Z}(t) = \{Z_1(t), \dots, Z_n(t)\} \in R^n, \qquad (3.54)$$

where $\boldsymbol{t}$ – time, $\boldsymbol{R^n}$ – state space. In the space $\boldsymbol{R^n}$, a region $\boldsymbol{\Omega}$ s distinguished such that $\boldsymbol{Z(t) \in \Omega}$ at $\boldsymbol{t \in I_t = [t_1, t_1 + \tau]}$ is acceptable, satisfying the functional purpose of the system. On the contrary, $\boldsymbol{Z(t) \notin \Omega}$ orresponds to a deviation from normal functioning, for example, an aviation event or its precondition. It depends on the level of consideration of the formulated task. Thus, the requirement for flight safety is to keep the phase point of the system, which is represented by the vector $\boldsymbol{\vec{Z}(t)}$, within the region $\boldsymbol{\Omega}$. Note that the region $\boldsymbol{\Omega}$ depends in general on time $\boldsymbol{t}$, and the boundary of the region $\boldsymbol{\Gamma_\Omega}$ is the surface in the space of $\boldsymbol{n+1}$ measurements of the variables $\boldsymbol{\{Z_1, Z_2, \dots, Z_n, t\}}$.

If the probability distribution of the components of the state vector $\boldsymbol{F\{Z_1, Z_2, \dots, Z_n, \tau\}}$ is known, provided that the boundary has not been violated until time $\boldsymbol{t + \tau}$. The density of this probability is usually determined as a solution to the second Kolmogorov equation. Let's denote by $\boldsymbol{Q}$ a certain safety criterion. Then $\boldsymbol{Q}$ an be represented as follows:

$$Q = \int_{\Omega(\tau)} f(\vec{Z})\, dF(\vec{Z}, \tau). \qquad (3.55)$$

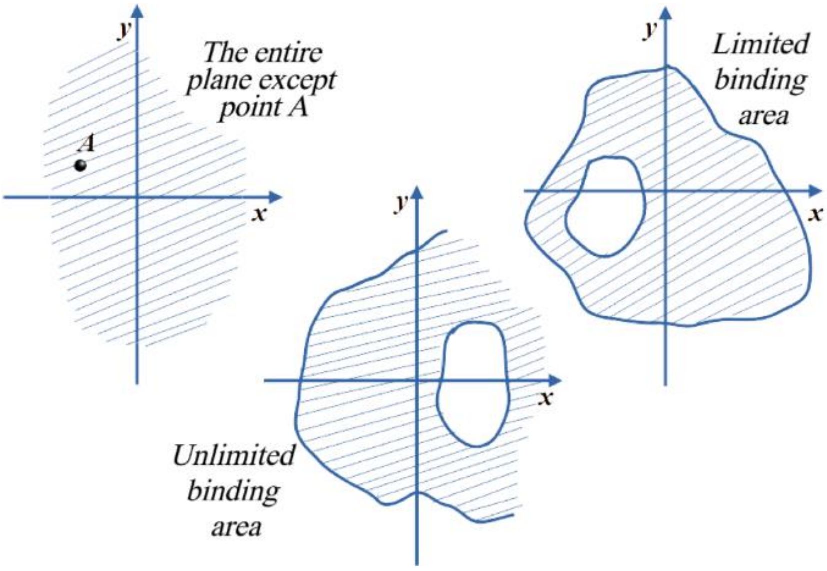
Here $\boldsymbol{f(\vec{Z})}$ – weighting function that determines the content of the criterion $\boldsymbol{Q}$; $\boldsymbol{\Omega(\tau)}$ – the region of permissible values of the vector $\boldsymbol{\vec{Z}}$. As can be seen from (3.55), to quantify the level of flight safety, it is necessary to know or be able to construct the area $\boldsymbol{\Omega(\tau)}$.

The problem of solving (3.55), as well as (3.33), is that the domains for random events $\boldsymbol{\beta}$ (3.33) and random processes $\boldsymbol{\Omega(\tau)}$ (3.54) in general can be not only single-connected, but also multi-connected.

The set M⊂Rn is called connected if any two of its points can be connected by a broken (or piecewise smooth) curve, all points belonging to this set.

If $M \subseteq R^n$ - an open connected set, then any two points from M can be connected by a curve completely located in M (Fig. 3.1).

Example. The ring $M = \{(x_{1,}x_2)|0 < a < x_1^2 + x_2^2 < b \subset \boldsymbol{R^2} \in$ is a connected set. An open connected point set is called a domain. A domain *G* is called one-connected if its boundary is a connected set. Otherwise, *G* is called a multi-connected domain. The union of a domain *G* and its boundary is called a closed domain. If a domain *G* is one-connected, then any closed curve without self-intersections lying in *G* can be contracted to a point by continuous deformation inside *G*.



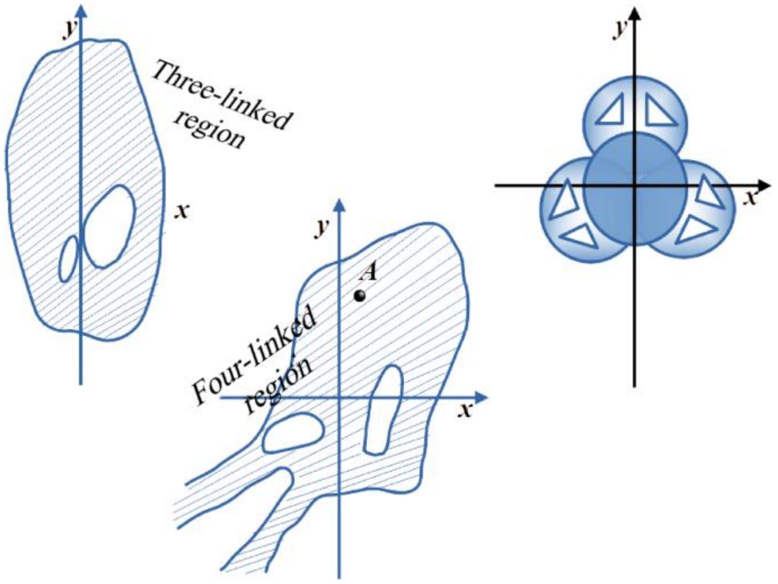


Fig. 3.1. Areas of connectivity of sets of parameters.

The simplest case of flight safety analysis is to maintain a binary criterion that takes on only two values $\{\mathbf{0}, \mathbf{1}\}$.

The economic effect has a multifaceted expression due to the large number of different indicators. The economic effect of using a UAS system can be represented, on the one hand, in terms of resource costs associated with development, production, and operation, and, on the other hand, in terms of the additional effect obtained by improving air traffic performance.

Along with the generalized ones, individual performance indicators can be used. They are used to assess certain important aspects of production efficiency, analyze the factors that generate economic effect, and verify the initial assumptions to form a set of acceptable options for implementing the measure.

Despite the difference between the forms of expression of the economic effect, the methods of their calculation are identical. The national economic and self-supporting forms of the effect are defined in the same way – as the difference between the results and the costs of achieving them. In other words, the economic effect is a difference indicator. This indicator can be presented in one of the following forms:

$$\max_j \epsilon^j$$

$$\max_j (P_T^j - \varepsilon_T^j)$$

$$\max_j \left(\sum_{t=t_n}^{t_k} P_t^j \cdot \alpha_t \sum_{t=t_n}^{t_k} \varepsilon_t^j \cdot \alpha_t\right)$$

$$\max_{j} \sum_{t=t_n}^{t=t_k} (P_t^j - \varepsilon_t^j) \cdot (1 + E_H)^{t_p - t} \text{ , (3.56)}$$

where $\boldsymbol{P_T^j, P_t^j, \varepsilon_T^j, \varepsilon_t^j}$ – respectively, the full results and costs for the entire period of the measure implementation in the $\boldsymbol{t}$-th year; $\boldsymbol{\alpha_t = (1 + E_H)^{t_p - t}}$ – the coefficient of bringing the results and costs of the $\boldsymbol{t}$-th year to one point in time (the calculation year $\boldsymbol{t_p}$); $\boldsymbol{E_H = 0.1}$ – the standard capital investment efficiency ratio; $\boldsymbol{t_H, t_k}$ – espectively, the initial year (the year of the start of financing the work related to the measure implementation) and the final year of the calculation period; $\boldsymbol{j}$ – the index of the option under consideration.

One case of implementing a measure is when the choice must be made among options that differ only in the dynamics and magnitude of the cost components (one-time and recurrent). In this case, the economic criterion of maximum effect (3.56) is transformed into another, simpler one – minimum total costs:

$$\max_{j} \sum_{t=t_n}^{t_k} \varepsilon_T^j \cdot (1 + E_H)^{t_p - t}. \max_{j} \varepsilon_T^j, \qquad (3.57)$$

However, the absence of a change in the results does not eliminate the need to evaluate these results in cost terms. This is because the reduction in costs in the production of final products using the new technique compared to the use of the basic technique is not a reason to use the new technique if the products are ultimately unprofitable.

In this regard, and for measures of the type under consideration, the economic effect is calculated using the formula:

$$\epsilon_T = \sum_{t=t_n}^{t_k} (P_t - \varepsilon_t) \cdot (1 + E_H)^{t_p - t}. \qquad (3.58)$$

The fundamental point of this methodology is the need to value the production, social, economic and other results achieved, even if they are identical in the compared options.

The complexity of assessing the economic effect of the UAS system lies in the lack of methods for calculating components (3.55) – (3.58) and the need to take into account component (3.55).

It is obvious that, when calculating $\boldsymbol{\epsilon_T}$, it is necessary to take into account the savings due to the reduction of non-productive costs associated with aircraft waste to the alternate airfield, erroneous change of echelons, unnecessary waste to the second circle; to take into account the savings to reduce the consumption of fuels and lubricants as a result of streamlining the flow of aircraft and optimizing flight paths, reducing non-productive maneuvers of aircraft, etc.

To solve problems (3.55) – (3.58), a formalized linkage of air navigation system parameters with cost indicators is required. Until recently, this problem has not been solved and requires an assessment of the functional effect.

The functional effect is manifested in the influence of the characteristics of the means of a complex system on the indicators of its functioning.

If a system $\boldsymbol{G}$ performs $\boldsymbol{N}$ functions $\boldsymbol{\Phi_1}, \boldsymbol{\Phi_2}, \dots, \boldsymbol{\Phi_g}, \dots, \boldsymbol{\Phi_N}$, which depend on $\boldsymbol{n}$ processes or quality indicators $\boldsymbol{F_1^{(1)}}, \boldsymbol{F_2^{(1)}}, \dots, \boldsymbol{F_i^{(1)}}, \dots, \boldsymbol{F_n^1}$, the efficiency of the g-th function is equal:

$$\epsilon_{\phi} = \epsilon_{\phi}\left(F_1^{(g)}, F_2^{(g)}, \dots, F_n^{(g)}\right) = \epsilon_{\phi}\left(\left\{F_i^{(g)}\right\}\right), i = \overline{1,n}; g = \overline{1,N}. \qquad (3.59)$$

Estimating this effect is one of the problems of ANO that needs to be addressed. Its complexity lies in the fact that:

a) it is necessary to take into account a large number of quality indicators (endogenous variables);

b) there is uncertainty in the conditions of functioning and use of UAS at the stage of operation.

The overall effectiveness of the system, which includes the considered types of effect, is, as will be shown below, a vector-function.

It is obvious that the assessment of obviousness will be more accurate the more indicators that influence it are taken into account. In this case, we have to overcome the problem of solving multi-criteria problems and use one of the following two approaches.

The first approach is associated with the formation of a resulting (complex) quality indicator, which simplifies the solution of the efficiency measurement problem and has the form (3.17). This task will be called the task with the convolution of indicators or the task of the first type.

The second approach is associated with the explicit expression of the determining factors and represents one of the central problematic tasks. The solution of such problems is necessary to manage the efficiency of a complex system of the problem type (3.33). The essence of this problem lies in the multidimensionality and multiconnectivity of a weakly structured system.

A rational way to formalize such a system is to use a multi-level hierarchy of descriptions, whereby the formalization of a higher level will depend on the generalized and factorized variables of a lower level. The hierarchy is created by multilevel factorization of processes $\{\boldsymbol{F_i}\}$ using generalized parameters $\{\boldsymbol{\lambda_i}\}$, which are functionalities of $\{\boldsymbol{F_i}\}$.

This approach allows us to link the properties of the elements (lower-level subsystems) interacting with the environment to the efficiency of the system. This is the second type of task.

It should also be noted that, depending on the degree of uncertainty in the conditions of UAS application, which is caused in many cases by unpredictable or poorly predictable situations of the operation process, a certain efficiency model should be applied. The complexity of such a model is due to the presence of explicit (allowed in the analytical form) or implicit (informal) relationships between the parameters of hierarchically related systems. Explicit relationships are taken into account at the macro- or microsystem levels. The microsystem level of description refers to the stage of measuring the functional effect. Different types of effects are determined by the functioning of the entire UAS system, the characteristics of the controlling and controlled subsystems, and the control and management circuits. It is clear that under such conditions, efficiency measurement can be carried out only by solving the problem of formalizing the problem of UAS system efficiency and building appropriate models.

3.3. Setting the task of measuring efficiency and methods for its solution

Performance measurement involves solving a set of individual tasks. Among these tasks, the main one is related to the formalization of different types of effects and their interconnection.

The task of measuring efficiency in general can be formulated as follows. Let the ANS system be characterized by $\boldsymbol{g_1}$- a measured vector $\boldsymbol{\lambda}' = \{\boldsymbol{\lambda}'_1, \boldsymbol{\lambda}'_2, \dots, \boldsymbol{\lambda}'_{g1}\}$ controlled variables and $\boldsymbol{g_2}$- a measured vector $\boldsymbol{\lambda}''\{\boldsymbol{\lambda}''_1, \boldsymbol{\lambda}''_2, \dots, \boldsymbol{\lambda}''_{g2}\}$ of uncontrolled variables, and its quality – $\boldsymbol{g}$- a measured vector function:

$$F\{\lambda', \lambda''\} = \{F_i(\lambda', \lambda''), i \in \mathrm{I}_g\}, \mathrm{I}_g = \overline{1, g}.$$

The system efficiency is represented as a vector functional:

$$\epsilon c = \{\epsilon_j, j \in \mathrm{I}_1\}, \mathrm{I}_1 = \overline{1, g}, \qquad (3.60)$$

where $\boldsymbol{\epsilon_j}$ – indicator of the $\boldsymbol{j}$-th effect. For example:

$$\epsilon_j = \epsilon_j[F(\lambda', \lambda'')].$$

A set of **1** vectors of type $\boldsymbol{\epsilon_j}, \boldsymbol{j} = \overline{\mathbf{1}, \mathbf{1}}$ describes the components of different types of effect of the system under consideration. Then their composition, which has dimension $\boldsymbol{L} = \{\mathbf{1}\}$, describes the integral efficiency of the ANO system.

When determining the integral efficiency (hereinafter simply the efficiency of the system), two cases can be distinguished.

Case 1. The joint (integral) criterion has the following structure:

$$\epsilon = F(\epsilon_1, \epsilon_2, \dots, \epsilon_1), j = \overline{1,1},$$

where $\boldsymbol{\epsilon_j}$ – value of the criterion for the j-th type of effect ($\boldsymbol{j}$- th separate criterion).

Case 2. The resulting criterion is represented as a function of the coordinates of the new operation. However, it is not a function of the individual criteria as in the first case. This means that the new combined operation has its own objective that is not related to the individual objectives of the individual operations. The combined operation is based only on the assets of the individual operations and does not use the process of deriving a common criterion from the individual ones. Nevertheless, the result is a type diagram:

$$\epsilon = F\big[\epsilon_1\big(\epsilon_2(\epsilon_1)\big)\big],$$

that is, there is a "dimensional absorption" due to the corresponding transformations. This means that when we talk about a combined operation and obtaining a common criterion, only the first case is meant. Both of these cases are studied below.

Measuring efficiency is reduced to selecting a strategy $\boldsymbol{F(\lambda',\lambda'')}$ from the domain $\boldsymbol{Q_F}$ of its acceptable values. The domain $\boldsymbol{Q_F}$ зis defined by a set of constraints on individual quality indicators:

$$F_i(\lambda',\lambda'') \in Q_F, i = \overline{1,g}.$$

The vector-functional$\boldsymbol{\epsilon c}$ is associated with the strategy $\boldsymbol{F(\lambda',\lambda'')}$ through the mapping $\boldsymbol{\hat{R}}$. In this case, the mathematical model of the efficiency evaluation problem is as follows:

$$\epsilon c = [F(\lambda',\lambda'')] = \sup_{F(\lambda',\lambda'')\in Q_F} \hat{R}\,[F(\lambda',\lambda'')]. \qquad (3.61)$$

In a number of practical cases, the vector of uncontrollable variables $\boldsymbol{\lambda''}$ is a random variable. Then the model (3.61) takes the form:

$$\epsilon c = [F(\lambda',\lambda'')] = \sup_{F\in Q_F} M''_{\lambda}\,\{\hat{R}[F(\lambda',\lambda'')]\}. \qquad (3.62)$$

under probabilistic constraints $\boldsymbol{P\{g_i(\lambda'') \le b_i\}, i = \overline{1,g}}$.

It is clear that a system will be effective if it meets the set of criteria to the fullest extent possible. Then you can write it down:

$$\max_{F(\lambda',\lambda'')\in Q_F} \hat{R}\,[F(\lambda',\lambda'')] = \left\{\hat{R}_1[F(\lambda',\lambda'')],\dots,\hat{R}_g[F(\lambda',\lambda'')]\right\} \qquad (3.63)$$

$$Q_F = \{F(\lambda',\lambda'')\mathrm{I}g_i[F(\lambda',\lambda'')] \le 0, j = \overline{1,m}, F(\lambda',\lambda'') \in E^r\}, \ (3.64)$$

where $\boldsymbol{g_i(\dots)}$ – the constraint function of the $\boldsymbol{j}$- th index of $\boldsymbol{F(\lambda',\lambda'')}$; $\boldsymbol{E^r}$ – $\boldsymbol{r}$-dimensional Euclidean space.

In (3.63) $\boldsymbol{F_i(x)}$ epresents the maximized values or their mathematical expectations, if the maximized values themselves depend on random parameters $\boldsymbol{\lambda''}$. An essential feature of the problem (3.63), (3.64) is that the components of the target vector $\boldsymbol{R[F(\lambda',\lambda'')]}$ re measured in different physical quantities, and their maximum values are achieved at the coincident points $\boldsymbol{F^i(\lambda',\lambda'') \in Q_F, i = \overline{1,g}}$. The usual approach to solving it with convex objective functions $\boldsymbol{R_i(\lambda',\lambda'')}$ and a valid domain $\boldsymbol{Q_F}$ is to replace the original problem (3.63), (3.64) by a parameterized one:

$$\max_{F(\lambda',\lambda'')\in Q_F} \hat{R}[\alpha, F(\lambda',\lambda'')] = \sum_{i=1}^{g} \alpha_i \hat{R}_i[F(\lambda',\lambda'')]\,, \alpha_i \ge 0, \sum_{i=1}^{g} \alpha_i = 1. \ (3.65)$$

By solving problem (3.65) for a set of parameters $(\boldsymbol{\alpha_i}, \dots, \boldsymbol{\alpha_g})^{\boldsymbol{T}}$, we obtain a set of Pareto (effective) solutions $\boldsymbol{\Pi_F}$.

$$\Pi_F = \{F_0(\lambda', \lambda'') | F_0(\lambda', \lambda'') \in Q_F, F(\lambda', \lambda'') \in Q_F\},$$

$$\hat{R}_i[F(\lambda', \lambda'')] \geq \hat{R}_i[F_0(\lambda', \lambda'')] \text{ at } \hat{R}[\alpha, F(\lambda', \lambda'')] = \hat{R}[\alpha, F_0(\lambda', \lambda'')].$$

An alternative $\boldsymbol{F_0(\lambda', \lambda'')} \in \boldsymbol{Q_F}$ is Pareto-optimal if there is no alternative $\boldsymbol{H(\lambda', \lambda'')} \in \boldsymbol{Q_F}$ that satisfies each criterion to a lesser extent as well as $\boldsymbol{F_0(\lambda', \lambda'')}$ and that is strictly better than $\boldsymbol{F_0(\lambda', \lambda'')}$ with respect to at least one criterion.

If $\boldsymbol{Q_F}$ is convex and $\boldsymbol{\hat{R}_i}$ is a real function defined ona $\boldsymbol{Q_F}$, then $\boldsymbol{\hat{R}_i}$ is a quasi-concave function, provided that the sets are bounded from above:

$$\{F_0(\lambda', \lambda'') | \hat{R}_i[F(\lambda', \lambda'')] \geq \beta\}$$

are convex for every real number.

Accordingly, $\boldsymbol{R_i}$ is quasi-concave if:

$$\hat{R}_i[\alpha \cdot F_1(\lambda', \lambda'') + (1 - \alpha) \cdot F_2(\lambda', \lambda'')] \geq min\{\hat{R}_i[F_1(\lambda', \lambda'')], \hat{R}_i[F_2(\lambda, \lambda'')]\} \tag{3.66}$$

whenever $\boldsymbol{F_1(\lambda', \lambda''), F_2(\lambda', \lambda'')} \in \boldsymbol{Q_F}$ and $\boldsymbol{0 \leq \alpha \leq 1}$. The function $\boldsymbol{\hat{R}_i[F(\lambda', \lambda'')]}$ is strictly quasi-concave if:

$$\hat{R}_i[\alpha \cdot F_1(\lambda', \lambda'') + (1 - \alpha) \cdot F_2(\lambda', \lambda'')] > min\{\hat{R}_i[F_1(\lambda', \lambda'')], \hat{R}_i[F_2(\lambda, \lambda'')]\} \tag{3.67}$$

always for $\boldsymbol{F_1(\lambda', \lambda''), F_2(\lambda', \lambda'')} \in \boldsymbol{Q_F}$ and $\boldsymbol{0 \leq \alpha \leq 1}$. Of course, he concept of quasi-concavity includes the concept of concavity.

The resulting finite set of points from the domain $\boldsymbol{\Pi_F}$ in accordance with (3.66) is presented to the expert, who selects one that is preferred over the others.

If the conditions (3.65), (3.67) are not met, then it is advisable to analyze only inefficient solutions that are located in the zone of global extremes of the maximized functions.

The process of solving the problem (3.65) can be represented geometrically as a movement in the space of hyperplane criteria:

$$G = \sum_{i=1}^{g} \alpha_i \hat{R}_i[F(\lambda', \lambda'')] \qquad (3.68)$$

in the direction opposite to the parameter vector $(\boldsymbol{\alpha_1}, \dots, \boldsymbol{\alpha_g})^{\mathrm{E}}$. The maximum is reached when the hyperplane $\boldsymbol{G}$ becomes tangent to the valid region of the objective function $\boldsymbol{\Phi}$. The region of target values:

$$\Phi = \{\hat{R}_i[F_1(\lambda', \lambda'')] | F(\lambda', \lambda'') \in Q_F\}$$

is a mapping of the set $\boldsymbol{Q_F}$ in the criteria space. To calculate the required number of effective points, it is necessary to find for each set of parameters $(\boldsymbol{\alpha_1}, \dots, \boldsymbol{\alpha_g})^{\mathrm{E}}$ the global extremum of expression (3.65).

The Pareto principle does not single out a single solution $\boldsymbol{\in c}[\boldsymbol{F}(\boldsymbol{\lambda}', \boldsymbol{\lambda}'')]$, it only narrows the set of alternatives $\boldsymbol{F}(\boldsymbol{\lambda}', \boldsymbol{\lambda}'')$. The construction of the set (3.65) facilitates the procedure for selecting UAV indicators, takes into account their impact on system efficiency, and reduces the set of initial options.

Another approach to solving the problem (3.60) or (3.61) is to form a resulting quality indicator in order to ensure the comparability of system options. One of the options for such formation is a linear reconciliation of indicators, i.e., instead of $\boldsymbol{g}$ different indicators, one resulting indicator of the form is formed:

$$\Xi[F(\lambda', \lambda'')] = \sum_{i=1}^{g} \alpha_i \hat{R}_i[F(\lambda', \lambda'')], \quad (3.69)$$

where $\boldsymbol{\alpha_i}$ —a positive number, and in the case of a dimensionless one.

$$\hat{R}_i[F(\lambda', \lambda'')] \sum_{i=1}^{g} \alpha_i = 1.$$

This method of convolution is equivalent to ranking indicators, since the value of $\boldsymbol{\alpha_i}$ shows how much the objective function Ξ changes when the indicator with the number $\boldsymbol{i}$ changes by one:

$$\alpha_i = \frac{\delta \Xi}{\delta \hat{R}_i}, i = \overline{1, g}. \quad (3.70)$$

One of the challenges in measuring the effectiveness of ANS is to take into account the level of flight safety as one of the components (3.60). In this case, two fundamentally different approaches are possible. The first is to convert the level of flight safety into monetary terms, which is notoriously difficult and fraught with moral and social implications. Another approach is based on the conversion of flight safety indicators into the category of restrictions. The restriction is based on a guaranteed level. The complexity of measuring performance in this way is determined by the possibility of obtaining guaranteed estimates. The meaning of the guaranteed result principle is as follows.

Since for any $F(\lambda',\lambda'')\hat{R}[F(\lambda',\lambda'')] \leq \max\limits_{F(\lambda\prime,\lambda'')} \hat{R}[F(\lambda',\lambda'')]$, then for $\boldsymbol{\lambda''}$.

$$\hat{R}^*[F(\lambda',\lambda'')] = \max_{F(\lambda\prime,\lambda'')} \min_{\lambda''\in Q_\lambda} \hat{R}[F(\lambda',\lambda'')] \leq \max_{F(\lambda',\lambda'')} \hat{R}[F(\lambda',\lambda'')]. \quad (3.71)$$

Here, $\boldsymbol{\hat{R}}^*[\boldsymbol{F}(\boldsymbol{\lambda}',\boldsymbol{\lambda}'')]$ is called a guaranteed estimate (a guaranteeing strategy) in the sense that $\exists\boldsymbol{\lambda}''$ it guarantees a choice of $\boldsymbol{F}(\boldsymbol{\lambda}',\boldsymbol{\lambda}'') = \boldsymbol{F}^*(\boldsymbol{\lambda}',\boldsymbol{\lambda}'')$ such that the value of the objective function is not less than $\boldsymbol{\hat{R}}^*$. guaranteeing strategy can be obtained by solving optimization problems of the following form.

a) $\min\limits_{\boldsymbol{\lambda}''\in \boldsymbol{Q}_\lambda} \boldsymbol{\hat{R}}[\boldsymbol{F}(\boldsymbol{\lambda}',\boldsymbol{\lambda}'')]\ \forall\ \boldsymbol{F}(\boldsymbol{\lambda}',\boldsymbol{\lambda}'')$.

which leads to estimates $\boldsymbol{\lambda}'' = \boldsymbol{\tilde{\lambda}}''$ and $\boldsymbol{\hat{R}}^*[\boldsymbol{F}(\boldsymbol{\lambda}',\boldsymbol{\lambda}'')] = \boldsymbol{\hat{R}}[\boldsymbol{F}(\boldsymbol{\lambda}',\boldsymbol{\lambda}'')]$.

Hereafter, the ∀ symbol means "for all",

б) $\boldsymbol{max}\ \boldsymbol{\hat{R}}[\boldsymbol{F}(\boldsymbol{\lambda}',\boldsymbol{\lambda}'')]$ and we get the result:

$$F(\lambda',\lambda'') = F(\lambda',\tilde{\lambda}'') \text{ та } \hat{R}^*[F(\lambda',\lambda'')].$$

The guaranteed assessment can be significantly improved if the values of the parameter $\boldsymbol{\lambda}''$ are known in advance. Thus, the problem of assessing the effectiveness of the ANS, taking into account the guaranteed level of flight safety, given (3.60), (3.62), (3.71), takes the form:

$$\epsilon\text{c}[F(\lambda',\lambda'')] = \left\{ \max_{F(\lambda\prime,\lambda'')\in Q_F} M''_\lambda\{\hat{R}_i[F(\lambda',\lambda'')]\}, i = 1,\ldots,1-1 \right\}, \quad (3.72)$$

$$\max_{F(\lambda\prime,\lambda'')} \min_{\lambda''\in Q_\lambda} R_1[F(\lambda',\lambda'')] \leq \max_{F(\lambda\prime,\lambda'')} R_1[F(\lambda',\lambda'')] \quad (3.73)$$

$$P\{g_j(\lambda'') \leq b_j\}, j = \overline{1,g}. \quad (3.74)$$

Solving the problem (3.72) - (3.74) allows us to obtain an estimate of the real efficiency, taking into account the operating conditions of the UAS..

Depending on the conditions of use of UAS, an implicit or explicit link can be established between their performance and that of the system being serviced. Replacing one vehicle with another that has higher quality indicators does not always lead to a gain in terms of improving higher-order system parameters. For example, ensuring a potential increase in the capacity of zones, regularity and efficiency of flights by improving the quality of radar, communication, and radio navigation support is not always realized under normal operating conditions. Nevertheless, the effect can be obtained in special (extreme) situations, especially in terms of improving flight safety. ***Thus, when solving the problems of evaluating the effectiveness of the first type with implicit system linkages, as mentioned above, it is necessary to bring the compared options into a comparable form in terms of $\boldsymbol{F(\lambda',\lambda'')}$ indicators or functional tasks. This is based on the use of additional information about the types of system links and operating conditions.*** In this case, a step-by-step multi-step decision-making procedure is performed, which is characterized by a transformation string:

$$\{\Phi[F(\lambda',\lambda'')],\mathrm{I}(F,\lambda',\lambda'',y)\}, \qquad (3.75)$$

where $\mathbf{I}(\boldsymbol{F},\boldsymbol{\lambda}',\boldsymbol{\lambda}'',\boldsymbol{y}) -$ is additional information about the system and the conditions of $\boldsymbol{y}$.

Thus, for example, with implicit system linkages, applying informal procedures at the first stage and transformations of the type (3.75), in particular (3.69), at the following stages it is possible to formulate the resulting quality indicator $\boldsymbol{b}$ of the applied tool. This indicator can be used to adjust the given costs of production of a unit of the basic system, the associated capital investment and operating costs of the basic option.

In the case of explicit systemic relationships, the transformation of the type (3.75) is used to assess the impact of quality indicators $\boldsymbol{F}(\boldsymbol{\lambda}',\boldsymbol{\lambda}'')$ on the components of efficiency (3.60).

The magnitude of the effect is estimated using this approach when the components are expressed as a function of many variables:

– performance $\boldsymbol{P}\ [\boldsymbol{F}(\boldsymbol{\lambda}',\boldsymbol{\lambda}'')]$,

– operating costs $\boldsymbol{EB}\ [\boldsymbol{F}(\boldsymbol{\lambda}',\boldsymbol{\lambda}'')]$,

– reduced costs $\Pi\boldsymbol{B}[\boldsymbol{F}(\boldsymbol{\lambda}',\boldsymbol{\lambda}'')]$.

In accordance with the considered formula (3.58), it is necessary to build an efficiency model in which the variables are expressed as $\boldsymbol{P}_t[\boldsymbol{F}(\boldsymbol{\lambda}',\boldsymbol{\lambda}'')], \Pi\boldsymbol{B}_t[\boldsymbol{F}(\boldsymbol{\lambda}',\boldsymbol{\lambda}'')]$ and $\boldsymbol{EB}_t[\boldsymbol{F}(\boldsymbol{\lambda}',\boldsymbol{\lambda}'')]$. It is obvious here that it is possible to estimate the actual efficiency of a UAS or an air navigation system (ANS) as a whole.

Since systems of this class are used to support flights, special attention should be paid to measuring performance with regard to extreme situations that arise in the operating environment. However, such a measurement can only be made for specific types of systems, taking into account their specific functioning and structure. A prerequisite is also the presence of microsystem links between the object under study and a higher-order system, such as CNS/ATM tools. The basis of the efficiency model for this case is the functional effect model.

3.4. Evaluation of UAV efficiency with implicit system links

Methods for measuring the effectiveness of air navigation tools with implicit system links can be used in the following cases:

1) uncertainty of functional relationships between UAV quality indicators and air navigation system indicators;

2) impossibility or difficulty in assessing the impact of individual UAV quality indicators on the value of the system;

3) lack of knowledge at the design and development stages about specific operating conditions;

4) the need to take into account non-quantitative quality indicators;

5) the requirement to take into account subjective factors.

One of the ways to solve problems (3.61), (3.62) in the above cases is to form the resulting quality indicator and use it to adjust economic indicators in order to ensure the comparability of options in the first type of problems. The formation of the resulting quality indicator is based on the theory of decision making. In this case, the preference of different quality indicators is determined in terms of the usefulness of certain results. To make a decision on a given preference, it is necessary to overcome certain computational difficulties. Calculations are much easier if the preference is measurable and replaced by a quantitative quality indicator. The issue of representing preferences in the form of quantitative functions is related to the mathematical theory of utility.

Let's divide the set of components of the vector of quality indicators of the ANO into groups that reflect a certain set of object properties and place them in a series of advantages according to their usefulness. In the theory of utility, it is proved that if a decision maker (DM) bases his actions on a number of assumptions, then a quantitative utility function can be determined on the set $\boldsymbol{\mathfrak{R}}$ of expected outcomes of possible decisions. In other words, for each expected outcome of a possible decision $\boldsymbol{F(\lambda',\lambda'')}$ there is a certain number $\boldsymbol{u}\,[\boldsymbol{F(\lambda',\lambda'')}]$, which is called the utility of the decision. According to the theory of utility, a decision maker prefers one solution to another when the utility of one is greater than the utility of the other. Thus, the choice of the most preferred solution is considered in this case as a problem of maximizing its utility.

Thus, if the utility function exists, then to find the optimal solution (the alternative that is maximal according to the given priority), it is enough to find the maximum of the function $\boldsymbol{u}\,[\boldsymbol{F(\lambda',\lambda'')}$ on $\boldsymbol{\mathfrak{R}}$, or which you can use traditional mathematical analysis or optimization methods. Accordingly, the conditions for achieving the maximum become clearer.

To solve the problem of forming the resulting quality indicator, we will apply the theory of additive utility. Its practical application is based on the following axioms:

1) The outcome $\boldsymbol{F(\lambda',\lambda'')}$ is more prioritized than $\boldsymbol{F_j(\lambda',\lambda'')}$ only if $\boldsymbol{u}\,[\boldsymbol{F_i(\lambda',\lambda'')}] \geq \boldsymbol{u}\,[\boldsymbol{F_j(\lambda',\lambda'')}]$, where $\boldsymbol{u}\,[\boldsymbol{F_i(\lambda',\lambda'')}]$ and $\boldsymbol{u}\,[\boldsymbol{F_j(\lambda',\lambda'')}]$ are the utility of the outcomes $\boldsymbol{F_i(\lambda',\lambda'')}$ and $\boldsymbol{F_j(\lambda',\lambda'')}$, respectively.

2) Transitivity: if $\boldsymbol{F_i(\lambda',\lambda'')} > \boldsymbol{F_j(\lambda',\lambda'')}$, and $\boldsymbol{F_j(\lambda',\lambda'')} > \boldsymbol{F_k(\lambda',\lambda'')}$, then $\boldsymbol{u}\,[\boldsymbol{F_i(\lambda',\lambda'')}] > u\,\left[\boldsymbol{F_j(\lambda',\lambda'')}\right]$.

3) Linearity: if some outcome $\boldsymbol{F(\lambda',\lambda'')}$ is represented in the form: $\boldsymbol{F(\lambda',\lambda'')} = (\boldsymbol{1}-\boldsymbol{\alpha})\cdot\boldsymbol{F_1(\lambda',\lambda'')}+\boldsymbol{\alpha}\cdot\boldsymbol{F_2(\lambda',\lambda'')}$, where $\boldsymbol{0 \leq \alpha \leq 1}$, then:

$$u\,[F(\lambda',\lambda'')] = (1-\alpha)\cdot u\,[F_1(\lambda',\lambda'')] + \alpha\cdot u\,[F_2(\lambda',\lambda'')].$$

4) Additivity: if $\boldsymbol{u}\,[\boldsymbol{F_1(\lambda',\lambda''), F_2(\lambda',\lambda'')}]$ is the utility of achieving both outcomes $\boldsymbol{F_1(\lambda',\lambda'')}$ and $\boldsymbol{F_2(\lambda',\lambda'')}$, then the additivity property is as follows:

$$u\,[F_1(\lambda',\lambda''), F_2(\lambda',\lambda'')] = u\,[F_1(\lambda',\lambda'') + F_2(\lambda',\lambda'')].$$

Similarly, for$\boldsymbol{g}$ the outcomes $\boldsymbol{F_1(\lambda',\lambda''), F_2(\lambda',\lambda''), \dots, F_g(\lambda',\lambda'')}$, which are achieved simultaneously, can be written down:

$$\boldsymbol{u\left[F_1(\lambda',\lambda''), F_2(\lambda',\lambda''), \dots, F_g(\lambda',\lambda'')\right] = u\left[F_1(\lambda',\lambda'') + F_2(\lambda',\lambda'') + \cdots + F_g(\lambda',\lambda'')\right] = \sum_{i=1}^{g} u\,[F_i(\lambda',\lambda'')]}. \quad (3.76)$$

Expression (3.76) is conveniently represented in the form:

$$u\,[F(\lambda',\lambda'')] = \sum_{i=1}^{g} \alpha_i \cdot F_i(\lambda',\lambda'').$$

Based on the above axiomatics, after splitting the original set $\mathfrak{R}$ of components of the vector $\boldsymbol{F(\lambda',\lambda'')}$ into $\boldsymbol{r}$ groups:

$$F(\lambda',\lambda'') = \{F_{ij}(\lambda',\lambda'');\ i = \overline{1, g_1}\}$$

the usefulness of each $\boldsymbol{j}$- th group of indicators is assessed. Within each $\boldsymbol{j}$-th group, the coefficients of relative utility of the $\boldsymbol{i}$- th indicators $\boldsymbol{F_{ij}(\lambda',\lambda'')}$.

As a result, a certain order of priority is established among the components of the vector $\boldsymbol{F(\lambda',\lambda'')}$, which is called mixed priority. The mixed priority among the components of the vector $\boldsymbol{F(\lambda',\lambda'')}$ can be mutually unambiguously accepted by the ordered partitioning $\mathbf{I_1, I_2, \dots, I_{g_1}}, \boldsymbol{g_1} < g$, the set of indices $\mathbf{I} = \{\mathbf{1, 2, \dots,} \boldsymbol{g}\}$ and the numbers $\boldsymbol{C_{ij}} > 0, i = \overline{\mathbf{1}, \boldsymbol{p_1}},\ \boldsymbol{g} = \overline{\mathbf{1}, \boldsymbol{g_1}}$ such that:

$$\sum_{i \in \mathrm{I}_{m_1}} \sum_{i \in \mathrm{I}_{m_2}} C_{ij} = 1, m_1 = \overline{1, p_1}, m_2 = \overline{1, g_1}.$$

By ordering the partitioning of the original set $\boldsymbol{F}$ into $\boldsymbol{g}$, groups with $\boldsymbol{p_1}$ indicators, we obtain a certain quality matrix of dimension $\boldsymbol{K}$ for the product $\boldsymbol{G}$ under consideration:

$$K = \left|F_{ij}(\lambda',\lambda'')\right|(i = \overline{1, p_1};\ g = \overline{1, g_1}).$$

The matrix $\boldsymbol{K}$ can be viewed as a multidimensional alternative decision.

Denoting the value of the utility function of the $\boldsymbol{S}$-го th alternative decision $\boldsymbol{G_s}$ by $\boldsymbol{u(G_s)}$ and taking into account the basic provisions of the theory of additive utility, we obtain:

$$u(G_S) = \sum_{j=1}^{r} \sum_{i=1}^{g} \gamma_j \cdot \alpha_i \cdot F_{ij}^{S}(\lambda',\lambda''), \quad (3.77)$$

where

$\boldsymbol{\gamma_j}$ – weight coefficient of the $\boldsymbol{j}$-th group of quality indicators;

$\boldsymbol{\alpha_i}$ – weighting factor of the $\boldsymbol{i}$-th indicator of the $\boldsymbol{j}$-th group;

$\boldsymbol{S}$ – number of system variants.

The following original methodology can be used to determine the usefulness of groups and indicators.

Suppose there are $\boldsymbol{p_1}$ possible outcomes $\boldsymbol{F_1(\lambda',\lambda''), F_2(\lambda',\lambda''), \dots, F_{p_1}(\lambda',\lambda'')}$ with a priority relation between them:

$$F_1(\lambda',\lambda'') > F_2(\lambda',\lambda'') > F_3(\lambda',\lambda'') > \cdots > F_{p_1}(\lambda',\lambda'').$$

From the condition $\boldsymbol{\alpha_1 \cdot u\,[F_1(\lambda',\lambda'')] = u\,[F_2(\lambda',\lambda'')]}$ we determine the value of $\boldsymbol{\alpha_1}$. In the same way, we define:

$$\alpha_2 \cdot u\,[F_2(\lambda',\lambda'')] = u\,[F_3(\lambda',\lambda'')],$$

$$\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots,$$

$$\alpha_{n-1} \cdot u\left[F_{p_1-1}(\lambda',\lambda'')\right] = u\left[F_{p_1}(\lambda',\lambda'')\right].$$

Assuming the utility of the lowest-priority outcome $\boldsymbol{F_{p_1}(\lambda',\lambda'')}$ is equal to one, we find:

$$u\left[F_{p_1}(\lambda',\lambda'')\right] = 1;\;\; u\left[F_{p_1-1}(\lambda',\lambda'')\right] = \frac{1}{\alpha_{p_1-1}};\dots u\,[F_1(\lambda',\lambda'')] = \frac{1}{\prod_{i=1}^{p_1-1}\alpha_i}.$$

System quality indicators are usually measured on different scales. Therefore, they need to be normalized. For this purpose, in each $\boldsymbol{j}$-th group of indicators, we distinguish maximized and minimized indicators, i.e., indicators whose increase or decrease leads to a corresponding increase or decrease in the quality level of the tool $\boldsymbol{G}$ and, accordingly, to a change in its effectiveness.

Enter the notation:

$\boldsymbol{F_i^+}$ –indicator that can be maximized, $(\boldsymbol{i = \overline{1,p}})$;

$\boldsymbol{F_i^-}$ – indicator that can be minimized, $(\boldsymbol{i = \overline{p+1,g_1}}); \boldsymbol{p \le g_1}$;

$\boldsymbol{F_i^0}$ – reference value of the $\boldsymbol{i}$-th indicator $(\boldsymbol{i = \overline{1,g_1}})$;

$\boldsymbol{\widetilde{F}_i^+}$ – the permissible minimum value of the maximized indicator, $\boldsymbol{\widetilde{F}_i^+ \in Q_F}$;

$\boldsymbol{\widetilde{F}_i^-}$ – the permissible maximum value of the maximized indicator, $\boldsymbol{\widetilde{F}_i^- \in Q_F}$.

We normalize the indicators $\boldsymbol{F_i(\lambda',\lambda'')}$ according to the rule:

to maximize performance:

$$\alpha_i = \frac{F_i^+}{F_i^0}, i = \overline{1, p}, F_i^0 \neq 0; \quad (3.78)$$

for minimized performance:

$$b = \frac{F_i^0}{F_j^-}, j = \overline{p+1, g_1}, F_j^- \neq 0;\ F_i^+ \geq \tilde{F}_i^+;\ F_j^- \leq \tilde{F}_j^-. (3.79)$$

Tables 3.3 and 3.4 show the main indicators that affect the efficiency of drone use.

Table 3.3: Weighting coefficients γ_j of groups of local quality indicators of primary radar stations of different classes.

Table 3.3

Weighting factors γ of groups of local quality indicators of primary radar stations of different classes

№	Names of groups of local quality indicators	Landing RES	Highway		Airfield stations RES		
			ORL-T	ORL-TA	B_1	B_2	B_3
1	Indicators of the reliability of information issuance	0.31	0.2534	0.2649	0.2689	0.2558	0.2686
2	Operational performance indicators	0.29	0.2409	0.2421	0.2293	0.2388	0.2354
3	Interference immunity indicators	0.21	0.2398	0.2468	0.2404	0.2446	0.2393
4	Informational indicators	019	0.2659	0.2463	0.2608	0.2608	0.2567

Table 3.4: Weighting coefficients γ_j f groups of local quality indicators of secondary radar stations of different classes

Table 3.4

Weighting factors γ of groups of local quality indicators for secondary radar stations

№	Name of quality indicator groups	Weight coefficient
1	Information indicators	0.3572
2	Functional indicators	0.3279
3	Operational indicators	0.3149

Table 3.5. Weight coefficients and reference values of radar landing systems

Table 3.5

Weighting coefficients and reference values of quality indicators of landing radar stations

Groups of local quality indicators	Name of indicators	Index	Weight coefficient α_{ij}	Reference value F°
Indicators of the reliability of information issuance	1. Measurement error along the glide path (angle of place), min	-	0.1297	5
	2. Measurement error by course, min	-	0.2095	7
	3. Range measurement error at the decision-making	-	0.1984	30

	height, m			
	4. Probability of correct detection	+	0.1912	1
	5. Speed measurement error at the decision-making height, m/sec	-	0.1812	2
Performance indicators	1. Time between failures, hours	+	0.5299	1000
	2. Average repair time, min	-	0.4701	30
Interference resistance indicators	1. Coefficient of interference visibility	+	0.5689	23
	2. Reflections suppression factor from weather formations	+	0.4311	18
Informational indicators	1. Resolution by the angle of the place, °	-	0.1259	0.6
	2. Number of simultaneously tracked targets	+	0.1239	6
	3. Azimuth resolution, °	-	0.1211	1.2
	4. Limits of work by azimuth, °	+	0.1149	20
	5. Maximum range, km	+	0.1107	17
	6. Rate of information update, sec	-	0.1050	1
	7. The minimum angle of the place, °	-	0.1014	-1
	8. Maximum space angle, °	+	0.0992	9
	9. Range resolution, m	-	0.0970	120

Table 3.6. Weighting coefficients and reference values of quality indicators of primary radar systems

Table 3.6

Weighting coefficients and reference values of quality indicators of primary radar stations

Groups of local quality indicators	Name of indicators	Index	ORL-T		ORL-TA		ORL-A					
							B_1		B_2		B_3	
			α_{ij}	F°	α_{ij}	F°	α_{ij}	F°	α_{ij}	F°	α_{ij}	F°
Indicators of the reliability of information issuance	Detection probability	+	0.3335	0.9	0.3302	0.9	0.2942	0.9	0.2916	0.9	0.2749	0.9
	Probability of false alarms	-	0.2154	10^{-6}	0.2215	10^{-6}	0.2337	10^{-6}	0.2348	10^{-6}	0.2749	10^{-6}
	Mean square error - by range, m - by azimuth, °	-	0.2286	1000	0.2282	1000	0.2377	1000	0.2417	1000	0.2377	1000
		-	0.2225	1	0.2201	1	0.2354	1	0.2319	1	0.2395	2
Informational indicators	Maximum range, km	+	0.1684	400	0.1607	250	0.1627	160	0.1621	100	0.1485	46
	Minimum range, km	-	0.0959	5	0.1302	5	0.1099	1.5	0.1179	1.5	0.1221	1.5
	Maximum detection height, km	+	133	20	0.0868	20	0.0996	12	0.0950	7	0.1043	2.4
	The maximum angle of the place,°	+	0.1002	45	0.1103	45	0.0939	45	0.1185	45	0.0983	30
	Resolution capacity - by range, m - by azimuth, °	-	0.1465	1000	0.1484	1000	0.1450	1000	0.1389	350	0.1439	350
		-	0.1459	1.3	0.1499	1.5	0.1445	1.5	0.1371	1.5	0.1425	4
	Rate of	-	0.117	12	0.126	12	0.125	4	0.105	4	0.114	2

	information detection, s		4		6		1		2		0	
Interference resistance indicators	Background visibility coefficient, dB	+	0.5543	35	0.5612	35	0.5649	30	0.5639	30	0.5634	30
	Suppression coefficient	+	0.4457	33	0.4388	23	0.4351	23	0.4361	18	0.4366	18
Performance indicators	Mean time between failures, hours	+	0.5444	1000	0.5272	1000	0.5381	1000	0.5204	1000	0.5216	1000
	Average time to eliminate deficiencies, hours	-	0.4556	0.5	0.4728	0.5	0.4619	0.5	0.4796	0.5	0.4784	0.5

Table 3.7

Weighting coefficients and reference values of quality indicators of secondary radar stations

Groups of local quality indicators	Name of indicators	Index	Weight coefficient α_{ij}	Reference value F°
Informational indicators	1. Amount of information transmitted, bits	+	0.1587	112
	2. Azimuth resolution,°	-	0.1295	4
	3. Range resolution, m	-	0.1275	1000
	4. The maximum number of targets in the radar beam located in the same azimuth from which information is processed simultaneously	+	0.1205	63
	5. The maximum angle of the place, °	+	0.1041	45
	6. Detection resolution, km	+	0.09357	370
	7. The minimum angle of the place, °	-	0.08916	0.5
	8. Inspection rate, s	-	0.08880	10
	9. Minimum detection range, km	-	0.08817	2
Functional indicators	1. Probability of obtaining reliable information	+	0.2855	0.9
	2. Azimuth measurement error, °	-	0.2459	1
	3. Number of false targets	-	0.2428	40
	4. Range measurement error	-	0.2258	800
Operational performance indicators	1. Time between failures, hours	+	0.5166	1000
	2. Average time for troubleshooting, min	-	0.4834	30

Table. 3.8

The main flight and technical characteristics of the UAV

№	Characteristic	Parameter score	Marking	Dimension	Reference value	Comparative option
F1	Maximum flight duration	9	T_{max}	h	>7	
F2	Maximum flight range	9	L_{max}	km	>1000	
F3	Combat radius	8	R_c	km	>80	
F4	Takeoff mass	7	m_{max}	kg	<200	
F5	Economic speed	6	V_e	km/h	150	
F6	Maximum speed	6	V_{max}	km/h	>250	
F7	Static ceiling	6	H_{st}	m	6000	
F8	The maximum power of the power plant	6	N_0	h.p.	>50	

F9	Maximum operating load	6	$n^e_{y\,max}$	unit	>4	
F10	Crosswind takeoff and landing	5	Vy_{max}	m/sec	15	
F11	Run length	5	L_l	m	<200	
F12	Mileage length	5	L_{ml}	m	<200	
F13	Maximum mass of fuel	4	m_{Tmax}	kg	<30	
F14	Minimum speed	4	V_{min}	km/h	<100	
F15	Specific fuel consumption at the start	4	C_0	kg/h.p.h	<0.2	
F16	The mass of the target load	1	m_{tl}	kg	<50	

Remedy $\boldsymbol{G}$ is effective provided that:

$$\bar{F} = \{F_i(\lambda', \lambda'') \in F | \alpha_i \in Q_{F_1}, \text{and } Q_{F_2} \forall\, i = \overline{1, g}\},$$

where $\boldsymbol{Q_{F_1}}$ and $\boldsymbol{Q_{F_2}}$ – the regions of existence of variable relative indicators that provide an effect not lower than a given value.

Splitting the vector of quality indicators of the $\boldsymbol{j}$-th groups into maximized and minimized indicators transforms the quality matrix $\boldsymbol{K}$ into a Then the resulting quality indicator, taking into account (3.77), (3.78), the block structure of the matrix $\boldsymbol{K}$ and the matrix of weighting coefficients of individual indicators $\boldsymbol{F_i(\lambda', \lambda'')}$ in matrix form for the $\boldsymbol{S}$- th variant, can be written:

$$\beta_S(G) = (A_k E)^T \Gamma, S = \overline{1, m}, \qquad (3.80)$$

where

$\boldsymbol{A_k = (\alpha_{ij}, k_{ij}), i = \overline{1, p_1},\ j = \overline{1, g_1}\ p_1 \text{ x } g_2 = g}$ – the original quality matrix for the weighting matrix $\boldsymbol{A = (\alpha_{ij}), i = \overline{1, p_1},\ j = \overline{1, g_1}}$ and the matrix of normalized indicators $\boldsymbol{(k_{ij}), i = \overline{1, p_1},\ j = \overline{1, g_1}}$;

$\boldsymbol{E}$ – unit matrix of dimension $\boldsymbol{g_1}$ x $\boldsymbol{1}$;

$\boldsymbol{\Gamma}$ – a matrix of weighting coefficients of the $\boldsymbol{j}$- th groups. The dimension of this matrix is $\boldsymbol{p_1}$ x $\boldsymbol{1}$.

Expression (3.80) was used to estimate the comparative technical and economic efficiency in the case when the improvement in the quality of the new product $\boldsymbol{G}$ is not reflected in a reduction in operating costs. In this case, the present value costs $\text{ПВ}_{\boldsymbol{1}}$, capital investment $\boldsymbol{K_1}$, and operating costs $\text{EB}_{\boldsymbol{1}}$ of the basic asset are adjusted by the relation $\frac{\boldsymbol{\beta_S(G)}}{\boldsymbol{\beta_{S-1}(G)}}$. The meaning of this adjustment is as follows. A positive difference in the reduced costs for $\boldsymbol{S}$ options indicates that the improvement of consumer properties of the new product was achieved with a lower cost increase than for previously released analogues.

Thus, **the solution to the problem of measuring the effectiveness of UAS means with implicit system links can be represented as the following algorithm for evaluating UAVs with implicit system links**.

Step 1. $\boldsymbol{S}$ block matrices $\boldsymbol{K}$ of values of quality indicators of the considered variants of the product $\boldsymbol{G}$ are compared.

Step 2. Based on the estimates (e.g., expert estimates) of the matrix $\boldsymbol{K}$ the utility matrix of indicators $\boldsymbol{F_i(\lambda', \lambda'')}$ is matched.

Step 3. Determine the matrix of weighting coefficients of groups of quality indicators $\boldsymbol{\Gamma} = \left|\boldsymbol{\gamma_1, \gamma_2, \dots, \gamma_{p_1}}\right|$.

Step 4. Determine the weighting matrix:

$$\boldsymbol{A = (\alpha_{ij}), i = \overline{1, p_1}, j = 1, \overline{g_1}}.$$

Step 5. Calculate the elements of the original matrix $\boldsymbol{A_k}$.

Step 6. Для кожного з $\boldsymbol{S}$ варіантів визначається результуючий показник якості за формулою (3.80).

Step 7. The quality level of pairs of compared options is determined as the ratio of the resulting quality indicators.

Крок 8. Economic indicators are adjusted for the level of quality.

Крок 9. The economic effect is estimated.

As an example, Fig. 3.2 shows the dependence of the normalized value of the annual economic effect on the level of quality:

$$\frac{\beta_S(G)}{\beta_{S-1}(G)}$$

at different operating costs, specific capital investments, and present value costs. Here, $\boldsymbol{\beta_Q}$ – is a complex indicator of the equipment being evaluated, and $\boldsymbol{\beta_\sigma}$ – is the basic equipment.

TABLES OF UAV INDICATORS

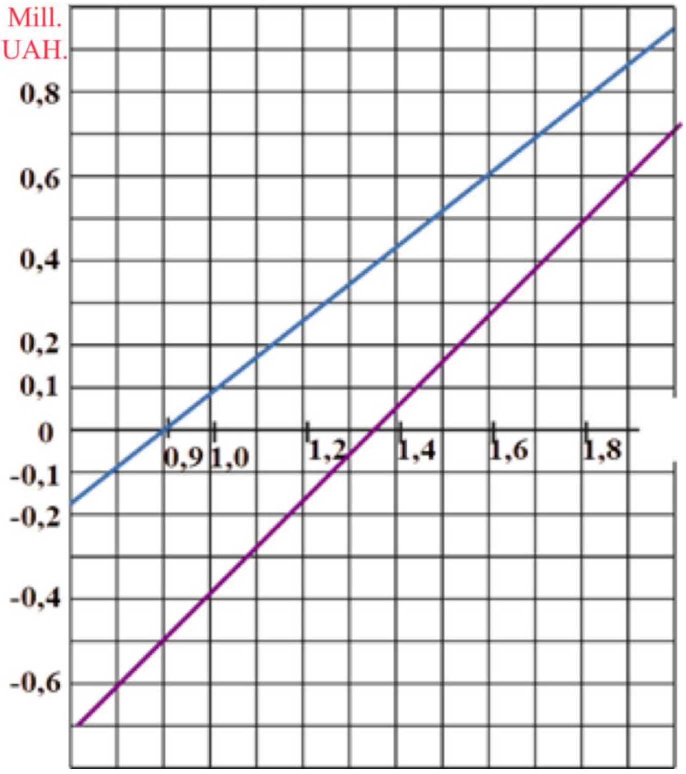


Fig. 3.2. Dependence of the normalized value of the annual economic effect on the quality level of UAS equipment

As can be seen from the figure, the economic effect of UAS implementation increases in proportion to the increase in equipment quality $\frac{\beta_Q}{\beta_\sigma}$. Based on the graph, it is possible to determine at what value of the quality level a positive economic effect can be obtained, which allows us to reasonably reject inefficient options.

A more complex assessment of effectiveness is one based on quantitative and non-quantitative indicators that reflect both objective and subjective factors. Subjective factors need to be taken into account because the effectiveness of such systems depends to a large extent on the people who operate the system and use its information. In this case, the ideal method would be one that allows objective factors to be expressed using quantitative values, and subjective factors to be expressed using the simplest language that does not require artificial translation into quantitative values. In this case, it would be possible not to pay much attention to the issues of measurement and its accuracy.

One method of assessing the subjective factor is to use the theory of fuzzy sets and fuzzy logic, which allows you to assign quantitative values to words that are not available for mathematical processing.

We would like to make a few remarks about the method of performance evaluation with implicit systemic linkages. The advantage of this approach is that a set of system quality indicators is taken into account. In addition, there is no need for an explicit formalized link between the quality indicators of the means and the quality indicators of the air navigation system. It is sufficient to use the relationship established when determining the usefulness of the indicators. Nevertheless, this approach is characterized by the conditional nature of the efficiency assessment caused by the lack of consideration of the UAS system's response to the improvement of the quality of assets and subjectivity in determining the significance of the quality indicators of ANO assets.

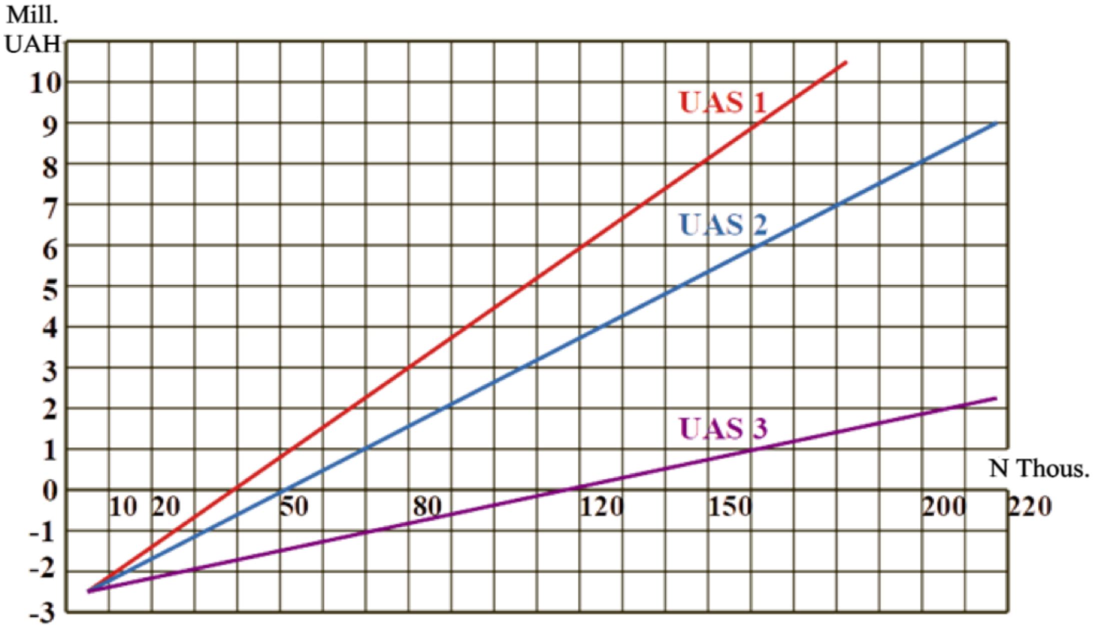


Fig.3.3. Dependence of the efficiency of cargo drones on their carrying capacity

As an example, for given operating conditions, Fig. 3.3 shows the dependence of the annual effect on the number of aircraft landing approaches when using standard navigation aids in the form of an autonomous landing aid.

A real assessment of UAV performance is possible only when explicit links between the indicators of CNS/ATM and the air navigation system are established and used.

3.5. Method for evaluating the effectiveness of cargo drones with explicit system links

3.5.1. General provisions

This method of performance evaluation is based on taking into account all three types of effect: functional, economic and social. The choice of a system of indicators for this purpose is made after defining the goals and objectives of a complex system.

A number of sub-problems arise when formulating the goal, criteria, and performance evaluation:

1. The first of them refers to the definition of the goal, which should be unambiguous despite the initial uncertainty.
2. The second subproblem is related to the estimation of resource costs. Rigorous quantitative analysis of resource estimates, their receipt, realization, renewal and expenditure in all details is not always available.
3. The third subproblem is related to the estimation of time. The analysis cannot go beyond the initial data, and they largely depend on the estimation of time.
4. The fourth subproblem is the choice of criteria. The adequacy of the criteria and the goal in terms of content and commonality determines the reliability of the result.

Let's consider one of the most difficult tasks of formalizing practical goals that have areas of incomplete achievement.

In general, the goal can be set in some $\boldsymbol{n}$- dimensional space of essential parameters $\boldsymbol{Z_1, Z_2, \dots, Z_n}$. It has external "dangerous" borders $\boldsymbol{\Gamma(Z_{O\Gamma})}$, which distinguish the zone of orderliness in which the goal is fully achieved with an acceptable accuracy$\boldsymbol{\varepsilon}$ or probability $\boldsymbol{P}_{\text{доп}}$ (рис. 2.3) boundaries is the area of partial achievement of the $\boldsymbol{D(Z_{O\Gamma})}$. The entire goal area can be divided into a set of different elements $\boldsymbol{\Delta}$.

The difference of elements will be considered potential if it is determined based on the limitations of physical measurements and existing interference, and real if it is determined by the requirements of the problem being solved and the capabilities of the equipment used.

Having divided the goal area into elements, we will assume that if the vector $\vec{\boldsymbol{Z}}$, hich characterizes the functioning of the system, belongs to the set $\boldsymbol{D}(\boldsymbol{Z}_{\boldsymbol{O}\Gamma})$, that is, $\vec{\boldsymbol{Z}} \in \boldsymbol{D}(\boldsymbol{Z}_{\boldsymbol{O}\Gamma})$, hen the functioning will be optimal in some sense. And if the vector is inside the area of partial achievement of the goal, ie:

$$\vec{Z} \in \Delta_i \subset D(Z_{O\Gamma}), \qquad (3.81)$$

then the functioning of the system will be somewhat worse than optimal due to a certain loss in the quality of the system's functioning. In this case, of course, there is a decrease in its efficiency.

The amount of damage will be determined using a weight that depends on the position of the $\boldsymbol{i}$- th element in the target area and the duration of the vector $\boldsymbol{Z}$ in the element $\boldsymbol{\Delta}_{\boldsymbol{i}}$.

The damage can be:

а) a deterministic amount of damage (loss $\overline{\boldsymbol{\Pi}}_{\boldsymbol{k}_i}$ within a unit of time);

б) a probabilistic amount of damage (risk) $\overline{\boldsymbol{\Pi}}_{\boldsymbol{k}_i} = \overline{\boldsymbol{\Pi}}_{\boldsymbol{i}}\boldsymbol{P}_{\boldsymbol{i}}$, where $\boldsymbol{P}_{\boldsymbol{i}} -$ the probability of an event that causes a loss $\overline{\boldsymbol{\Pi}}_{\boldsymbol{i}}$;

в) probability of failure to perform certain functions.

The degree of goal achievement is related to situations that arise in the process of system functioning. Let us introduce the concept of the situation space $\{\boldsymbol{S}\}$. It is formed using the parameters $\boldsymbol{s}_{\boldsymbol{i}}(\boldsymbol{i} = \overline{\boldsymbol{l},\boldsymbol{l}})$. Each point of this space defines a specific situation that has developed as a result of the system's functioning and is characterized by target variables $\boldsymbol{Z} = (\boldsymbol{z}_1, \boldsymbol{z}_2, \dots, \boldsymbol{z}_n)$. Each target variable $\boldsymbol{z}_{\boldsymbol{i}}$ is uniquely determined by the situation $\boldsymbol{S}$, i.e. $\boldsymbol{z}_{\boldsymbol{i}} = \boldsymbol{\psi}_{\boldsymbol{i}}(\boldsymbol{S}), \boldsymbol{i} = \overline{\boldsymbol{1},\boldsymbol{n}}$, and the function $\boldsymbol{\psi}_{\boldsymbol{i}}(\cdot)$ determines the relationship between the situation $\boldsymbol{S}$ and the target parameter $\boldsymbol{z}_{\boldsymbol{i}}$. In vector form, this relationship is represented as follows:

$$Z = \psi(S), \qquad (3.82)$$

where $\boldsymbol{\psi}(\cdot) = \left(\boldsymbol{\psi}_1(\cdot), \boldsymbol{\psi}_2(\cdot), \dots, \boldsymbol{\psi}_{\boldsymbol{n}}(\cdot)\right) -$ a vector function is defined that relates the state of the environment and the target variables.

The target variables may be of a different nature. However, the form of their representation should be unified and look like this:

$$z_i = \psi_i(S) = \begin{Bmatrix} z_i = a_i, & i = l, \dots, k_1 \\ z_j \geq b_j, & j = l, \dots, k_2 \\ z_1 \to extr, & l = l, \dots, k_3 \end{Bmatrix} \qquad (3.83)$$

So, for the given goals, you need to determine, first of all, their structure, that is, belonging to one of the three forms, and then set the numbers $\boldsymbol{a_i}$ and $\boldsymbol{b_j}$, for the number of goals of the first $\boldsymbol{k_1}$ and second $\boldsymbol{k_2}$ kind. For the first goal, we are looking for an extremum, i.e., depending on its nature, a maximum or minimum. In this case, the number of extreme goal requirements can be $\boldsymbol{k_3}$. ЯIf any goals are not reduced to the forms (3.83), then we cannot talk about the formal creation of a management system to achieve the goals.

The target point or region $\boldsymbol{S}^*$ that satisfies all the requirements simultaneously is the state that is achieved as a result of UAS operation. However, this can only be accomplished if there is an opportunity to influence the situation, i.e., if the situation is controllable:

$$S(U) = [s_1(U), \dots, s_n(U)] \qquad (3.84)$$

and the sufficiency of available management resources $\boldsymbol{R}$.

Here $\boldsymbol{U} = (\boldsymbol{u_1}, \dots, \boldsymbol{u_q})$ is the control with controlled parameters $\boldsymbol{u_1}, \dots, \boldsymbol{u_q}$. Resource constraints lead to the fact that the control $\boldsymbol{U}$ of the system is limited:

$$U \in \{U\}_R,$$

where $\{\boldsymbol{U}\}_{\boldsymbol{R}} -$ the set of controls limited by resources $\boldsymbol{R}$. Such resources are determined by the energy, material, professional and other capabilities of the polyergistic ANO system.

In the process of UAS operation, under the influence of external factors, the trajectory $\boldsymbol{S(t)} -$ the drift of situations in the target area $\{\boldsymbol{S}^*\}$, which in turn affects the conditional target vector:

$$Z^* = (Z_1, \dots, Z_n), \qquad (3.85)$$

where $\boldsymbol{Z}^* -$ are no longer numbers, but requirements for the state $\boldsymbol{S}$.

If the trajectory $\boldsymbol{S}(\boldsymbol{t})$ passes through the target region $\{\boldsymbol{S}^{*}\}$, i.e. $\boldsymbol{S}(\boldsymbol{t}) \subset \{\boldsymbol{S}^{*}\}$, then no control is needed. In this case $\boldsymbol{z}_{\boldsymbol{j}} \in \boldsymbol{D}(\boldsymbol{Z}_{\boldsymbol{B\Gamma}})$ (Fig. 3.4).

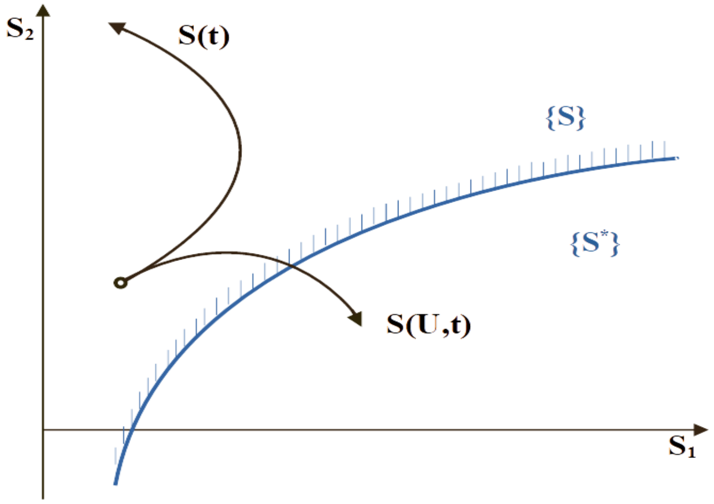


Fig. 3.4. Interaction of drift of UAV trajectory motion S(t) and control S(U,t) with the terminal target area $\{S^{*}\}$.

In order to keep the controlled object in this state under external influences, you need to manage the situation:

$$\boldsymbol{S} = \boldsymbol{S}(\boldsymbol{U}, \boldsymbol{t}) \qquad (3.86)$$

in such a way that:

$$\boldsymbol{S}(\boldsymbol{U}, \boldsymbol{t}) \in \{\boldsymbol{S}^{*}\} \textbf{ and } \in \boldsymbol{D}(\boldsymbol{Z}_{\boldsymbol{B\Gamma}}).$$

Management $\boldsymbol{U}$ should be considered, firstly, as a means of achieving the set goals, and secondly, as a means of compensating for unfavorable changes in the environment that impede this.

In the following, UAS controllability will be understood as the probability of achieving the set goals in different situations. At the same time, the situation that has developed in the control process, in the most general case, should be understood as three:

$$S =< X, E, Z^{*} >, \qquad (3.87)$$

which determines the state of uncontrolled inputs of the system (observed input $\boldsymbol{X}$,and disturbance $\boldsymbol{E}$ (unobserved) and the goal $\boldsymbol{Z}^{*}$ to be achieved. All situations encountered in the process of control can be divided into two subsets of situations - controllable, in which the given goal $\boldsymbol{Z}^{*}$ is always achieved, and uncontrollable, when this goal $\boldsymbol{Z}^{*}$ is not achieved.

Let us denote by $\{\boldsymbol{S}\}$ the set of all possible situations $\boldsymbol{S}$ that occur in the process of system operation. Let $\{\mathbf{I}_{\boldsymbol{S}}\}-$ be a subset of situations where the object is controllable, i.e., the goals from $\{\boldsymbol{Z}^*\}$ are achieved, and $\{\mathbf{I}_{\boldsymbol{S}}^{\mathbf{0}}\}$ be a subset of situations $\{\boldsymbol{S}\}$ where the object is uncontrollable, i.e., not all goals from $\{\boldsymbol{Z}^*\}$ are achieved. It is obvious that:

$$\{S\} = \{\mathrm{I}_S\} \cup \{\mathrm{I}_S^0\}\,. \qquad (3.88)$$

Each element of the set $\{\boldsymbol{S}\}$, i.e., each situation $\boldsymbol{S}$, is associated with a number $\boldsymbol{p} = \boldsymbol{p}(\boldsymbol{S})$, which would determine the probability of occurrence of this situation $\boldsymbol{S}$**.** This is a discrete case, and:

$$\textstyle\sum_{i=1}^{n} \rho(S_i), \qquad (3.89)$$

where $\boldsymbol{n} -$ the total number of situations.

If the number of elements of the set $\{\boldsymbol{S}\}$ is infinite, then $\boldsymbol{\rho}(\boldsymbol{S})$ should usually be understood as the density of this probability. Then in the continuous case, we can write:

$$\textstyle\int_{\{S\}} \boldsymbol{\rho}(\boldsymbol{S}), \qquad (3.90)$$

where the integral is taken over the entire set $\{\boldsymbol{S}\}$. This expression characterizes the fact that real situations S cannot occur outside the domain $\boldsymbol{S}$.

Now we can clarify the concept of controllability. The controllability of an object is the probability that a randomly selected situation $\boldsymbol{S}$ from the set $\{\boldsymbol{S}\}$ is controllable. This probability is equal to:

$$P = \textstyle\int_{\{I_S\}} \rho(S)dS. \qquad (3.91)$$

Uncontrollability is defined similarly as an integral over the set $\{\mathbf{I}_{\boldsymbol{S}}^{\mathbf{0}}\}$ of uncontrollable situations:

$$\bar{P} = \textstyle\int_{\{\mathrm{I}_S^0\}} \rho(S)dS. \qquad (3.92)$$

The probabilities $\boldsymbol{P}$ and $\overline{\boldsymbol{P}}$ form a complete group of events.

Attention should be paid to the problem of defining the sets $\{\boldsymbol{I}_{\boldsymbol{S}}\}$ and $\{\mathbf{I}_{\boldsymbol{S}}^{\mathbf{0}}\}$, as well as the function $\boldsymbol{\rho}(\boldsymbol{S})$, due to the lack of a formal description of the ANO system. How to get out of this situation will be shown below. Let us consider different forms of controllability and uncontrollability of the object of study. The object is absolutely controllable ($\boldsymbol{P} = \mathbf{1}$)if every situation in $\{\boldsymbol{S}\}$ is controllable, then the goal is always achieved. This means that for any controlled state of the environment $\boldsymbol{X} \in \{\boldsymbol{X}\}$, any uncontrolled input $\boldsymbol{E} \in \{\boldsymbol{E}\}$ and any goal $\boldsymbol{Z}^* \in \{\boldsymbol{Z}^*\}$, зthere will always be a control $\boldsymbol{U}^* \in \{\boldsymbol{U}\}_{\boldsymbol{R}}$, that will bring the object to the required state, i.e:

$$Z = Z(X, U^*, E) = \Phi[F^0(X, U^*, E) = Z^*, \quad (3.93)$$

where

$\boldsymbol{\Phi}(\cdot)$ – the transformation of the object's state space $\{\boldsymbol{Y}\}$ into the goal space $\{\boldsymbol{Z}\}$, presented in (3.92);

$\boldsymbol{Z}$ – the state of the object in the goal space;

$\boldsymbol{Z}(.,.,.,.)$ – a function that characterizes the dependence of $\boldsymbol{Z}$ on $\boldsymbol{X}, \boldsymbol{U}, \boldsymbol{E}$. The absolute controllability of an object can be written more compactly:

$$\forall X \in \{X\}, \forall E \in \{E\}, \forall Z^* \in \{Z^*\}, \exists U^* \in \{U^*\}_R : Z(X, U^*, E) = Z^*.$$

It is known that absolute controllability ($\boldsymbol{P} = \mathbf{1}$) is rarely found in the control of complex objects [58]. This is due to the need to narrow the set of goals, or to fulfill the requirement of state constancy ($\boldsymbol{X} = \boldsymbol{const}$), or to allocate very large resources $\boldsymbol{R}$ for control.

In this regard, the concept of partial or relative controllability is introduced. In this case, one should distinguish the unmanageability of situations, which can be represented by $\boldsymbol{X}$- unmanageability:

$$\mathrm{I}_{\bar{X}}: (\exists X \in \{X\}: \forall E \in \{E\}, \forall Z^* \in \{Z^*\}, \bar{\exists} U \in \{U\}_R: Z, U, E) = Z^*).$$

$\boldsymbol{E}$ – unmanageability is also possible, which means that there are uncontrollable states of the environment in which, for any valid $\boldsymbol{X}$, не вдається досягти будь-якої допустимої цілі:

$$\mathrm{I}_{\bar{E}}: (\exists E \in \{E\}: \forall X \in \{X\}, \forall Z^* \in \{Z^*\}, \bar{\exists} U \in \{U\}_R: Z(X, U, E) = Z^*).$$

$\boldsymbol{Z}^*$ – unmanageability, which is characterized by the presence of such admissible goals that are never achieved under other admissible conditions:

$$\mathrm{I}_{Z}^{*}: (\exists Z^* \in \{Z\}: \forall X \in \{X\}, \forall E \in \{E\}, \bar{\exists} U \in (U)_R: Z(X, U, E) = Z^*).$$

This implies that there are goals that are not achievable in all states of the environment.

The uncontrollability of situations $\{\mathbf{I}_{\overline{\boldsymbol{S}}}\}$ can be associated not only with one of the factors $\boldsymbol{X}, \boldsymbol{E}, \boldsymbol{Z}^*$ separately, but also with several factors simultaneously. In particular, we should distinguish between $\boldsymbol{XE}, \boldsymbol{XZ}^*, \boldsymbol{Z}^*\boldsymbol{E}, \boldsymbol{X}, \boldsymbol{E}, \boldsymbol{Z}^* -$ uncontrollability.

$\boldsymbol{XE} -$ unmanageability is defined as the simultaneous existence of such $\boldsymbol{X}$ and $\boldsymbol{E}$ that not every goal is achievable:

$$\mathrm{I}_{\overline{XE}}: (\exists(X,E): \forall X \in \{X\}, \forall E \in \{E\}, \forall Z^* \in \{Z\}, \forall U \in \{U\}_R, \overline{\exists} U \in \{U\}_R: Z(X,U,E) = Z^*);$$

$$\mathrm{I}_{\overline{XZ^*}}: (\exists(XZ^*): \forall X \in \{X\}, \forall E \in \{E\}, \forall Z^* \in \{Z^*\}, \forall U \in \{U\}_R, \overline{\exists} U: Z(X,U,E) = Z^*);$$

$$\mathrm{I}_{\overline{Z^*E}}: (\exists(Z^*E): \forall X \in \{X\}, \forall E \in \{E\}, \forall Z^* \in \{Z^*\}, \forall U \in \{U\}_R, \overline{\exists} U: Z(X,U,E) = Z^*);$$

$$\mathrm{I}_{\overline{XEZ^*}}: (\exists(X,E,Z^*): \forall X \in \{X\}, \forall E \in \{E\}, \forall Z^* \in \{Z^*\}, \forall U \in \{U\}_R, \overline{\exists} U: Z(X,U,E) = Z^*).$$

The above expressions define cases of uncontrollability in the space of situations $\{\boldsymbol{S}\} = \{\boldsymbol{X}, \boldsymbol{E}, \boldsymbol{Z}^*\}$. In [58], it is proposed to evaluate the occurrence of these types of controllability by the expert method. In the author's works [88, 89, 99, 101, 143, 149], his problem was solved by numerical methods.

Thus, it can be argued that the controllability of situations makes it possible to manage the efficiency of a complex system. This is because the situations that arise in the system characterize the quality of its functioning.

Thus, the assessment of UAS performance is related to the problem of performance management. To solve it, it is necessary to decompose this problem, i.e., to present it as a series of simpler tasks. Their solution involves the following steps:

1. Management objectives are defined, i.e., the set of management objectives $\{\boldsymbol{Z}^*\}$ to be realized in the system is described sufficiently.
2. The available resources $\boldsymbol{R}$ allocated for the creation of the system and its operation are estimated.
3. The object $\boldsymbol{F}^{\mathbf{0}}$.
4. The set $\{\boldsymbol{X}\}$ of controlled states that can be used to synthesize control and assess situations is described.

5. The set of controls $\{\boldsymbol{U}\}_{\boldsymbol{R}}$ allowed by resources $\boldsymbol{R}$ is estimated.

6. The set of uncontrollable factors of the environment and the object $\{\mathbf{E}\}$ is estimated.

7. A spectrum of situations is built.

In general, the controllability of an object is presented as follows:

$$P =< \{Z^*\}, R, F^0, \{X\}, \{U\}_R, E >. \qquad (3.94)$$

As noted above, the controllability of an object is assessed based on the controllability of situations $\{\boldsymbol{S}\}$ which characterize the achievability of goals, and thus determine the effectiveness of a complex system. Since a range of situations is used, including catastrophic ones, this approach makes it possible to evaluate the system's efficiency taking into account the main types of effect: functional, economic, and social.

3.5.2. Principles of determining the functional effect when controlling dynamic objects

For many technical control systems of dynamic objects, in our case UAS, the purpose of functioning is to achieve a given final state, for example, a terminal set, from some initial state under the constraints on control resources and the phase state of the object, under the influence of external disturbing factors.

The degree to which the system reaches a given end state and the timing of achievement can serve as generalized indicators of the functional effect [149].

Let us consider a fairly wide class of dynamic object control systems that allow for an initial division into **Information-Management (IM)** and **Control (C)** subsystems, i.e., a ground control station of a remote pilot with a **C2** line **(IM)** and UAV (C). We denote UAS by $\boldsymbol{G} = \boldsymbol{G_1}\mathbf{x}\,\boldsymbol{G_2}$, where $\boldsymbol{G_1} -$ **IM**, $\boldsymbol{G_2} -$ **C**. The state of the system $\boldsymbol{G}$ can be represented by a mapping vector $\boldsymbol{Y} \in \boldsymbol{R^n}$,$\boldsymbol{n}$- imensional Euclidean space: $\boldsymbol{Y} = (\boldsymbol{x}, \boldsymbol{\lambda})$, where $\boldsymbol{x} -$ the phase state vector of the UAS, $\boldsymbol{\lambda} -$ its parameter vector. In turn: $\boldsymbol{x} = (\boldsymbol{x_1}, \boldsymbol{x_2}), \boldsymbol{\lambda} = (\boldsymbol{\lambda_1}, \boldsymbol{\lambda_2})$, where $\boldsymbol{x_i}\boldsymbol{\lambda_i}$ – respectively, the phase state vector and the parameter vector of the UAS subsystems. By introducing an ordered set of real numbers $\mathbf{I}$, which reflect the time parameter $\boldsymbol{t}$, we define a complete event in the UAS as a pair of elements: $(\boldsymbol{Y}, \boldsymbol{t}) \in \boldsymbol{R}^{n}$ $\mathbf{x}\,\mathbf{I}$. Due to the fact that the parameter vector $\boldsymbol{\lambda}$ contains both constant (or weakly dependent on the phase state of the control object) and time-varying values, the concepts of phase $(\boldsymbol{x}, \boldsymbol{t})$ and parametric $(\boldsymbol{\lambda}, \boldsymbol{t})$ events are similarly introduced. For the sake of completeness, it is necessary to introduce the disturbing event $(\boldsymbol{\xi}, \boldsymbol{t}) \in \boldsymbol{R}^{m}\mathbf{x}\,\mathbf{I}$, where $\boldsymbol{\xi}$ – the disturbance vector, and the control event $(\boldsymbol{u}, \boldsymbol{t}) \in \boldsymbol{R}^{q}\mathbf{x}\,\mathbf{I}$, where $\boldsymbol{u}$ – as before – the control vector.

If the UAS is functioning normally, then the structure of event connectivity must also be valid: two events $(\boldsymbol{Y}_1, \boldsymbol{t}_1)$ and $(\boldsymbol{Y}_2, \boldsymbol{t}_2)$ $\boldsymbol{t}_1 < \boldsymbol{t}_2$ ϵ are connected if $\forall \boldsymbol{\xi} \in \boldsymbol{E}$ there is a sequence of control events $(\boldsymbol{u}, \boldsymbol{t}), \boldsymbol{t}_1 \leq \boldsymbol{t} \leq \boldsymbol{t}_2$ such that $(\boldsymbol{Y}_1, \boldsymbol{t}_1)$ and $(\boldsymbol{Y}_2, \boldsymbol{t}_2)$ are the initial and final events for the UAS, respectively.

Similarly, connectivity is determined by phase and parametric events. For UAS, as a purposefully functioning system, the connectivity of events is used to determine the controllability of events: event $(\boldsymbol{Y}_1, \boldsymbol{t}_1)$ s controllable relative to event $(\boldsymbol{Y}_2, \boldsymbol{t}_2)$ if this pair of events is connected; event $(\boldsymbol{Y}_2, \boldsymbol{t}_2)$ is achievable from event $(\boldsymbol{Y}_1, \boldsymbol{t}_1)$ if this pair of events is connected due to the action of system $\boldsymbol{G}$.

Let us define the set of initial events $\boldsymbol{\Omega}(\boldsymbol{t}_0)$ for the UAS as a valid set of subsystem states at the initial time $\boldsymbol{t}_0$ and the set of final events $\boldsymbol{\omega}(\boldsymbol{t}_k)$, which reflects the purpose of the UAS action.

Then the process of functioning of the control system of a dynamic object is determined by the sequence of events $(\boldsymbol{Y}, \boldsymbol{t})$, controlled with respect to $\boldsymbol{\omega}(\boldsymbol{t}_k)$.

If the event $\boldsymbol{\omega}(\boldsymbol{t}_k)$ is controllable with respect to $\boldsymbol{\omega}(\boldsymbol{t}_k)$, then we say that it generates a situation $\boldsymbol{S}^{\text{пр}_1}$ – a prerequisite for continuing the control process, if not, it generates a situation $\boldsymbol{S}^{\text{пр}_2}$ – a prerequisite for interrupting the control process. And depending on the situation, the decision maker must choose a certain strategy of action. Let's call the strategy of continuing the management process strategy $\boldsymbol{A}_1$, which realizes the expected outcome of the situation $\boldsymbol{S}^{\text{пр}_1}$, and the strategy of interrupting the management process - strategy $\boldsymbol{A}_2$, which realizes the expected outcome of the situation $\boldsymbol{S}^{\text{пр}_2}$.

Since the task of event identification is solved in UAS on the basis of information about $\boldsymbol{Y}$ received by the information and control system, the incompleteness of this information caused by the inevitable errors of the latter gives rise to additional situations. If the event $(\boldsymbol{Y},\boldsymbol{t})$ is controlled with respect to $\boldsymbol{\omega}(\boldsymbol{t_k})$, and the event $(\boldsymbol{Y}^*,\boldsymbol{t})$, where $\boldsymbol{Y}^* = (\boldsymbol{x}^*,\boldsymbol{\lambda}^*)$; $\boldsymbol{x}^*,\boldsymbol{\lambda}^*$ – the observed phase state vector and the UAS parameter vector, is uncontrollable, then the situation $\boldsymbol{S}^{\text{пр}_3}$ – a prerequisite for the false continuation of the control process- arises. The concept of IR strategy $\boldsymbol{A_2}$ in situation $\boldsymbol{S}^{\text{пр}_3}$ and strategy $\boldsymbol{A_1}$ in situation $\boldsymbol{S}^{\text{пр}_4}$ is an erroneous action, and strategy $\boldsymbol{A_1}$ n some cases can lead to catastrophic consequences.

The fact of the controllability of events $(\boldsymbol{Y}^*,\boldsymbol{t})$ or $(\boldsymbol{Y},\boldsymbol{t})$ is established by the fact that these events belong to the set of admissible current events $\boldsymbol{\Omega}(\boldsymbol{t})$ controlled with respect to $\boldsymbol{\omega}(\boldsymbol{t_k})$.

The possibility of the occurrence of situations $\boldsymbol{S}^{\text{пр}_1}$ and $\boldsymbol{S}^{\text{пр}_2}$ in the process of SUDO functioning requires that the choice of the IM action strategy be made according to a rule that guarantees the quality of the decisions made.

The degree of objective possibility of occurrence of any of the situations $\boldsymbol{S}^{\text{пр}_i}, \boldsymbol{i} = \overline{\boldsymbol{l},\boldsymbol{4}}$ will be evaluated using the probabilities $\boldsymbol{P}(\boldsymbol{S}^{\text{пр}_i},\boldsymbol{t})$, which are defined as follows:

$$P(S^{\text{пр}_1},t) = \text{Ймовір}\{(Y^*,t) \in \Omega(t)|(Y,t) \in \Omega(t)\}$$
$$P(S^{\text{пр}_2},t) = \text{Ймовір}\{(Y^*,t) \notin \Omega(t)|(Y,t) \notin \Omega(t)\} \quad (3.95)$$
$$P(S^{\text{пр}_3},t) = \text{Ймовір}\{(Y^*,t) \notin \Omega(t)|(Y,t) \in \Omega(t)\}$$
$$P(S^{\text{пр}_4},t) = \text{Ймовір}\{(Y^*,t) \notin \Omega(t)|(Y,t) \notin \Omega(t)\}.$$

A given level of quality, the level of acceptance, will be ensured by a proper partitioning of the entire set of events $\boldsymbol{\Omega}(\boldsymbol{t})$. To specify the development rule, several definitions are necessary [89, 149].

Definition 2.2. The reflexive resource of a UAS action of order $\boldsymbol{\beta}$ is the set:

$$L_1(t,\beta_1) = \{(Y,t)|P(S_1,t) > \beta_1\}, \quad (3.96)$$

where $\boldsymbol{\beta_1}$ – the selected level of $\boldsymbol{P}(\boldsymbol{S_1},\boldsymbol{t})$.

The convexity of the set $\boldsymbol{\Omega}(\boldsymbol{t})$ and the concavity of the function $\boldsymbol{P}(\boldsymbol{S_1},\boldsymbol{t})$ in

$(\boldsymbol{Y}, \boldsymbol{t})$, as well as the definition (3.96), gives rise to the inclusion $\boldsymbol{L_1}(\boldsymbol{t}, \boldsymbol{\beta_1}) \subset \boldsymbol{\Omega}(\boldsymbol{t})$. 3This makes clear the meaning of the name of the specified set, which is nothing more than the set of current events, from the point of view of IM, controlled relative to the terminal set $\boldsymbol{\omega}(\boldsymbol{t})$ with probability not lower than $\boldsymbol{\beta_1}$. In this case $\boldsymbol{\Omega}(\boldsymbol{t})$ can be considered the initial current resource of the system.

Нехай $\boldsymbol{\mu}(\cdot) -$ be a measure on the set of events $\{\boldsymbol{\Omega}(\boldsymbol{t})\}$.

Definition 2.3. The coefficient of permissible use of the resource of a SUDO is a ratio:

$$R(t) = \frac{\mu(L_1(t,\beta_1))}{\mu(\Omega(t))}. \qquad (3.97)$$

From the definitions **(2.2)** and **(2.3)** , it follows that $\boldsymbol{0} \leq \boldsymbol{R}(\boldsymbol{t}) < \boldsymbol{1}$. This coefficient can serve as one of the generalized indicators of UAS quality.

Such events belonging to $\boldsymbol{\Omega}(\boldsymbol{t})$ are uncontrollable with respect to $\boldsymbol{\omega}(\boldsymbol{t_k})$. To ensure that the system can recognize the relevant situations, it is necessary to distinguish the following action element.

Definition 2.4. The set of UAS goal failure of order $\boldsymbol{\beta_2}$ is called the set of failure to achieve the goal:

$$L_2(t, \beta_2) = \{(Y, t) | P(S_2, t) > \beta_2, \qquad (3.98)$$

where $\boldsymbol{\beta_2} = \boldsymbol{P}(\boldsymbol{S_2}, \boldsymbol{t}) -$ the selected level of $\boldsymbol{P}(\boldsymbol{S_2}, \boldsymbol{t})$.

$\boldsymbol{L_2}(\boldsymbol{t}, \boldsymbol{\beta_1}) \subset \overline{\boldsymbol{\Omega}}(\boldsymbol{t})$. Using this set, the UAS recognizes the situation $\boldsymbol{S_2}$ with a probability not lower than $\boldsymbol{\beta_2}$.

Let $\boldsymbol{L}$ denote the set of different events $(\boldsymbol{Y}, \boldsymbol{t})$. It is obvious that $\boldsymbol{L} = \overline{\boldsymbol{\Omega}}(\boldsymbol{t}) \cup \boldsymbol{\Omega}(\boldsymbol{t})$. Then, for completeness, we define it as follows.

Definition 2.5. The set of uncertainty in the estimation of the connectivity of events $(\boldsymbol{Y}, \boldsymbol{t})$ is a set:

$$L_3(t, \beta_1, \beta_2) = L | \big(L_1(t, \beta_1) \cup L_2(t, \beta_2)\big). \qquad (3.99)$$

If the current event assessment belongs to this set, the system cannot recognize any of the situations $\boldsymbol{S_1}$ and $\boldsymbol{S_2}$ with levels not lower than the specified $\boldsymbol{\beta_1}$ and $\boldsymbol{\beta_2}$.

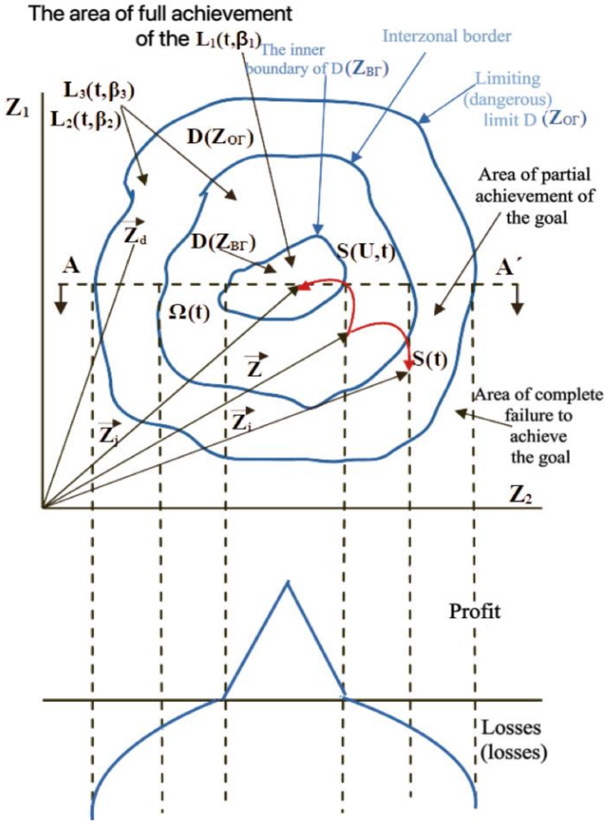


Fig. 3.5. To the task of formalizing the goal and achieving it.

Fig. 3.5 shows the relations between the considered sets for some fixed moment $\boldsymbol{t}$ in the space $\boldsymbol{R^2}$. The dotted line is the limit of the set $\boldsymbol{\Omega(t)}$. Inside it, the solid line shows the boundary of the set $\boldsymbol{L_1(t,\beta_1) = D(Z_{B\Gamma})}$ – the reflexive resource of UAS action, and the solid line outside highlights the set of failure to achieve the goal of the SUDO $\boldsymbol{L_2(t,\beta_2)}$.

Now let's write down the formal relations that express the rule for adopting action strategies $\boldsymbol{A_1}$ and $\boldsymbol{A_2}$:

$$(Y^*,t) \in L_1(t,\beta_1) \to A_1; (Y^*,t) \in L_2(t,\beta_2) \to A_2. \qquad (3.100)$$

The degree of fidelity of strategies $\boldsymbol{A_1}$ and $\boldsymbol{A_2}$ s guaranteed by the value of the chosen levels – $\boldsymbol{\beta_1}$ and $\boldsymbol{\beta_2}$, respectively. As can be seen, rule (3.100) does not cover the case $\boldsymbol{(Y^*,t) \in L_3(t,\beta_1,\beta_2)}$. This is a special case. Belonging of the current event estimate to the uncertainty set in the event connectivity estimate (or simply the uncertainty set) does not allow us to guarantee the choice of one of the action strategies $A_i, i = \overline{1,2}$. In order to increase the level of safety for some systems, a rule can be recommended:

$$(Y^*, t) \in L_3(t, \beta_1, \beta_2) \rightarrow A_2. \quad (3.101)$$

However, due to the presence of the situation $\boldsymbol{S}^{\text{пр}з}$, additional losses may occur, caused, for example, by the interruption of the control process. These losses reduce the performance of the UAS. In order to indicate ways to reduce these losses and increase system efficiency, the following definitions are necessary.

Definition 2.6. The critical moment in the functioning of the UAS is the time $\boldsymbol{t_c} \in [\boldsymbol{t_0}, \boldsymbol{t_k}]$ at which the action resource utilization rate is $\boldsymbol{R}(\boldsymbol{t_c})$.

The set of critical moments is denoted by $\boldsymbol{T_c}, \boldsymbol{T_c} \in [\boldsymbol{t_0}, \boldsymbol{t_k}]$.

Definition 2.7. The boundary of a UAS is a moment in time:

$$t_c^* = \inf_{t_c} T_c\,. \quad (3.102)$$

At $\boldsymbol{t} > \boldsymbol{t_c^*}$, none of the estimates of current events in the system can be correlated with any situation with the selected levels of assurance. The critical moment in the functioning and the limit of action can be correlated with the critical phase state $\boldsymbol{x_c}$ and the parameter vector $\boldsymbol{\lambda_c}$, the limit phase state $\boldsymbol{x_c^*}$ and the parameter vector $\boldsymbol{\lambda_c^*}$.

The possibility of using the above concepts for UAS characteristics will be considered on the example of analyzing the side channel of the aircraft landing system. As an information and control subsystem, two navigation options were considered, with lines for transmitting control signals (telemetry) to the board, which differ from each other in terms of accuracy.

The first option: accuracy of measuring the lateral deviation from the specified descent trajectory (in sensi, a circular radar station) in angular units $\boldsymbol{\sigma_\Omega} = \boldsymbol{3'}$; accuracy of measuring the direction of the ground speed vector $\boldsymbol{\sigma_\varphi} = \boldsymbol{0.37}°$.

The second option: $\boldsymbol{\sigma_\Omega} = \boldsymbol{4'}$. For both variants, $\boldsymbol{\beta_1} = \boldsymbol{\beta_2} = \boldsymbol{0.99}$.

As a controlled subsystem, we considered two types of aircraft, LA1 та LA2, which differ significantly in the rate of descent on the glide path and in maneuvering characteristics (LA2 - a maneuverable aircraft, has a higher rate of descent). As the final events of the set, $\boldsymbol{\omega}(\boldsymbol{t})$ the sets of permissible phase states for each type of aircraft at the ILS reference point were selected, taking into account the selected value of the runway width (60 m). For each type of aircraft, sets of permissible current events $\boldsymbol{\Omega(t)}$ at coordinates $\boldsymbol{z, 0}$, controlled relative to the initial $\boldsymbol{\omega(t)}$, were further constructed.

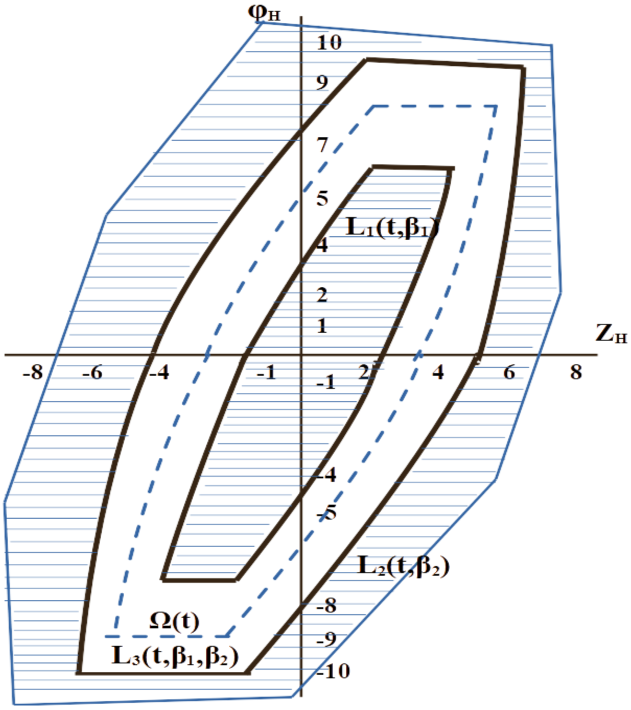


Fig. 3.6. UAS resource and UAV target failure sets..

In Fig. 3.6, the dotted line shows the characteristic form of the set $\boldsymbol{\Omega(t)}$ for an airplane. The coordinates $\boldsymbol{z}$ and $\boldsymbol{\Phi}$ are normalized. In the same figure, the solid line inside $\boldsymbol{\Omega(t)}$ denotes the set $\boldsymbol{L_1(t, \beta_1)}$ – the reflexive resource of the SP action at time $\boldsymbol{t}$, constructed for $\boldsymbol{\beta_1} = \boldsymbol{0.97}$, and the solid line outside highlights the set of failure to achieve the SP goal $\boldsymbol{L_2(t, \beta_2)}$ for $\boldsymbol{\beta_2}$.

In Fig. 3.7, for the selected types of control and controlled subsystems, the intersection of the sets $\boldsymbol{L_1(t, \beta_1)}$ and $\boldsymbol{L_2(t, \beta_2)}$ by the plane $\boldsymbol{\Phi} = \boldsymbol{0}$ is presented for different moments of time $\boldsymbol{t}$. Comparison of these results shows that for both PRLS variants, the transition to a lower-speed aircraft reduced the limit of the instrument landing system (ILS) by about 1.5 times. For each type of aircraft, the use of a more accurate PRLS can reduce the range by about 2 times. With increasing requirements for the quality of decisions made, the ILS limit of action increases, as illustrated by the effect of the level of $\boldsymbol{\beta_1}$**(0.97** and **0.99)** on the size of $\boldsymbol{L_1(t, \beta_1)}$.

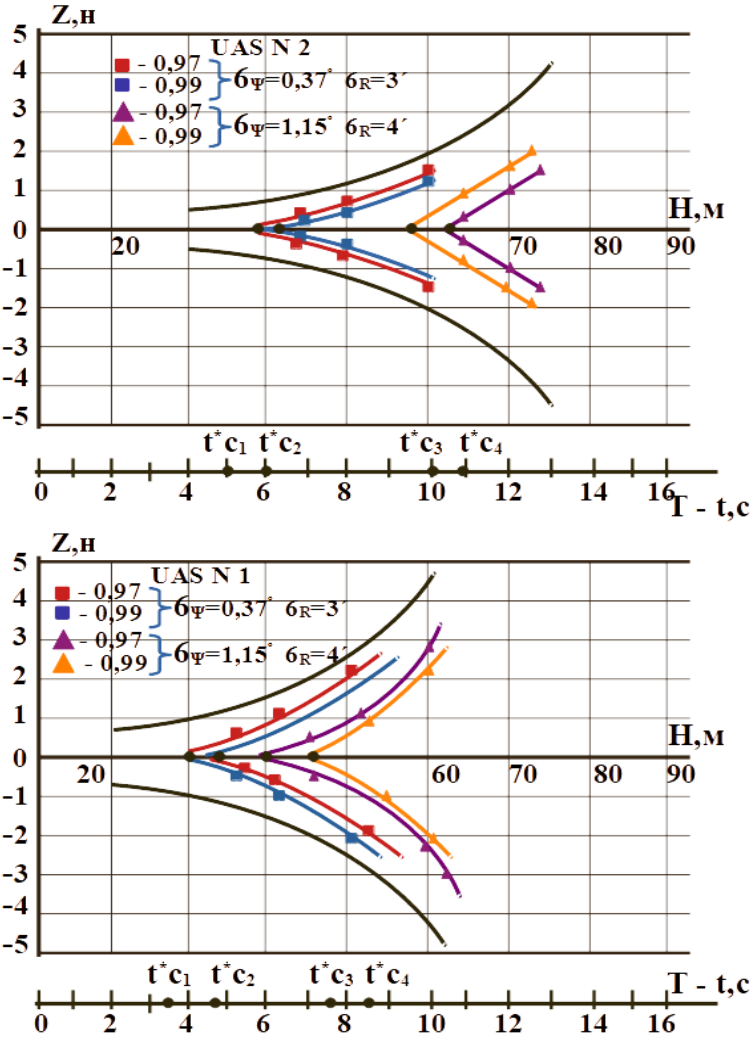


Fig. 3.7. Changes in the current and reflexive resources of UAS action depending on the parameters of the controlling and controlled subsystems and the moment of time (T= $t_k - t_0$)

Ha Fig. 3.8. similarly shows the impact on the UAS service life utilization factor of the parameters of the information management and controlled subsystems. It is easy to see that this coefficient is quite sensitive to the characteristics of both subsystems.

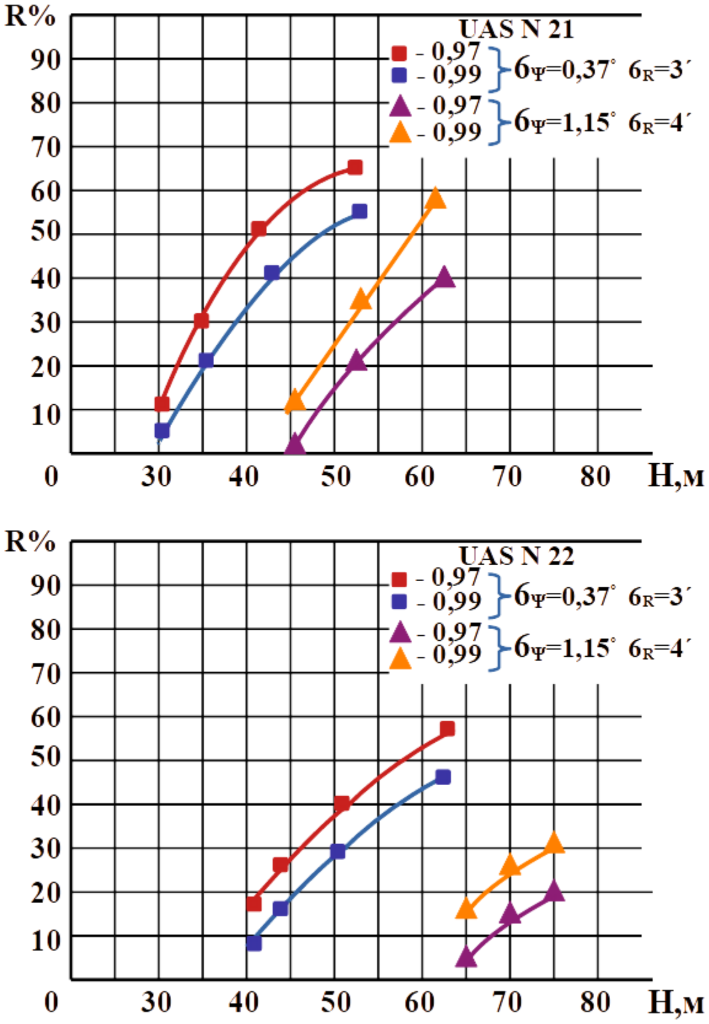


Fig. 3.8. Influence of the parameters of the controlling and controlled subsystems on the UAS service life utilization factor

Let's characterize the degree of achievement of the UAS goal with the following concept.

Definition 2.8. The minimum of the control system of a dynamic object is the distance in the space of phase events between the boundary phase event and the set of final phase events $\boldsymbol{\omega(t)}$.

$$d[(x,t_c^*),\omega(t)] = \min\{||(x,t_c^*) - z|| \in \omega(t_k)\}. \qquad (3.103)$$

The introduced concept of minimum is applicable to a wide class of technical control systems and can serve as a quality indicator that determines the functional effect.

To evaluate the functional effect, it is necessary to be able to build and evaluate a range of situations that characterizes the functionality of a complex system. For an air navigation service system, it is necessary to consider air situation situations for this purpose.

3.6. Air situation situations that determine the quality of operation and efficiency of UAS

Situations in the air navigation system (ANS) are formed as a result of direct influences on its subsystems and their operating conditions. Based on the structure and connections of the ANS, these influences can be determined by individual subsystems, which are characterized by: internal properties of the crew-aircraft system related to the functional efficiency of the crew and the functional efficiency of the LA; efficiency of the air traffic system, in particular, the efficiency of the ATC system circuit and the efficiency of radio navigation systems; the level of influence of non-system factors (external conditions); parameters of movement and position of the LA in space, as well as a number of restrictions.

During operation, there are certain deviations from the optimal values of the system parameters, which leads to a range of situations. Moreover, the complexity of situations is determined by the sequence of events. The previous event is considered as a cause in relation to the subsequent event caused by it. In the process of development of a negative phenomenon, in general, there may be several causes that consistently complicate the situation and eventually lead to an aviation accident.

The trajectories of aircraft movement are uniquely defined at some point in time t by three position coordinates and three velocity components:

$$\bar{X} = (x_1, x_2, x_3, \dot{x}_1, \dot{x}_2, \dot{x}_3\}, \left\{\dot{x}_i = \frac{dx_i}{dt}, i = \overline{\Delta, 3}\right\}. \quad (3.104)$$

Let's select a pair of aircraft from the flow of aircraft, the position of each of which will be characterized by the longitudinal coordinate $\boldsymbol{x = x_1}$, height $\boldsymbol{H = x_2}$ and lateral component or deviation $\boldsymbol{y = x_3}$. Let us assume that at some point in time t there are true values of the observation coordinates $\boldsymbol{(x_1, y_1, H_1)}$ of the position of the first aircraft and $\boldsymbol{(x_2, y_2, H_2)}$ – of the second aircraft. In this case, we assume that there is a convergence of aircraft along the $\boldsymbol{OX}$: $\boldsymbol{\frac{d|x_2 - x_1|}{dt} < 0}$, i.e., the distance between the aircraft along the $\boldsymbol{OX}$ axis decreases.

It is in this case that it is necessary to analyze situations, since with a decrease in the value $|x_2 - x_1|$, aircraft can threaten each other with a collision. Therefore, in order to assess the degree of danger of situations that arise when aircraft approach at a particular coordinate, it is necessary to introduce a measure that would allow characterizing these situations. As such a measure, we will introduce a metric in the three-dimensional Cartesian coordinate space that describes the distance of the aircraft (Fig. 3.9).

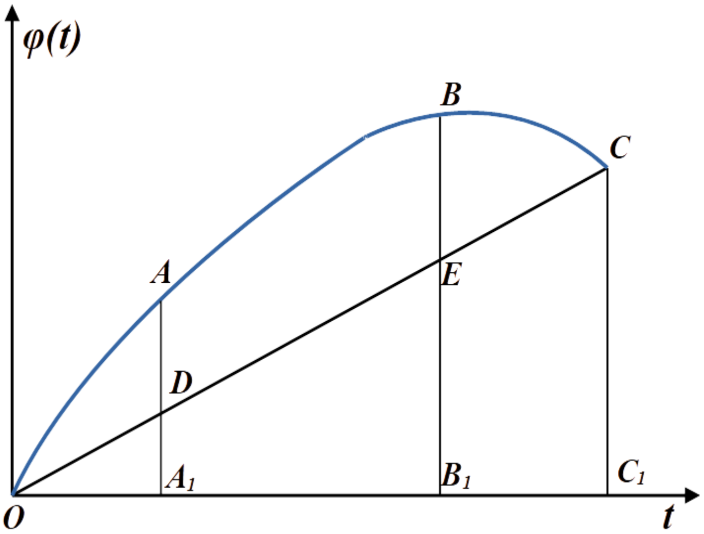


Fig. 3.9. Toward a justification of the UAV air situation metric

After entering the situation metric, a spectrum of situations is built (Fig. 3.10).

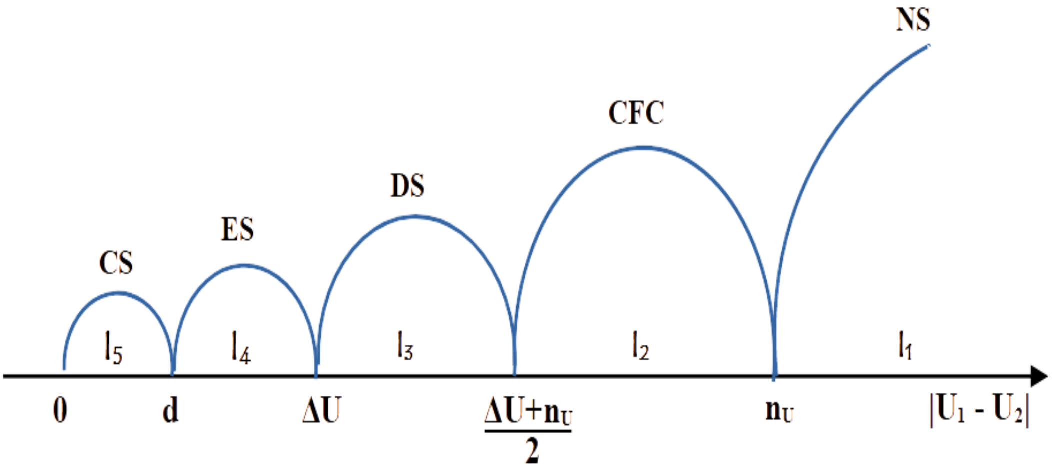


Fig.3.10. Development of situations along one coordinate: NS- normal situation (НС - нормальна ситуація), CFC - complicated flight conditions (УУП - ускладнення умов польоту), DS - difficult situation (СС - складна ситуація),

ES - emergency situation (АС - аварійна ситуація), CS - catastrophic situation (КС – катастрофічна ситуація).

The principle of their construction is as follows. Consider the range of situations for two airplanes (Figure 3.11):

a) Two airplanes are flying in neighboring corridors. One is searching, the other maintains a given flight path along the x-axis. Situations are generated for the coordinates $\boldsymbol{x_2 - x_1, y_2, H_2}$. We have three situations $(\boldsymbol{S_{x_{12}}, S_y, S_H})$. The global situation is described by the metric (3.104).

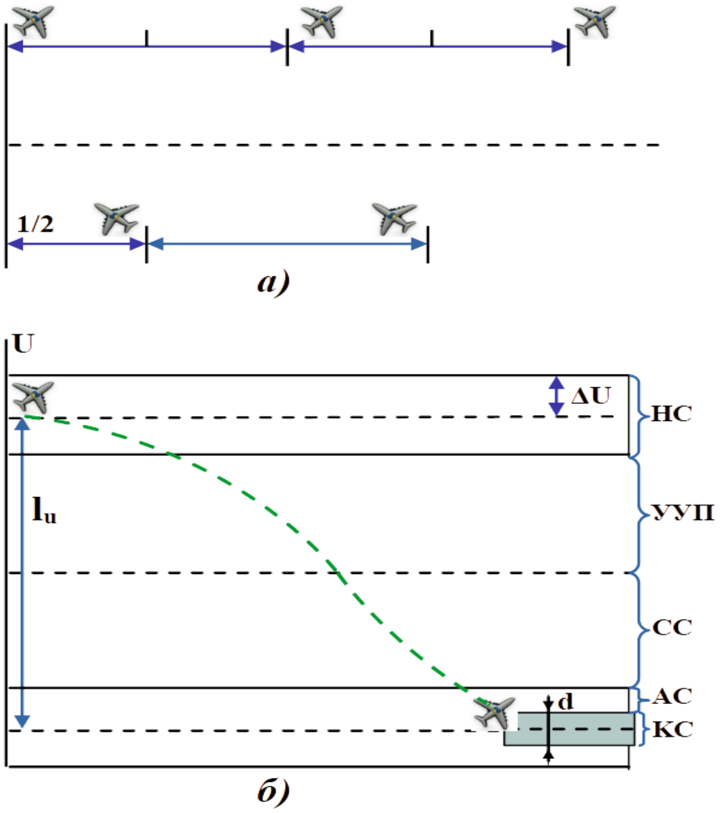


Fig 3.11.The global situation is described by the metric

b) Two airplanes are flying in neighboring corridors and both are searching. The situations are worked out for the coordinates $\boldsymbol{x_2 - x_1, y_2 - y_1, H_2 - H_1}$. In this case, the three situations are as follows: $(\boldsymbol{S_{x_{12}}, S_{y_{12}}, S_{H_{12}}})$ and the global situation is described by the metric (3.104).

c) Two airplanes are flying in the same air corridor along the $\boldsymbol{X}$-axis. The situations are developed for the difference $\boldsymbol{x_2 - x_1}$ and have the form $(\boldsymbol{S_{x_{12}}}, 0,0)$.

Let's consider a range of situations for two oncoming streams. The danger of mutual collision exists for pairs of aircraft $(\boldsymbol{L_i}, Д_i), \boldsymbol{i} = \overline{\boldsymbol{1}, \boldsymbol{n}}$, as well as for pairs of aircraft $(\boldsymbol{L_i}, (\boldsymbol{L_{i+1}}); (Д_i, Д_{i+1}), \boldsymbol{i} = \overline{\boldsymbol{1}, \boldsymbol{n} - \boldsymbol{1}}$:

a) For the pairs $(\boldsymbol{L_i}, Д_i), \boldsymbol{i} = \overline{\boldsymbol{1}, \boldsymbol{n}}$ we have a spectrum of situations $\boldsymbol{S_x}(\boldsymbol{L_i}, Д_i), \boldsymbol{S_y}(\boldsymbol{L_i}, Д_i), \boldsymbol{S_H}(\boldsymbol{L_i}, Д_i), \boldsymbol{i} = \overline{\boldsymbol{1}, \boldsymbol{n}}$. Here, the situation $\boldsymbol{S_x}(\boldsymbol{L_i}, Д_i)$ is determined by the difference of the observed coordinates $\boldsymbol{x}(\boldsymbol{L_i}) - \boldsymbol{x}(Д_i)$. As for the situations $\boldsymbol{S_y}$ and $\boldsymbol{S_H}$, there are two possibilities for them:

– develop situations based on the differences $\boldsymbol{y}(\boldsymbol{L_i}) - \boldsymbol{y}(Д_i)$ or, respectively, on the differences $\boldsymbol{H}(\boldsymbol{L_i}) - \boldsymbol{H}(Д_i)$;

– to develop situations $\boldsymbol{S_y}(\boldsymbol{L_i}), \boldsymbol{S_y}(Д_i)$ and $\boldsymbol{S_H}(\boldsymbol{L_i}), \boldsymbol{S_H}(Д_i)$ for each aircraft separately, respectively. In this case, we alternately assume that one of the aircraft $(\boldsymbol{L_i}, Д_i)$ is at risk, and the other is flying along a given trajectory. This approach to situations corresponds to n-a for two aircraft.

b) For pairs $(\boldsymbol{L_i}, \boldsymbol{L_{i+1}})$ we have a spectrum of situations $\{\boldsymbol{S_x}(\boldsymbol{L_i}, \boldsymbol{L_{i+1}}),\ \boldsymbol{i} = \overline{\boldsymbol{1}, \boldsymbol{n} - \boldsymbol{1}}\}$. Here, $\boldsymbol{S_x} \in \{\boldsymbol{S_1}, \dots, \boldsymbol{S_8}\}, \boldsymbol{S_1}$ is the, $\boldsymbol{S_2}$ – the UUP, etc., and $\boldsymbol{S_8}$ is the CS at the $\boldsymbol{X}$. The situations here are resolved by the difference of the observed coordinates $\boldsymbol{x}(\boldsymbol{L_i}) - \boldsymbol{x}(\boldsymbol{L_{i+1}})$.

For the pairs $(Д_i, Д_{i+1})$, we also have a spectrum of situations $\{\boldsymbol{S_x}(Д_i, Д_{i+1}),\ \boldsymbol{i} = \overline{\boldsymbol{1}, \boldsymbol{n} - \boldsymbol{1}}\}$, which are resolved by the difference $x(Д_i) - \boldsymbol{x}(Д_{i+1})$.

Thus, the observed flows are described by the following number of situations:

$$(n-1) + (n-1) + n - 2nK_n = (3n-2) = 2nK_n.$$

Here

$(\boldsymbol{n} - \boldsymbol{1})$ – the number of situations along the $\boldsymbol{x}$ -coordinate for aircraft of the same stream;

$\boldsymbol{n}$ – the number of situations along the $\boldsymbol{x}$ -coordinate for pairs of aircraft of both streams flying towards each other;

$\boldsymbol{2nK_n}$ – the number of the same situations in the $\boldsymbol{y}$ and $\boldsymbol{H}$ coordinate. $\boldsymbol{K_n} = \boldsymbol{1}$, if the situations $\boldsymbol{S_y}(\boldsymbol{L_i}, Д_i), \boldsymbol{S_H}(\boldsymbol{L_i}, Д_i)$ are worked out by coordinate differences;

$\boldsymbol{K_n} = \boldsymbol{0}$, if situations $\boldsymbol{S_y}(\boldsymbol{L_i}, Д_i)$ are split into two situations $\boldsymbol{S_y}(\boldsymbol{L_i}), \boldsymbol{S_y}(Д_i)$, and situations $\boldsymbol{S_H}(\boldsymbol{L_i}, Д_i)$ are also split into two situations $\boldsymbol{S_H}(\boldsymbol{L_i}), \boldsymbol{S_H}(Д_i)$, and the processing is carried out as described for the second case.

The considered spectrum of situations fully characterizes the quality of UAS functioning in ANS and determines their effectiveness. To assess this efficiency, it is necessary to develop an appropriate generalized criterion.

3.7. Construction and justification of a generalized indicator of UAV efficiency

In accordance with the formulations of the performance measurement tasks (2.6) and (2.7) given in clause (2.2), it is advisable to use appropriate measures, taking into account the situational state (Fig. 3.12).

Since the system is affected at different times by various random factors and operating conditions can change randomly over time, it is natural to use probabilistic metrics. Such metrics have a structure:

$$\mu(X,Y) = \sup_{f \in F} |Mf(x) - Mf(y)| \qquad (3.105)$$

and differ from each other in the kind of set ***F*** from which **SUP** is taken. Their properties are given in mathematics reference books [41].

Using the structure and its well-known mathematical properties [41], we will present the efficiency criterion also in the form of a difference. We will use the following initial data.

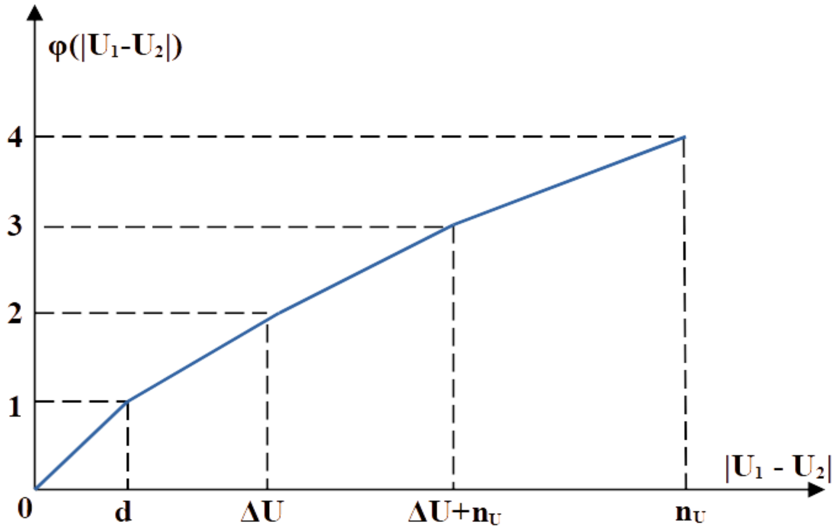


Fig. 3.12. A piecewise linear function aligned with the spectrum of situations

The structure of the airspace must be such that the specified values $\boldsymbol{P}(\boldsymbol{S_i})$ of the probability of occurrence of situations $\boldsymbol{S_i}, \boldsymbol{i} = \overline{\mathbf{1,5}}$are maintained. Thus, $\boldsymbol{P}(\boldsymbol{S_i})$ is the a priori probability of the situation. These probabilities form a complete group of probabilities (i.e., the appropriate normalization has been performed):

$$\sum_{i=1}^{5} P(S_i) = 1.$$

Let us denote by $\boldsymbol{C_1}$ the value of the air navigation fee rate for flying a section of the route in the normal situation $\boldsymbol{S_i}$, and by $\boldsymbol{C_2}, \dots, \boldsymbol{C_5} -$ losses due to the corresponding situation $\boldsymbol{S_2}, \dots, \boldsymbol{S_5}$. The value of $\boldsymbol{C_1}$ also depends on the correct classification of the situation $\boldsymbol{S_i}$.

Нехай, $\boldsymbol{EB'} -$ be the cost of resources associated with the use of ANO. This includes capital investments and operating costs. The value of the air navigation charge rate $\boldsymbol{C_1}$ depends on the duration of the service provided, the weight of the aircraft, and the basic tariff $\boldsymbol{C_0}$, which in turn depends on the amount of ANS costs and flight intensity. The amount of air navigation charges in EURO CONTROL countries is calculated by the formula:

$$C_1 = C_0 \cdot \frac{S}{100} \cdot \sqrt{\frac{M}{50}}, \qquad (3.106)$$

where

$\boldsymbol{C_0} -$ basic tariff;

$\boldsymbol{S} -$ he length of the section in kilometers where the ANO is presented;

$\boldsymbol{M} -$mass of the aircraft in tons.

The value of $\boldsymbol{C_0}$ s different in different countries. Then the effectiveness of the ANO system for a mixed flow of manned and unmanned aircraft can be estimated by the formula:

$$\epsilon = C_1 \cdot P(S_1) \cdot N - [N \sum_{i=1}^{5} C_1 \cdot P(S_1) + EB'] \ , \qquad (3.107)$$

If it is difficult to translate a catastrophic situation into a value expression, an expression should be used:

$$\epsilon = C_1 \cdot P(S_1) \cdot N - [N \sum_{i=2}^{4} C_i \cdot P(S_i) + EB' \ ] \ , \qquad (3.108)$$

$$P(S_5) \leq P_{\text{ДОД}}.$$

As can be seen from expression (3.108), the catastrophic situation is transferred to the category of limitation. According to the ICAO recommendations, the risk of collision that causes a catastrophe in the air traffic system is limited to $\boldsymbol{P}_{\text{ДОД}} = \mathbf{0.2} \cdot \mathbf{10^{-7}}$ for each of the three echeloning standards. The accepted level of safety in relation to the total risk associated with all causes is 6.3 aircraft accidents per 10 million hours of aircraft flight [21].

UAS types should be chosen in such a way as to maximize expressions (3.107) or (3.108).

Let there be a situation $\boldsymbol{S_i}$. As a result of using ANO tools in the process of classifying situations, situation $\boldsymbol{S_{ij}}$ an be accepted. This happens with a conditional probability $\boldsymbol{\beta_{ij}}$. A penalty is imposed for a recognition error. When $\boldsymbol{i = 1}$, in the case of $\boldsymbol{j = 1}$, we get a profit $\boldsymbol{C_1}$ we get a profit $\boldsymbol{N}$ aircraft, and when $\boldsymbol{j \neq 1}$, the profit will decrease and will be $\boldsymbol{C_1} - \Delta_{\mathbf{1}}\boldsymbol{j}$. When $\boldsymbol{i \neq 1}$, in the case of $\boldsymbol{i = j}$, we have losses from one aircraft $\boldsymbol{C_1}$, and when $\boldsymbol{i \neq j}$, the losses increase and amount to $\boldsymbol{C_1} + \Delta_{\boldsymbol{ij}}$. Here $\{\Delta_{\boldsymbol{ij}}, \mathbf{1} \leq \boldsymbol{i} \neq \boldsymbol{j} \leq \mathbf{5}\}$ – an additional penalty for misclassification of situations. Then the functional (2.69) is refined and takes the following form:

$$\epsilon = \left(C_1 \cdot \beta_{11} \cdot P(S_1) + \textstyle\sum_{j \neq 1}\left(C - \Delta_{1j}\right) \cdot \beta_{1j} \cdot P(S_1)\right) \cdot N - [N \textstyle\sum_{i=2}^{5} P(S_1) \cdot$$

$$\cdot \left(C_i \cdot \beta_{ij} + \textstyle\sum_{\substack{1 \leq j \leq 5 \\ j \neq i}}\left(C_i \cdot \Delta_{ij}\right) \cdot \beta_{ij} + EB'\right)] =$$

$$= P(S_1) \cdot N \cdot \left(C_1 \textstyle\sum_{j=5}^{1} \beta_{1j} - \textstyle\sum_{j \neq 1}^{5} \Delta_{1j}\, \beta_{1j}\right) - [N \cdot \textstyle\sum_{i=1}^{5} P(S_i) \cdot (C_i \cdot \textstyle\sum_{j=1}^{5} \beta_{ij} +$$

$$+ \textstyle\sum_{j=1}^{5} \Delta_{ij}\beta_{ij}) + EB'] .$$

Since

$$\textstyle\sum_{j=1}^{5} \beta_{ij}) = 1,$$

Then we have:

$$\epsilon = C_1 \cdot P(S_i) \cdot N - \left[N \cdot \textstyle\sum_{i=1}^{5} C_1 \cdot P(S_i) + N \textstyle\sum_{i=1}^{5} \textstyle\sum_{\substack{j=1 \\ j \neq i}}^{5} \Delta_{ij} \cdot \beta_{ij} \cdot P(S_i) + EB' \right].$$

Amount

$$R = \sum_{i=1}^{5} \sum_{\substack{j=1 \\ j \neq i}}^{5} \Delta_{ij} \cdot \beta_{ij} \cdot P(S_i) = \sum_{\substack{1 \leq i,j \leq 5 \\ j \neq i}}^{5} \Delta_{ij} \cdot \beta_{ij} \cdot P(S_i)$$

There is an average risk function that is used to select the thresholds of the sequential rule. Then:

$$€= N\left[C_1 \cdot P(S_1) - \sum_{i=2}^{5} C_1 \cdot P(S_1)\right] - [NR + EB']. \quad (3.109)$$

Let us consider the features of the proposed criterion.

1. *The developed efficiency criterion has an understandable physical meaning* – he excess of the mathematical expectation of the ANO cost estimate over the cost estimate of the total resource costs for the period of time under consideration.

Indeed, the path per unit of time along a given section of the route is flown by $\boldsymbol{N}$ aircraft, of which $\boldsymbol{N_i}$ are in a state of repair:

$$S_1, i = \overline{1{,}5}; \sum_{i=1}^{5} N_i = N.$$

Then the economic effect per unit of time is the difference between the cost estimate of the result of the ANO and the cost estimate of the costs:

$$€ = C_1 \cdot N_1 - \left(\sum_{i=2}^{5} C_1 \cdot N_1 + EB'\right). \quad (3.110)$$

However, according to the content of the probability $\boldsymbol{P(S_i)}$, the mathematical expectation of the ratio $\boldsymbol{N_i/N}$ is equal: $\boldsymbol{M\{N_i/N\} = P(S_i)}$, or $\boldsymbol{M\{N_i\} = P(S_i)}$. Then from (3.110) we have that the average effect is equal to:

$$M\{€\} = C_1 \cdot M\{N_1\} - \left(\sum_{i=2}^{5} C_1 \cdot M\{N_i\} + EB'\right) = C_1 \cdot P(S_1) \cdot N -$$

$$-\left[N \cdot \sum_{i=2}^{5} C_i \cdot P(S_i)\right] + EB'], \quad (3.111)$$

which coincides with (3.107).

2. In expressions (3.107), (3.108), and (3.109), *all parameters* $\boldsymbol{C_i, P(S_i), N, EB'}$ *enter linearly*. This leads to convexity for each argument and even for their set:{ $\boldsymbol{P(S_i), i = \overline{1,5}}$, { $\boldsymbol{C_i, i = \overline{1,5}}$ }. Note that such convexity may be absent for other criterion structures.

Convexity gives uniqueness to the solution of optimization procedures. For convex optimization, robust, efficient quantitative methods have been developed to deal with the "rawness", i.e., poor conditionality of the optimization problem. In parameter estimation based on the optimization of convex functionalities, it is possible to prove the validity of the estimates, i.e., the convergence in probability or near convergence of the estimate to the true value of the parameter.

Regarding the functional (3.107), linearity in $\boldsymbol{C_i}$ leads to the fact that, since $\boldsymbol{C_i}$ is linearly expressed in terms of individual classification errors $\boldsymbol{\beta}_{ij}$, the criterion is linearly dependent on $\boldsymbol{\beta}_{ij}$, i.e., there is a convex dependence of the criterion E on individual errors $\boldsymbol{\beta}_{ij}$. This greatly simplifies the optimization of the efficiency based on these individual errors.

3. *The structure of the E functional is such that it is expressed through the risk functional:*

$$R = \sum_{\substack{1\le i,j\le 5 \\ j\ne i}}^{5} \Delta_{ij} \cdot \beta_{ij} \cdot P(S_i). \quad (3.112)$$

Here, $\Delta_{ij}, \boldsymbol{i \neq j}$ – n additional penalty for misclassifying a situation, for example, $\boldsymbol{S_j}$ instead of $\boldsymbol{S_i}$; $\boldsymbol{\beta}_{ij}, \boldsymbol{i \neq j}$ – the probability of making a decision about situation $\boldsymbol{S_j}$ when in fact the situation $\boldsymbol{S_i}$ occurs. The linearity of the entry of the risk functional (3.112) into the efficiency functional allows the application of multi-alternative sequential analysis methods. Thus, the structure of the criterion (3.107) and its modifications (3.108), (3.109) is consistent with the risk function. This makes it convenient to use criterion (3.107) in practice when solving problems of analysis and synthesis of ANO and the air navigation system as a whole.

At the same time, an attempt to apply the second variant of the criterion structure in the form of a relative value, for example:

$$Q = \frac{C_i P(S_1)}{[N \cdot \sum C_i P(S_1) + EB']} \qquad (3.113)$$

has a number of drawbacks. This includes a less clear physical meaning. The functional (3.113) is not expressed in terms of a risk function. Optimization of (3.113) requires fundamentally different procedures for distinguishing between multiple alternative hypotheses that are not based on the risk function. In this case, it is necessary to develop new procedures that are the subject of relevant research.

4. *The application of the difference criterion allows the following.*

a) First, this method is based on a direct comparison of options without any recalculations or adjustments. In this case, the value of the effect reflects both resource savings in one of the options compared to the other and the growth of results.

b) Secondly, the conditionality that was allowed in the calculation of the effect by the criteria of relative efficiency is eliminated. Using this criterion, the number of options under consideration should include all possible options, including those that provide the same result, but with the mandatory consideration of the specifics of each option when determining the corresponding costs. In this case, a direct recalculation of resources in proportion to the increase in results is not used.

c) Third, it becomes possible to compare options not only with different inputs, but also with different outputs, i.e. to reflect the difference between options in terms of the degree of satisfaction of needs.

d) Fourth, it is possible to explicitly assess the response of the system to changes in the quality of individual subsystems.

Unlike relative criteria, it does not require special restrictions on its application, and therefore is valid for all cases of implementation of ANO improvement measures, i.e. with different volumes and quality of information support, social, environmental and other factors, implementation timeframes etc.

Conclusions of chapter 3

1. A method for evaluating the effectiveness of UAS in an air navigation system has been developed. Efficiency is represented by a category of action in the operation of the system at a certain time interval, which reflects the correspondence of the result obtained to the resources invested.
2. The concept of UAS efficiency evaluation is based on the consideration of social, economic and functional types of effect.
3. Two approaches to evaluating the effectiveness of UAS are proposed and developed: with implicit and explicit systemic links of the means with a higher order system.
4. Evaluation of efficiency in the case of implicit links of UAS means is based on the formation of the resulting quality indicator and the reduction of a multicriteria problem to a scalar one. An algorithm for selecting the priority option of the means is developed.

5. The subproblems that arise when formulating goals, criteria and performance evaluation with explicit systemic links are systematized.
6. It is proved that the evaluation of the effectiveness of the UAS system is related to the problem of performance management, which depends, in turn, on the controllability of situations.
7. The principles of determining the functional effect in the management of dynamic objects are formulated.
8. The basics of the theory of situational analysis of the air situation are developed, including:

- principles of situation formation in ANS;
- construction of a metric as a measure of situations;
- selection of a function that characterizes the danger of flight situations by the corresponding coordinates;
- construction of a priori probability densities of the measured parameter;
- construction of a priori probabilities of situations;
- construction of conditional probability densities by zones;
- building a spectrum of situations.

9. A generalized criterion for UAS efficiency is developed and substantiated. For the first time, it is possible to assess the real efficiency of UAS in the air navigation system of ANO.

CHAPTER 4. ALGORITHMIZATION AND MODELING OF TASKS OF INFORMATION SUPPORT FOR THE EFFICIENCY OF FREIGHT BPL

Many problems in decision theory are reduced to choosing the best options from a set of options that are allowed for comparison. The complexity of solving such problems in relation to the tasks of assessing performance under risk is primarily due to the large dimensionality, significant nonlinearity of variables, and the complex nature of the constraints on phase coordinates. In this regard, the practical results of UAV flight research can be obtained mainly by means of quantitative methods with the use of appropriate efficient machine learning algorithms.

This chapter proposes methods and algorithms for solving the problems formulated in the previous chapters of this thesis.

4.1. Algorithm for calculating system constraints

Most methods that allow solving multi-extreme problems are associated to some extent with random search [45, 51, 59, 78, 103, 106, 113, 151, 158]. With increased requirements for the extremum estimation algorithm, it is advisable to use random search methods in combination with other machine learning-based methods.

The first task to be solved when developing an algorithm is the formation of a basic ensemble of control realizations randomly distributed in a given region of the admissible set. This problem belongs to the class of random variable modeling problems and is considered in the relevant literature, and, depending on the conditions of the problem, this issue can be solved in different ways:

a) a random point is uniformly distributed in a $\boldsymbol{n}$-dimensional parallelepiped. Then:

$$F(x_1, x_2, \dots, x_n) = F(x_1) \cdot F(x_2) \cdot, \dots, F(x_n), \tag{4.1}$$

where $\boldsymbol{F_i(x_1)} -$ distribution function of the coordinate $\boldsymbol{X_1}$.

In this case, each coordinate can be modeled independently and as a result, we get a simple formula for calculating coordinates:

$$x_1 = a_i + \xi_i(b_i - a_i),\ i = 1,n\,, \qquad (4.2)$$

where

$\boldsymbol{a_i}$ and $\boldsymbol{b_i}$ are the coordinates of the vertices of the $\boldsymbol{n}$-dimensional parallelepiped;

$\boldsymbol{\xi_i}$ – independent random numbers;

б) a random point obeys an $\boldsymbol{n}$-dimensional normal law with mathematical expectation:

$$M(x_1) = a_i \qquad (4.3)$$

and other issues:

$$M\big[(x_1 - a_i)\big(x_j - a_j\big)\big] = b_{ij}. \qquad (4.4)$$

In this case, we also get a simple formula for calculating the coordinates:

$$x = A\xi + a, \qquad (4.5)$$

where

$\boldsymbol{\xi}$ – independent random variables in the interval **(0, 1)** that follow the normal law;

$\boldsymbol{A}$ – transformation matrix, which is determined from the condition:

$$AA^T = B, \qquad (4.6)$$

where $\boldsymbol{B} = \left|\boldsymbol{b_{ij}}\right|, \boldsymbol{T}$ – transportation index.

The calculation of system constraints imposed by dynamic objects includes the task of determining a random control implementation that satisfies the constraints on the phase coordinates. Finding the optimal control is reduced to determining the coordinates of a random point in an $\boldsymbol{n}$- dimensional parallelepiped.

The second problem that needs to be solved when developing an algorithm is the choice of a condition for stopping the computational process due to the achievement of a given accuracy of solving the problem or due to the end of available computing resources. The stopping condition can be described by introducing an appropriate sequence of functions $\boldsymbol{\Phi_k}$:

$$f^k = \Phi_k(\omega_k),\quad k = 1,2,\ldots \qquad (4.7)$$

such that if for some $\boldsymbol{\omega_k}$ it is true that $\boldsymbol{f^k = 0}$, then $\boldsymbol{f^{k+\gamma} = 0}$, $\boldsymbol{\gamma = 1,2}, \ldots$, regardless of the values of $\boldsymbol{\omega_k}$, i.e. $\big(\boldsymbol{x^{k+1}}, \boldsymbol{Z^{k+1}}\big), \ldots,\ (\boldsymbol{x^{k+\gamma}}, \boldsymbol{Z^{k+\gamma}})$. Here:

$$Z^i = \Phi(x_i) + \varepsilon^i,\ \ 1 \le i \le k, \qquad (4.8)$$

where $\boldsymbol{\varepsilon}^{\boldsymbol{i}}$ is the error of the $\boldsymbol{i}$- th trial.

In this case, the final estimate of the extremum is considered to be the estimate [120] $\boldsymbol{e}^{\boldsymbol{T}}$, which corresponds to the stopping step $\boldsymbol{T}$. Then the $\boldsymbol{\varepsilon} -$ optimal solution is obtained:

$$\Phi[x_\varepsilon] \leq \inf \Phi[x] + \varepsilon, \tag{4.9}$$

where $\boldsymbol{\varepsilon} > \boldsymbol{0}$.

Thus, it is practically necessary to set an acceptable degree of accuracy in terms of the deviation of the value of the functional obtained as a result of solving the problem from the minimum possible value and the number of steps to obtain it.

Let's take the best of the base points as the required solution of $\boldsymbol{\Phi}[\boldsymbol{x}_{\boldsymbol{\varepsilon}}]$ at the moment when, within a given number of iterations, the radius of the set of base points does not exceed a predetermined small value:

$$rad\, H \leq \varepsilon,\ x_\varepsilon \in H\,. \tag{4.10}$$

Now we can fully describe the algorithm for finding the optimal solution to the extreme problem 2.2.

$$Q = \int\limits_{\Omega(\tau)} f(\vec{Z})\ dF(\vec{Z}, \tau). \tag{2.2}$$

The task is to find a vector $\boldsymbol{u}^*$ that reports the largest (smallest) value of the functional $\boldsymbol{\Phi}[\boldsymbol{u}, \boldsymbol{x}, \boldsymbol{t}]$:

$$\Phi[u^*] = \sup_{u \in U} \Phi\ [u, x, t]. \tag{4.11}$$

At the first step, a zero approximation is chosen for the control vector u in such a way that all the constraints imposed on this dynamic system are satisfied. The control function approximation system is chosen and the number of approximation nodes is determined for a given flight interval $\boldsymbol{J}_{\boldsymbol{\tau}} = [\boldsymbol{t}_{\boldsymbol{0}}, \boldsymbol{t}_{\boldsymbol{k}}]$ (the number and coordinates of the nodes can be chosen from the condition of optimal compensation of the approximation error at the ends of the intervals $[\boldsymbol{t}_{\boldsymbol{0}}, \boldsymbol{t}_{\boldsymbol{k}}]$ and in the inter-node subintervals for the expected classes of functions).

Let $\boldsymbol{H}(\boldsymbol{x}, \boldsymbol{t}) -$ be the upper bound of the admissible set $\boldsymbol{U}$, abe the lower bound of this set. Then the values of the control function at the approximation nodes to obtain an ensemble of random control realizations of a dynamic system will be determined by the following formula:

$$u_{ij} = G(x_i, t_i) + \xi_{ij}[H(x_i, t_i) - G(x_i, t_i)], \qquad (4.12)$$

where

$\boldsymbol{i = \overline{1, L}}$ – index of the approximation node;

$\boldsymbol{j = 1, k - 1}$ – index of the realization from the ensemble of basic controls;

$\boldsymbol{\xi_{ij}}$ – random numbers $\boldsymbol{\xi_{ij} \in I = [0, 1]}$.

For each realization from the ensemble of basic controls $\boldsymbol{u_i \in \{u\}, i = \overline{1, k}}$, the value of the functional $\boldsymbol{\Phi_i \in \{\Phi\}, i = \overline{1, k}}$ is calculated. At the same time, the constraints imposed on the phase variables $(\boldsymbol{x \in X})$, as well as implicit type constraints, are checked.

If implicit constraints are violated for some realization $\boldsymbol{u_j}$, then a correction of this control is introduced. The new control $\boldsymbol{u_j^*}$ is obtained as follows.

1. First of all, the reflection is performed [151], which results in the vertex of the polyhedron:

$$\vec{u}^* = (1 + \eta_1)A - \eta_1 \vec{u}_r\,, \qquad (4.13)$$

where

$\boldsymbol{A}$ – the coordinate matrix of the center of the simplex excluding the worst vertex;

$\boldsymbol{\vec{u}_r}$ – ontrol, which corresponds to $\boldsymbol{\Phi_r = \max\{\Phi\}}$;

$\boldsymbol{\eta_1}$ – reflection coefficient $(\boldsymbol{\eta = 1})$.

If, as a result of reflection, $\boldsymbol{\Phi[u_1] < \Phi[u^*] < \Phi < \Phi[u_r]}$, then $\boldsymbol{u_r}$ is changed to $\boldsymbol{u^*}$. The resulting new simplex is used as the initial one for the first stage.

If $\boldsymbol{\Phi[u^*] < \Phi[u_1]}$, the stretching takes place, transforming the vector $\boldsymbol{u^*}$ to $\boldsymbol{\tilde{u}^*}$ за using the ratio:

$$\tilde{u}^* = \eta_2 u^* + (1 - \eta_2)A, \qquad (4.14)$$

where $\boldsymbol{\eta_2}$ – the stretching factor $(\boldsymbol{\eta_2 = 2})$.

If $\boldsymbol{\Phi[u^*] > \Phi_i}$, $\forall_i \boldsymbol{\neq r}$, i.e. $\boldsymbol{u^*}$ corresponds to the point that provides the maximum of $\boldsymbol{\Phi}$, then a new vector u_r is determined, which is equal to the previous vector $\boldsymbol{u_r}$ or equal to the control $\boldsymbol{u^*}$, which provides a smaller value of the functional

$\boldsymbol{\Phi}$. Then, compression is performed, transforming the vector $\boldsymbol{u}$ into $\tilde{\boldsymbol{u}}^*$ according to the formula:

$$\tilde{u}^* = \eta_3 u + (1 - \eta_3)A, \qquad (4.15)$$

where $\boldsymbol{\eta_3}$ − compression ratio, $\mathbf{0} \leq \boldsymbol{\eta_3} \leq \mathbf{1},\ (\boldsymbol{\eta_3} = \mathbf{0,5})$.

The vector $\boldsymbol{u}$ is changed to $\tilde{\boldsymbol{u}}^*$ and the first stage is repeated, provided that the vertex of the compression does not lead to a worse result than $\mathbf{max}\,\{\boldsymbol{\Phi}[\boldsymbol{u}], \boldsymbol{\Phi}[\boldsymbol{u}^*]\}$, i.e., if $\boldsymbol{\Phi}[\tilde{\boldsymbol{u}}^*] > \boldsymbol{min}\{\boldsymbol{\Phi}[\boldsymbol{u}], \boldsymbol{\Phi}[\boldsymbol{u}^*]\}$. In the latter case, all vectors $\boldsymbol{u_i}$ are changed by $\frac{u_i + u_l}{2}$ i and returned to the first stage.

In this case, it corresponds to the $\boldsymbol{u_l}$:

$$\Phi[u_l] = min\{\Phi[u_i]\}. \qquad (4.16)$$

If an extreme value of the functional $\boldsymbol{\Phi}[\boldsymbol{u}^*]$ exists, then the algorithm ensures that the condition is met:

$$|\max\{\Phi[x_j]\} - \min\{\Phi[x_i]\}| \leq \varepsilon;\ \ i, j = \overline{1, k}, \qquad (4.17)$$

where $\boldsymbol{\varepsilon}$ − a small value that defines the accuracy of the solution. The counting process stops if the inequality (4.17) is true for several iterations.

Based on the proposed algorithm, a program for calculating system constraints, which are determined using the dynamic characteristics of the aircraft as a controlled object, was developed.

The implementation of the considered algorithm allows us to construct the domain $\boldsymbol{D_\tau}$, which is used below to predict the sequence of event outcomes in the control system of such dynamic objects as UAVs.

4.2. Method for evaluating the sequence of event outcomes in the control system of dynamic objects

The method for evaluating the aircraft control system as a dynamic object can be built on the basis of assessing the states of the control and controlled subsystems.

To determine the effectiveness of FPV modes of drones, automatic or autonomous support, for example, at the landing stage, it is first necessary to consider the emerging flight situations (Fig. 2.10, 2.11), which lead to the following estimates of the results.

In subsection 2.1, we considered the spaces of initial and final events and the vector of strategies $(\boldsymbol{R}_{\boldsymbol{\Omega}}, \boldsymbol{R}_{\boldsymbol{\omega}}, \boldsymbol{R}_{\boldsymbol{v}})$ in the process of system operation and the transition to visual flight by landmarks or cartography. Let us now distinguish three stages in the system's operation:

I - the beginning of work;

II - the period of the landing system (ILS) operation;

III – the end of LS operation (transition to visual flight by ground reference points).

For the first stage, we take as determinative the event of belonging of the true and estimated by the indicators of the control subsystem $\boldsymbol{G}_{\boldsymbol{1}}$ position of the aircraft to the area of permissible localization $\boldsymbol{A}_{\boldsymbol{1}}\colon \{\boldsymbol{Y}, \boldsymbol{Y}^{*}, \boldsymbol{t}_{\boldsymbol{0}}\} \in \boldsymbol{\Omega}$.

For the second stage, the main events are the ratio of the ILS connectivity area $(\boldsymbol{D}_{\boldsymbol{\tau}})$ and the possible ILS operation area $(\boldsymbol{D}_{\boldsymbol{Y}})$ (possible maneuvering area of the controlled object) according to the current state and the control subsystem indicators $\boldsymbol{A}_{\boldsymbol{2}}\colon \boldsymbol{D}_{\boldsymbol{\tau}} \cap \boldsymbol{D}_{\boldsymbol{Y}} \neq \emptyset$; $\boldsymbol{A}_{\boldsymbol{3}}\colon \boldsymbol{D}_{\boldsymbol{\tau}} \cap \boldsymbol{D}_{\boldsymbol{Y}^{*}} \neq \emptyset$; $\boldsymbol{D}_{\boldsymbol{Y}^{*}} = \{\boldsymbol{Y}^{*} / \forall \boldsymbol{Y} \in \boldsymbol{D}_{\boldsymbol{Y}}\}$.

The third period of ILS operation is characterized by the target terminal - the output of the ILS, so the event of terminal reachability $\boldsymbol{\omega}(\boldsymbol{t}_{\boldsymbol{k}})$ according to the ILS estimate, the true ratio) can be called a significant event:

$$A_4\colon D_\tau \cap \omega(t_k) \neq \emptyset; \quad A_5\colon D_\tau \cap \omega_{Y^*}(t_k) \neq \emptyset. \qquad (4.18)$$

In this case, a prerequisite is the fulfillment of the admissibility of the terminal value $\boldsymbol{\omega}(\boldsymbol{t}_{\boldsymbol{k}}) \subset \boldsymbol{D}_{\boldsymbol{Y}}$. Thus, during the operation of the landing system, the leading events that determine the decision-making strategy are the following set:

$$\begin{aligned}
&A_1\colon \{Y, Y^*, t_0\} \in \Omega, \quad \bar{A}_1\colon \{Y, Y^*, t_0\} \notin \Omega; \\
&A_2\colon D_\tau \cap D_Y \neq \emptyset, \quad \bar{A}_2\colon D_\tau \cap D_Y = \emptyset; \\
&A_3\colon D_\tau \cap D_{Y^*} \neq \emptyset, \quad \bar{A}_3\colon D_\tau \cap D_{Y^*} = \emptyset; \\
&A_4\colon D_\tau \cap \omega(t_k) \neq \emptyset, \quad \bar{A}_4\colon D_\tau \cap \omega(t_k) = \emptyset; \\
&A_5\colon D_\tau \cap \omega_{Y^*}(t_k) \neq \emptyset, \quad \bar{A}_5\colon D_\tau \cap \omega_{Y^*}(t_k) = \emptyset.
\end{aligned} \qquad (4.19)$$

For a landing system, the situations determined by the triggering events will differ when the ILS is operating in control mode and in monitoring mode. Thus, in the control mode, ILS errors such as "false alarm" and others can lead to the termination of the landing process, while in the control mode, this event is accepted only as additional information, i.e. information with a lower weighting function. When recording events from the specified set, it is possible to determine the following flight situations (in the control mode):

$$
\begin{array}{ll}
S_1\colon A_1 \wedge A_2 \wedge A_3 \wedge A_4 \wedge A_5; & S_{11}\colon \bar{A}_1 \wedge A_2 \wedge A_3 \wedge A_4 \wedge A_5; \\
S_2\colon A_1 \wedge A_2 \wedge A_3 \wedge A_4 \wedge \bar{A}_5; & S_{12}\colon \bar{A}_1 \wedge A_2 \wedge A_3 \wedge A_4 \wedge \bar{A}_5; \\
S_3\colon A_1 \wedge A_2 \wedge A_3 \wedge \bar{A}_4 \wedge A_5; & S_{13}\colon \bar{A}_1 \wedge A_2 \wedge A_3 \wedge \bar{A}_4 \wedge A_5; \\
S_4\colon A_1 \wedge A_2 \wedge A_3 \wedge \bar{A}_4 \wedge \bar{A}_5; & S_{14}\colon \bar{A}_1 \wedge A_2 \wedge A_3 \wedge \bar{A}_4 \wedge \bar{A}_5; \\
S_5\colon A_1 \wedge A_2 \wedge A_3; & S_{15}\colon \bar{A}_1 \wedge A_2 \wedge \bar{A}_3; \\
S_6\colon A_1 \wedge \bar{A}_2 \wedge A_3 \wedge A_4 \wedge \bar{A}_5; & S_{16}\colon \bar{A}_1 \wedge \bar{A}_2 \wedge A_3 \wedge A_4 \wedge A_5; \\
S_7\colon A_1 \wedge \bar{A}_2 \wedge A_3 \wedge A_4 \wedge \bar{A}_5; & S_{17}\colon \bar{A}_1 \wedge \bar{A}_2 \wedge A_3 \wedge A_4 \wedge \bar{A}_5 \\
S_8\colon A_1 \wedge \bar{A}_2 \wedge A_3 \wedge \bar{A}_4 \wedge A_5; & S_{18}\colon \bar{A}_1 \wedge \bar{A}_2 \wedge A_3 \wedge \bar{A}_4 \wedge A_5; \\
S_9\colon A_1 \wedge \bar{A}_2 \wedge A_3 \wedge \bar{A}_4 \wedge \bar{A}_5; & S_{19}\colon \bar{A}_1 \wedge \bar{A}_2 \wedge A_3 \wedge \bar{A}_4 \wedge \bar{A}_5; \\
S_{10}\colon A_1 \wedge \bar{A}_2 \wedge \bar{A}_3; & S_{20}\colon \bar{A}_1 \wedge \bar{A}_2 \wedge \bar{A}_3.
\end{array}
\qquad (4.20)
$$

The probability of occurrence of each of the possible flight situations is determined according to the structure and compatibility of the selected key events.

If we represent the probability for each assessment of the selected events $\boldsymbol{P}\left[\boldsymbol{\pi}(\boldsymbol{S}_i, \boldsymbol{S}_j)^*\right]$, $\boldsymbol{i} = \overline{\boldsymbol{1}, \boldsymbol{20}}; \boldsymbol{j} = \overline{\boldsymbol{1}, \boldsymbol{5}}$ as a component of the composite vector $\boldsymbol{P}\left(\vec{\boldsymbol{S}}^*\right), \boldsymbol{S} = \{\boldsymbol{S}_i\}$, $\boldsymbol{i} = \overline{\boldsymbol{1}, \boldsymbol{5}}$ see Section 3), then the result of the probability assessment for each component can be obtained as follows. The probability of occurrence of each situation $\boldsymbol{S}_i$ is a row matrix:

$$B = |P(S_i)| \qquad i = \overline{1{,}20}. \qquad (4.21)$$

The determinant matrix based on the selected estimates $\boldsymbol{S}_i^*(\boldsymbol{i} = \overline{\boldsymbol{1}, \boldsymbol{5}})$ of the emerging situations $\boldsymbol{S}_i$, $\boldsymbol{i} = \overline{\boldsymbol{1}, \boldsymbol{20}}$, is a block matrix by columns:

$$C = \left|P\left(\alpha_j, S_1^*\right) \vdots\vdots\, P\left(\alpha_j, S_5^*\right)\right| \quad j = \overline{1{,}20}. \qquad (4.22)$$

For the selected events, you can determine their reliability, and the matrix $\boldsymbol{C}$ takes the form:

$$C = \begin{matrix} P(\alpha_1, S_1^*) & 0 & 0 & 0 & 0 \\ 0 & 0 & P(\alpha_2, S_3^*) & 0 & P(\alpha_2, S_5^*) \\ 0 & 0 & 0 & P(\alpha_3, S_4^*) & P(\alpha_3, S_5^*) \\ 0 & P(\alpha_4, S_2^*) & 0 & 0 & P(\alpha_4, S_5^*) \\ 0 & P(\alpha_5, S_2^*) & 0 & 0 & P(\alpha_5, S_5^*) \\ P(\alpha_6, S_1^*) & 0 & 0 & 0 & 0 \\ 0 & P(\alpha_7, S_2^*) & 0 & 0 & P(\alpha_7, S_5^*) \\ 0 & 0 & 0 & P(\alpha_8, S_4^*) & P(\alpha_8, S_5^*) \\ 0 & P(\alpha_9, S_2^*) & 0 & 0 & P(\alpha_9, S_5^*) \\ 0 & P(\alpha_{10}, S_2^*) & 0 & 0 & P(\alpha_{10}, S_5^*) \\ P(\alpha_{11}, S_1^*) & 0 & 0 & 0 & 0 \\ 0 & 0 & P(\alpha_{12}, S_3^*) & 0 & P(\alpha_{12}, S_5^*) \\ 0 & 0 & 0 & P(\alpha_{13}, S_4^*) & P(\alpha_{13}, S_5^*) \\ 0 & P(\alpha_{14}, S_2^*) & 0 & 0 & P(\alpha_{14}, S_5^*) \\ 0 & P(\alpha_{15}, S_2^*) & 0 & 0 & P(\alpha_{15}, S_5^*) \\ P(\alpha_{16}, S_1^*) & 0 & 0 & 0 & 0 \\ 0 & 0 & P(\alpha_{17}, S_3^*) & 0 & P(\alpha_{17}, S_5^*) \\ 0 & 0 & 0 & P(\alpha_{18}, S_4^*) & P(\alpha_{18}, S_5^*) \\ 0 & P(\alpha_{19}, S_2^*) & 0 & 0 & P(\alpha_{19}, S_5^*) \\ 0 & P(\alpha_{20}, S_2^*) & 0 & 0 & P(\alpha_{20}, S_5^*) \end{matrix} \tag{4.23}$$

where $\boldsymbol{P(\alpha_j, S_i^*)}$ $\boldsymbol{i = \overline{1,5}}$, $\boldsymbol{j = \overline{1,20}}$ can be a value:

a) the probability of determining the action parameter $\boldsymbol{\alpha_j}$ in case of perfect execution of the control algorithm;

b) the probability of maintaining the adopted control algorithm $\boldsymbol{l} \in \boldsymbol{L}$ for the adopted action parameter $\boldsymbol{\alpha_j}$;

c) the total probability of the action parameter $\boldsymbol{\alpha_j}$ for its adoption and execution.

The desired probabilities of situation assessments are obtained by multiplying the initial probability matrix of situations $\boldsymbol{B}$ and the defining matrix of selected assessments $\boldsymbol{C}$:

$$P(\vec{S}^*) = B \cdot C. \tag{4.24}$$

The initial probabilities of the matrix $\boldsymbol{B}$ (elements corresponding to different flight situations) are determined by the rule of combining compatible events that define the situation. The probability of each event $\boldsymbol{A_i}$ or $\boldsymbol{\bar{A}_i}$ is calculated by the following formulas:

$$P(A_1) = \iint_{D_\tau} W(Y, t_0)\, W(Y^*/Y) dY dY^*;$$

$$P(\bar{A}_1) = \iint_{D_\tau} W(Y, t_0)\, W(Y^*/Y) dY dY^*;$$

$$P(A_2) = \int_{D_Y \cap D_\tau} \int_T W(Y, t) dY, dt;$$

$$P(\bar{A}_2) = \int_{\bar{D}_Y \cap D_\tau} \int_T W(Y, t) dY, dt;$$

$$P(A_3) = \int_{D_{Y^*} \cap D_\tau} \int_T W(Y^*, t/Y) dY^*, dt;\;\; D_{Y^*} = \left\{ {}^{Y^*}\!/_{\forall}\, Y \in D_Y \right\};$$

$$P(\bar{A}_3) = \int_{\bar{D}_{Y^*} \cap \bar{D}_\tau} \int_T W(Y^*, t/Y) dY^*, dt; \qquad (4.25)$$

$$P(A_4) = \int_{D_\tau \cap D_Y} W(Y, t_k) dY;$$

$$P(\bar{A}_4) = \int_{\bar{D}_\tau \cap \bar{D}_Y} W(Y, t_k) dY;$$

$$P(A_5) = \int_{D_\tau \cap D_{Y^*}} W(Y^*, t_k/Y) dY^*; \quad D_{Y^*} = \left\{ {}^{Y^*}\!/_{\forall}\, Y \in D_Y \right\};$$

$$P(\bar{A}_5) = \int_{\bar{D}_\tau \cap \bar{D}_{Y^*}} W(Y^*, t_k/Y) dY.$$

For the case of the landing system operation in the control mode, as mentioned above, the information is accepted with a lower weighting, so ILS errors of the first and second kind have less influence on the ILS action result. In the control mode, the following flight situations may occur for the ILS:

$S_1 = A_1 \wedge A_2 \wedge A_3 \wedge A_4 \wedge A_5$;	$S_7 = A_1 \wedge \bar{A}_2 \wedge A_3 \wedge A_4 \wedge A_5 \wedge A$;	(4.26)
$S_2 = A_1 \wedge A_2 \wedge A_3 \wedge A_4 \wedge \bar{A}_5$;	$S_8 = A_1 \wedge \bar{A}_2 \wedge A_3 \wedge A_4 \wedge \bar{A}_5$;	
$S_3 = A_1 \wedge A_2 \wedge A_3 \wedge \bar{A}_4 \wedge A_5$;	$S_9 = A_1 \wedge \bar{A}_2 \wedge A_3 \wedge \bar{A}_4 \wedge A_5$;	
$S_4 = A_1 \wedge A_2 \wedge A_3 \wedge \bar{A}_4 \wedge \bar{A}_5$;	$S_{10} = A_1 \wedge \bar{A}_2 \wedge A_3 \wedge \bar{A}_4 \wedge \bar{A}_5$;	
$S_5 = A_1 \wedge A_2 \wedge \bar{A}_3 \wedge A_4 \wedge \bar{A}_5$;	$S_{11} = A_1 \wedge \bar{A}_2 \wedge \bar{A}_3 \wedge A_4 \wedge \bar{A}_5$;	
$S_6 = A_1 \wedge A_2 \wedge \bar{A}_3 \wedge \bar{A}_4 \wedge \bar{A}_5$;	$S_{12} = A_1 \wedge \bar{A}_2 \wedge \bar{A}_3 \wedge \bar{A}_4 \wedge \bar{A}_5$;	
$S_{13} = \bar{A}_1 \wedge A_2 \wedge A_3 \wedge A_4 \wedge A_5$;	$S_{19} = \bar{A}_1 \wedge \bar{A}_2 \wedge A_3 \wedge A_4 \wedge A_5$;	
$S_{14} = \bar{A}_1 \wedge A_2 \wedge A_3 \wedge A_4 \wedge \bar{A}_5$;	$S_{20} = \bar{A}_1 \wedge \bar{A}_2 \wedge A_3 \wedge A_4 \wedge \bar{A}_5$;	
$S_{15} = \bar{A}_1 \wedge A_2 \wedge A_3 \wedge \bar{A}_4 \wedge A_5$;	$S_{21} = \bar{A}_1 \wedge \bar{A}_2 \wedge A_3 \wedge \bar{A}_4 \wedge A_5$;	
$S_{16} = \bar{A}_1 \wedge A_2 \wedge A_3 \wedge \bar{A}_4 \wedge \bar{A}_5$;	$S_{22} = \bar{A}_1 \wedge \bar{A}_2 \wedge A_3 \wedge \bar{A}_4 \wedge \bar{A}_5$;	
$S_{17} = \bar{A}_1 \wedge A_2 \wedge \bar{A}_3 \wedge A_4 \wedge \bar{A}_5$;	$S_{23} = \bar{A}_1 \wedge \bar{A}_2 \wedge \bar{A}_3 \wedge A_4 \wedge A_5$;	
$S_{18} = \bar{A}_1 \wedge A_2 \wedge \bar{A}_3 \wedge \bar{A}_4 \wedge \bar{A}_5$;	$S_{24} = \bar{A}_1 \wedge \bar{A}_2 \wedge \bar{A}_3 \wedge \bar{A}_4 \wedge \bar{A}_5$.	

The determinant matrix for estimates $\boldsymbol{S_i^*}(\boldsymbol{i} = \overline{\mathbf{1,5}})$, merging situations $\boldsymbol{S_j}(\boldsymbol{j} = \overline{\mathbf{1,24}})$, in the control mode is also a block matrix by columns:

$$C = \left|P\left(\alpha_j, S_1^*\right) \vdots\vdots\, P\left(\alpha_j, S_5^*\right)\right|,\ j = \overline{1{,}24}, \qquad (4.27)$$

where $\boldsymbol{P}\left(\boldsymbol{\alpha_i}, \boldsymbol{S_j^*}\right)$ has the same meaning as in the previous case.

The considered stochastic sequence of results$\boldsymbol{P}(\vec{\boldsymbol{S}}^*)$ characterizes the quality of the closed-loop ILS functioning in the control and monitoring modes.

If an aircraft that has deviated from a given trajectory crosses the flight path of another aircraft, a catastrophic situation occurs (S_5).

Let's consider an example of UAV location detection by different navigation systems: *DME/DME, VOR/DME, VOR/VOR*.

Let's assume that the behavior of the aircraft is described by a distribution density ***f(x)*** with a mathematical expectation t and a standard deviation $\boldsymbol{\sigma}$**.**

The five situations introduced in Chapter 1 are assigned a priori probabilities $\boldsymbol{p_i}, \boldsymbol{i} = \overline{\mathbf{1,5}}$. The situations are numbered from top to bottom and the catastrophic situation is the last [80].

With the chosen probability density ***f(x)*** of situations, the a priori probability of finding an aircraft in the ***i***- th zone is calculated by the formula:

$$p_i = \int_{L_i} f(x)\, dx, \qquad (4.28)$$

where $\boldsymbol{L}$ – the value of the deviation corresponding to the ***i***- th situation.

The sub-integral function (4.28) is a defined density [39].

$$f(x) = (1-\alpha)\frac{1}{2_{\alpha_1}\Gamma(b_1)} exp\left(-\left|\frac{(x-\mu)}{\alpha_1}\right|^{1/b_1}\right) +$$

$$+\alpha\frac{1}{2\alpha_2 b_2 \Gamma(b_2)} exp\left(-\left|\frac{(x-\mu)}{\alpha_1}\right|^{1/b_1}\right), \qquad (4.29)$$

where the gamma function $\Gamma(\boldsymbol{b})$ is defined as:

$$\Gamma(b) = \int_0^\infty e^{-t} t^{b-1} dt.$$

The probabilities of finding a PC in one of the five defined situations are written as follows:

- probability that the PC is in a normal situation:

$$p_1 = \int_{A_0-l}^{A_0+l} f(x)dx \int_{A_0-l}^{A_0+l} \varphi(x)dx, \quad (4.30)$$

where $\boldsymbol{f(x)}$ – a priori distribution function, with parameters $\boldsymbol{m_1}$ and $\boldsymbol{\sigma_1}$; $\boldsymbol{\varphi(x)}$ – a posteriori distribution function, with parameters $\boldsymbol{m_2}$ and $\boldsymbol{\sigma_2}$; $\boldsymbol{A_0}$ – the beginning of the reference, $\boldsymbol{A_0 = 0}$; $\boldsymbol{\pm l}$ – the width of the corridor, $\boldsymbol{\pm l = 1,85}$ км ($\boldsymbol{RNP1}$); $\boldsymbol{\delta}$ – the distance between the corridors; $\boldsymbol{\pm k}$ – the wingspan of the aircraft, $\boldsymbol{\pm k = 0,025}$ км.

– the likelihood that the aircraft is in a difficult situation:

$$p_2 = \left[\int_{A_0-\frac{\delta}{2}}^{A_0-l} f(x)dx + \int_{A_0+l}^{A_0+\frac{\delta}{2}} f(x)dx\right]\left[\int_{A_0-\frac{\delta}{2}}^{A_0-l} \varphi(x)dx + \int_{A_0+l}^{A_0+\frac{\delta}{2}} \varphi(x)dx\right], \quad (4.31)$$

- probability of aircraft location in a difficult situation:

$$\left[p_3 = \int_{A_0-\delta+l}^{A_0-\frac{\delta}{2}} f(x)dx + \int_{A_0-\frac{\delta}{2}}^{A_0-\delta+l} f(x)dx\right] \left[p_3 = \int_{A_0-\delta+l}^{A_0-\frac{\delta}{2}} \varphi(x)dx + \int_{A_0+\frac{\delta}{2}}^{A_0+\delta-l} \varphi(x)dx\right],$$

(4.32)

- probability of PC location in an emergency situation:

$$\left[p_4 = \int_{A_0-\delta+k}^{A_0-\delta+l} f(x)dx \int_{A_0+\delta-l}^{A_0+\delta-k} f(x)dx\right]\left[\int_{A_0-\delta+k}^{A_0-\delta+l} f(x)dx \int_{A_0+\delta-l}^{A_0+\delta-k} f(x)dx\right], \quad (4.33)$$

- the probability that the PC is in a catastrophic situation:

$$\left[p_5 = \int_{A_0-\delta-k}^{A_0-\delta+k} f(x)dx \int_{A_0+\delta-k}^{A_0+\delta+k} f(x)dx\right]\left[\int_{A_0-\delta+k}^{A_0-\delta+k} f(x)dx \int_{A_0+\delta-l}^{A_0+\delta+k} f(x)dx\right]. \quad (4.34)$$

The sum of the first four probabilities is less than one and equal to one:

$$p_\Sigma = \sum_{i=l}^{4} p_i.$$

Let's assign probabilities to the first four situations:

$$\tilde{p}_i = \frac{p_i}{p_\Sigma}.$$

Then situations one through four will form a complete group of events, i.e:

$$\sum_{i=1}^{4} \tilde{p}_i = 1.$$

Calculation of the spectrum of probability characteristics for different PC location systems

1. The components of the spectrum of probability characteristics are the following probabilities:

1) the probability of being in a normal situation:

$$P_{S_1} = \int_{A_0+\delta}^{A_0+\delta} \left((1-\alpha) \frac{1}{2a_1 b_1 \Gamma(b_1)}\ exp\left(-\left|\frac{(x-\mu)}{a_1}\right|^{1/b_1}\right) + \right.$$

$$\left. +a \frac{1}{2a_2 b_2 \Gamma(b_2)} exp\left(-\left|\frac{(x-\mu)}{a_2}\right|^{1/b_2}\right)\right) dx \int_{A_0+\delta}^{A_0+\delta} \varphi(x)dx$$

2) the likelihood of getting into complicated flight conditions or a difficult situation:

$$P_{(S_2 \cup S_3)} = \int_{A_0-\delta}^{A_0+\delta} \left((1-\alpha) \frac{1}{2a_1 b_1 \Gamma(b_1)}\ exp\left(-\left|\frac{(x-\mu)}{a_1}\right|^{1/b_1}\right) + \right.$$

$$\left. +a \frac{1}{2a_2 b_2 \Gamma(b_2)} exp\left(-\left|\frac{(x-\mu)}{a_2}\right|^{1/b_2}\right)\right) dx \text{ x } \left[\int_{-\infty}^{A_0-\delta} \varphi(x)dx + \int_{A_0+\delta}^{\infty} \varphi(x)dx\right]$$

3) the likelihood of identifying an emergency situation:

$$P_{S_4} = \int_{A_0+\delta}^{A_0+\delta} \varphi(x)dx \left[\left[\int_{-\infty}^{A_0-\delta} \left((1-\alpha) \frac{1}{2a_1 b_1 \Gamma(b_1)}\ exp\left(-\left|\frac{(x-\mu)}{a_1}\right|^{1/b_1}\right) + \right.\right.\right.$$

$$\left. +a \frac{1}{2a_2 b_2 \Gamma(b_2)}\ exp\left(-\left|\frac{(x-\mu)}{a_2}\right|^{\frac{1}{b_2}}\right)\right) dx +$$

$$+ \ \int_{A_0+\delta}^{\infty} \left((1-\alpha) \frac{1}{2a_1 b_1 \Gamma(b_1)}\ exp\left(-\left|\frac{(x-\mu)}{a_1}\right|^{1/b_1}\right) + \right.$$

$$\left.\left.\left. +a \frac{1}{2a_2 b_2 \Gamma(b_2)}\ exp\left(-\left|\frac{(x-\mu)}{a_2}\right|^{\frac{1}{b_2}}\right)\right) dx \right]\right]$$

4) the likelihood of returning to a normal situation:

$$P_{S_6} = \left[\int_{-\infty}^{A_0-\delta} \left((1-\alpha) \frac{1}{2a_1 b_1 \Gamma(b_1)}\ exp\left(-\left|\frac{(x-\mu)}{a_1}\right|^{\frac{1}{b_1}}\right) + \right.\right.$$

$$\left. +a \frac{1}{2a_2 b_2 \Gamma(b_2)}\ exp\left(-\left|\frac{(x-\mu)}{a_2}\right|^{\frac{1}{b_2}}\right)\right) dx +$$

$$+ \ \int_{A_0+\delta}^{\infty} \left((1-\alpha) \frac{1}{2a_1 b_1 \Gamma(b_1)}\ exp\left(-\left|\frac{(x-\mu)}{a_1}\right|^{1/b_1}\right) + \right.$$

$$+a\frac{1}{2a_2b_2\Gamma(b_2)}\,exp\left(-\left|\frac{(x-\mu)}{a_2}\right|^{\frac{1}{b_2}}\right)\Bigg)dx\Bigg]\ \text{x}$$

$$\left[\int_{-\infty}^{A_0-\delta}\varphi(x)dx+\int_{A_0+\delta}^{\infty}\varphi(x)dx\right]$$

Let's calculate the spectrum of probability characteristics for the following systems: VOR/DME, DME/DME, VOR/VOR, GNSS, radar station (RS) depending on the distance (R, km) to the PC. Further, for the calculation, we take into account the compliance with ICAO documents and technical characteristics of the systems, take into account the fact that all navigation aids have limited accuracy, and also take into account the accuracy tolerances of display systems.

It follows that we will not use the probability p_5 This is reasonable, since its value is small compared to other a priori probabilities.

As the a priori data for the calculation, we will use the data obtained during the flight tests of the VAe-111 aircraft at the British Royal Air Force Center in Beckford. The a priori data are shown in Table 4.1.

Table 4.1

Flight Data

	Mathematical expectation	**SCM, σ_1**
*DME/DME/*INS	0,09	0,35
DME/DME/ Air data	0,07	0,45
*VOR/DME/*INC	0,1	0,98
VOR/DME/Air data	0,36	1,41
VOR, поєднаний з автопілотом	0,2	2,26

4.3. Quantitative method for constructing areas of acceptable values of information support parameters

On the basis of predicting the sequence of results in the system, it is possible to determine the quality of its functioning. This, in turn, makes it possible to formulate requirements for the parameters $\{\boldsymbol{F}\}$ of information support (see Section). Such requirements can be represented in the form of parameter domains constructed using quantitative methods.

Consider the set $\mathbf{\Omega}$, which defines the points of the boundary of the desired area. Let us denote each point of the boundary of this domain by $\boldsymbol{\lambda}$. If there exists a bounded region of admissible states of the system belonging to the Euclidean space $\boldsymbol{R^m}$, then there exists a set $\mathbf{\Omega}$, that gives a closure of the set $\wedge$, that defines the region of admissible states of the system:

$$\forall\lambda \in \Omega \subset \overline{\wedge},\ \wedge = \{\lambda / f_i(\lambda) \leq 0,\ i = 1,2,\dots,N\}, \quad (4.35)$$

where $\boldsymbol{f_i(\lambda) \leq 0}$ – constraints imposed on the system.

Suppose that each point $\boldsymbol{\lambda}$ of the boundary of the domain $\mathbf{\Omega}$ is a control vector-parameter of the given system (as well as each point of the domain itself):

$$\lambda = \{\lambda_1, \lambda_2, \dots, \lambda_m\},\ m \geq 1, \quad (4.36)$$

and the set of these points determines the limitations of controlling a given system when it still performs the functional tasks assigned to it.

If we move along the boundary of the region of permissible values of $\boldsymbol{\lambda}$, fixing the passing points-vectors, then we will get a certain sequence of vector-parameters $\{\boldsymbol{\lambda_n}\}$:

$$\lambda_n \in \{\lambda \in \Omega / f_i(\lambda) \leq 0,\ i = 1,2,\dots,N\},\ n = 0,1,2,\dots \quad (4.37)$$

Let's parameterize the resulting sequence$\{\boldsymbol{\lambda_n}\}, \boldsymbol{n = 0,1,2,\dots}$ with the help of some real parameter $\boldsymbol{\tau \geq 0}$. For parameterization, it will be enough to specify the values of the parameter $\boldsymbol{\tau_n}$ that correspond to the points $\boldsymbol{\lambda_n}$ of the boundary, that is, the sequence of real numbers $\{\boldsymbol{\tau_n}\},\ \boldsymbol{n = 0,1,2,\dots}$, which corresponds to the sequence $\{\boldsymbol{\lambda}\},\ \boldsymbol{n = 0,1,2,\dots}$. Then the boundary of the region of admissible values of the vector-parameter $\boldsymbol{\lambda}$ can be considered as a vector function $\boldsymbol{\lambda(\tau)}$ in such a way that:

$$f'\big(\lambda(\tau_n)\big) = \lim_{\Delta\tau \to 0} \frac{\lambda(\tau_n + \Delta\tau) - \lambda(\tau_n)}{\Delta\tau}, \quad (4.38)$$

and the number of points at which the function $\boldsymbol{\lambda(\tau)}$ is undifferentiated is bounded. Now, at all points of the boundary, except, as mentioned above, a limited number of points where the derivative cannot be calculated, we have the value of the vector-parameter and the direction of motion for traversing along the boundary of the permissible region of motion along $\boldsymbol{f'\big(\lambda(\tau_n)\big)}$. A similar picture is obtained when solving extreme problems using gradient-type methods.

Since, when quantitatively solving such a problem, the equation has to be replaced with a corresponding finite-difference approximation:

$$\left.\begin{aligned} x^{(n+1)} &= x^{(n)} + \alpha\rho^{(n)} \\ \rho^{(n+1)} &= \rho^{(n)} + \alpha\ grad\ \Phi(x) \end{aligned}\right\}, \qquad (4.39)$$

then an iterative process similar to (4.39) with a finite step length leads to a deviation from the boundary line. Therefore, it is necessary to specify an ε-band instead of the boundary line, which will make up the set $\boldsymbol{\Omega_\varepsilon}$ and the exit from which should be interpreted as a departure from the boundary line. Since the movement along the boundary essentially leads to the fact that the constraints of the form $\boldsymbol{f_i(\lambda) \leq 0,\ i = 1,2,\dots,N}$ are replaced at the corresponding points by constraints in the form of equality:

$$f_i(\lambda) = 0,\ i = 1,2,\dots,N \qquad (4.40)$$

or for quantitative methods:

$$\delta_i \leq f_i(\lambda) \leq 0, \quad \delta_i < 0, \quad i = 1,2,\dots,N\,, \qquad (4.41)$$

then the $\boldsymbol{\varepsilon}$- band requested earlier will be determined using expression (3.34), and the deviation from the boundary line and the location relative to the boundary of the point that has left the boundary will be determined using the value and sign of the violation of the constraint (4.40), i.e., the value of the function $\boldsymbol{f_i(\lambda)}$.

Since the quantitative method uses the magnitude of the violation for correction, it is necessary to apply the information function $\boldsymbol{U(\lambda)}$, яwhich can be built according to the following rule:

$$U(\lambda) = \left\{\begin{matrix} 1, & \forall\lambda \in int\ \Lambda \\ 0, & \forall\lambda \in \Omega_\varepsilon \\ -1, & \forall\lambda \notin \Lambda \end{matrix}\right\}. \qquad (4.42)$$

If you additionally use the value of the area boundary violation, then the correction can be performed according to the selected gradient law:

$$x^{(n+1)} = x^{(n)^*} + \alpha^* \rho^{(n)^*},\ n = 0,1,2,\dots$$

$$\rho^{(n+1)^*} = \rho^{(n)^*} + \alpha^* \cdot u(x)^n\ grad\ f(x^n). \quad (4.43)$$

In the absence of prior information about the nature of the trajectory when departing from the boundary, then it will be necessary to initially use the adjustment 4.43, i.e., for $\boldsymbol{n} = \boldsymbol{0}$:

$$x^{(n^*)^*} = x^{(n+1)}, \quad n^* = 0$$

$$\rho^{(n^*)^*} = 0, \qquad n^* = 0. \qquad (4.44)$$

In Expression 4.36, the «*» in the adjustment number is omitted to avoid cluttering the entry.

For more accurate movement along the boundary, higher order gradient methods can be used by performing similar transformations. However, it is obviously inappropriate to go above the second or third order, since the introduction of a sufficiently wide $\boldsymbol{\varepsilon}$-band significantly reduces the number of necessary corrections.

The parameterization of the boundary set also allows us to use the methods of classical quantitative analysis to more accurately solve the problem of finding the boundary of the admissible region.

Here, the problem is reduced to an approximate calculation of the value of the function $\boldsymbol{\lambda(\tau)}$ at the nodes. The choice of nodes can be made using statistical methods, as is done in the problem of planning an experiment. However, the nodes can also be specified as a set of equidistant points or be free. In the latter case, the problem of finding nodes is reduced to a Gaussian quadrature with nodal polynomials:

$$\prod_{i=1}^{n}(x - x_i) = \sum_{k=0}^{n} C_k(x)^k, \qquad (4.45)$$

whose rays are the desired nodes. Given a known grid, the task of finding the weight of each node is not very complicated and can be solved depending on the nature of the available information and the desired accuracy.

Let $\boldsymbol{L}$ – a linear operator, and $\boldsymbol{m_k}$ – $\boldsymbol{k}$- th moment of the operator:

$$m_k = L(x^k). \qquad (4.46)$$

Then you can record it:

$$\left.\begin{array}{r} m_0 = W_1 + W_2 + \cdots + W_n, \\ m_1 = W_1 x_1 + W_2 x_2 + \cdots + W_n x_n, \\ m_2 = W_1 x_1^2 + W_2 x_2^2 + \cdots + W_n x_n^2, \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots. \\ m_{n-1} = W_1 x_1^{n-1} + W_2 x_2^{n-1} + \cdots + W_n x_n^{n-1} \end{array}\right\}, \qquad (4.47)$$

where

$\boldsymbol{W_i}$ – weight of the $\boldsymbol{i}$-th node;

$\boldsymbol{x_i}$ – coordinate of the $\boldsymbol{i}$-th node.

The determinant of this system is the Vandermonde determinant and is different from zero if $\boldsymbol{x_i} \neq \boldsymbol{x_j}$. Now let's introduce the fundamental polynomials:

$$\varphi_i(x) = (x - x_1)(x - x_2) \dots (x - x_{i-1})(x - x_{i+1}) \dots (x - x_n)$$
$$i = 1,2, \dots, n \qquad (4.48)$$

for which the following conditions are met:

$$\varphi_i(x_j) = 0 \text{ для } i \neq j \text{ та } \varphi_i(x_i) \neq 0. \qquad (4.49)$$

Note that the polynomial (4.41) can be written in the form:

$$\varphi_i(x) = \sum_{k=0}^{n-1} C_{ik} x^k, \quad i = 1,2, \dots, n. \qquad (4.50)$$

Then, for the matrix of unknowns $\boldsymbol{X} = (\boldsymbol{x_i^k})$, the $\boldsymbol{m}$- th row of the inverse matrix will be written as follows:

$$\frac{C_{mk}}{\varphi_m(x_m)}. \qquad (4.51)$$

If the resulting matrix is multiplied on the right by the column of the moment vector, then the resultant vector-column gives the weights of the selected nodes. The result obtained refers to the solution of the problem of the function passing through the given points. However, this result is valid if the condition of passing through some of the points is replaced by the condition that the derivative values exist at the remaining points. Then we get the coefficients at the values of the function and its derivatives in the formula for calculating the value of the function at the node of interest. In our case, we can consider the value of its finite-difference approximation as a derivative:

$$\dot{\lambda}^{(i)} = (\lambda^{(i)} - \lambda^{(i-1)})/\Delta\tau, \quad i = 1,2, \dots, \qquad (4.52)$$

for the second and higher derivatives, respectively:

$$\ddot{\lambda}^{(i)} = \frac{\dot{\lambda}^{(i)} - \dot{\lambda}^{(i-1)}}{\Delta\tau}, \quad i = 1,2,3, \dots,. \qquad (4.53)$$

Here, due to the absence of external constraints on the law of parameterization of the boundary $\forall \boldsymbol{\lambda} \in \boldsymbol{\Omega_\varepsilon}$, we have assumed an equidistant placement of nodes with a step equal to one. If only the two previous points are used to construct the next point of the boundary of the region, then it is advisable to use a formula taking into account the first and second derivatives of the boundary function obtained by the above method:

$$\lambda^{(n+1)} = 8\lambda^{(n)} - 7\lambda^{(n-1)} - 4\dot{\lambda}^{(n)} - 2\dot{\lambda}^{(n+1)} + 2\ddot{\lambda}^{(n)} \text{ для } n \geq 2. \qquad (4.54)$$

The areas of limit values of radar support parameters presented in the next section were calculated using the method described above, with the first acceleration point determined by the Monte Carlo method (Section 3.1), and the second, as well as the correction, determined by the formulas of the gradient method (4.43 - 4.44).

Thus, it is quite obvious that the use of most of the known gradient methods for solving extreme problems gives a trajectory that is a rougher approximation to the desired boundary line, since any gradient method will be an individual, simplified version of formula (4.54). Consequently, more frequent adjustments will be applied and more time will be spent calculating the boundary of the area. But gradient methods also have advantages - simplicity of calculations and low sensitivity to the location of the initial points $\boldsymbol{\lambda_0}, \boldsymbol{\lambda_1}, \boldsymbol{\lambda_2}, \boldsymbol{\lambda_3}, \ldots$ in the $\boldsymbol{\varepsilon}$- band. For the adopted method (4.54), it is desirable to accurately determine the acceleration points on the boundary of the domain. This greatly affects the accuracy of the move along the boundary, i.e., it dramatically reduces the number of corrections.

The developed modeling system for determining quality indicators consists of three independent branches, each of which is designed to calculate the probabilistic characteristics of the system through one of the three channels. This system is based on unsupervised learning with general tasks that include clustering (grouping similar data points) and dimensionality reduction (reducing the number of features while preserving important information). In the case of information provision, these channels are the channels of azimuth (model φ), location angle (model ε) , and range (model r). The algorithm of the modeling system is shown in Fig 4.1. The figure shows the φ, model in detail, while the ε and r models are not disclosed, as they are similar to the φmodel. All three models are independent and are combined only at the output, where, based on the data obtained for each branch, the overall values of the objective function and the probability characteristics necessary to determine the decision point are calculated.

Let's consider the functioning of the model on the example of the azimuth channel. The model operates cyclically. The outer loop along $\boldsymbol{j}$ is designed to run the model at different specified values of the boundaries $(\boldsymbol{b_1}, \boldsymbol{b_2})$ of the domain $\boldsymbol{D_\tau}$ such that:

$$b_1(j+1) = b_1(j) + h_1,$$
$$b_2(j+1) = b_2(j) + h_2,$$

where $\boldsymbol{h_1}, \boldsymbol{h_2}$ – discrete steps, $\boldsymbol{j} = \overline{\boldsymbol{1}, \boldsymbol{J_3}}$.

The step discreteness is chosen based on the required accuracy of reproducing the change in the quality indicator $P[\boldsymbol{H_{ij}(t)}]$, $\boldsymbol{i} = \overline{\boldsymbol{0}, \boldsymbol{1}}$; $\boldsymbol{j} = \overline{\boldsymbol{0}, \boldsymbol{1}}$, which is of great importance when determining the height of decision making. The discreteness of the step can be increased if we have the results of the study of the quality function of the simplified model, i.e., if we have a priori information about the behavior of this function at a certain interval. Such a priori information can be analytical estimates of quality indicators obtained from simplified models. Reducing the step increases the time of computer modeling.

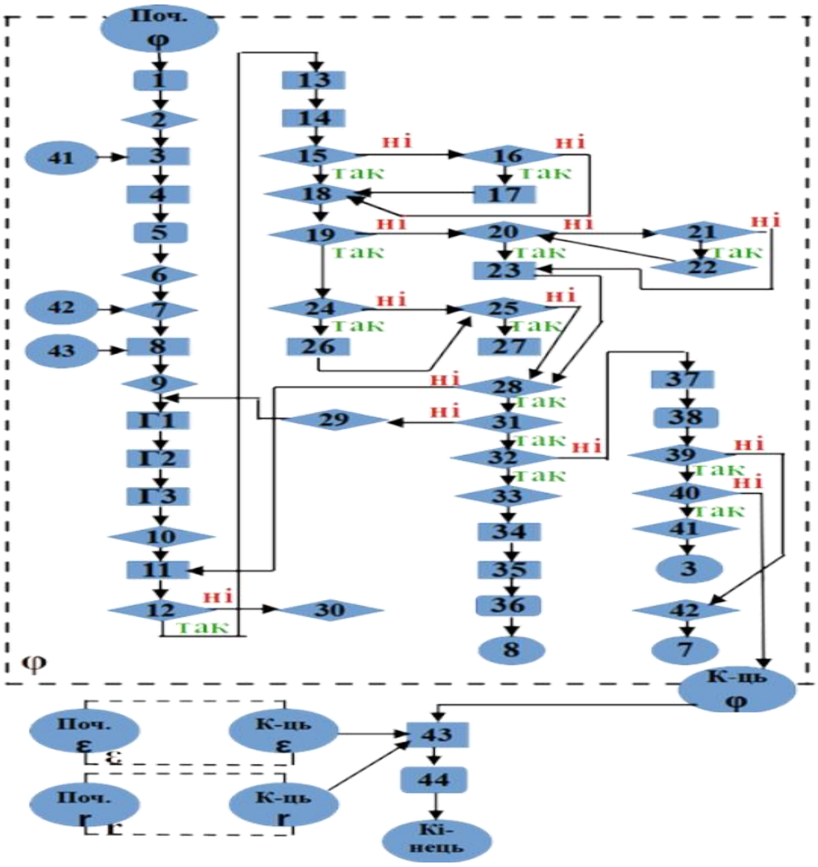


Fig. 4.1. Block diagram of modeling the probabilistic characteristics of aircraft landing by unsupervised machine learning with dimensionality reduction.

Table 4.2

List of steps of the structural scheme for modeling the probabilistic characteristics of aircraft in the air navigation service system

№	
1	Entering input data
2	$j = 1$
3	Setting the output for the j-th case
4	Calculation of systematic components
5	Printing systematic components
6	$l = 1$
7	$K = 1$
8	Preparing the model for operation
9	$n = 1$
10	$i = 1$
11	Setting the parameters of the i- th block
12	Is the i- th unit to be tested?
13	Generation of R_ρ
14	Conversion to the expression R
15	$R \geq b_2$?
16	$R > b_1$?
17	$n_n = n_n + 1$
18	$i = i + 1$
19	$K = 1$?
20	$R < X_1 + h - i_l$
21	$i_l < i$?
22	$i_l = i_l + 1$
23	$i_\tau(i_l) = i_\tau(i_l) + 1$
24	$X_1 > R$?
25	$X_2 < R$?
26	$X_1 = R$
27	$X_2 = R$
28	$i > i_k$?
29	$n = n + 1$
30	$i = i + 1$
31	$n = n_3$
32	$K = 1$?
33	$K = K + 1$
34	$h = (x_2 - x_1)/m$
35	Calculation of ρ
36	Print P, X_1, X_2, h
37	Calculation of probability characteristics
38	Print model characteristic φ
39	$l = l_3$?

40	$\boldsymbol{j} < \boldsymbol{j_3}$?
41	$\boldsymbol{j} = \boldsymbol{j} + \boldsymbol{1}$
42	$\boldsymbol{l} = \boldsymbol{l} + \boldsymbol{1}$
43	Calculating the probabilistic characteristics of the system
44	Print system characteristics
Г1	Generating $\boldsymbol{R_\rho}$
Г2	Conversion to the expression $\boldsymbol{R}$
Г3	Defining the boundaries $\boldsymbol{b_1}, \boldsymbol{b_2}$

Some of the sources of navigation errors are systematic and should be taken into account when studying the system, especially when these errors are self-measured or smaller than the random components. This is because in this case they cannot be compensated for. The calculation of the systematic components is carried out in block 4.

Next are nested cycles for $\boldsymbol{l}$, $\boldsymbol{K}$ and $\boldsymbol{n}$. The $\boldsymbol{l}$ cycle is intended to test the model with a different number of involved sources of system errors. When $\boldsymbol{l} = \boldsymbol{1}$, the system is studied "as a whole", when $1 < \boldsymbol{l} < \boldsymbol{l_3}$, the system is studied with individual sources of measurement errors turned off, which allows to evaluate their impact on the system characteristics. To do this, the simulation model of each source provides the possibility of bypassing it (turning it off and not being involved in this modeling cycle) depending on the value of $\boldsymbol{l}$ (block 12). The cycle by $\boldsymbol{K}$ works as follows. At the first pass $(\boldsymbol{k} = \boldsymbol{1})$, the number of random number occurrences and the interval $(\boldsymbol{b_1}, \boldsymbol{b_2})$, which are determined by the boundaries of the area of permissible deviations $\boldsymbol{D_\tau}$, are calculated, and preparatory operations are performed to build a histogram of the distribution of these numbers. The cycle of $\boldsymbol{n}$ $(\boldsymbol{n} = \overline{\boldsymbol{1}, \boldsymbol{n_3}})$ яis the modeling part. The number of model realizations $\boldsymbol{n_3}$ is chosen depending on the required accuracy of the result and is limited by the simulation time.

Due to the fact that the connectivity domain $\boldsymbol{D_\tau}$ generally has random boundaries, it was necessary to develop an algorithm that takes into account the fluctuation of the boundaries $(\boldsymbol{b_1}, \boldsymbol{b_2})$ according to an arbitrary law. This algorithm differs from the algorithm with deterministic boundaries only by the presence of blocks $\Gamma_1, \Gamma_2, \Gamma_3$. is used to generate a random number distributed according to a uniform law in the interval (0,1). In block Γ_2, we get a number distributed according to the law of change in the boundaries of the region $\boldsymbol{D_\tau}$. Block Γ_3 calculates the boundaries $(\boldsymbol{b_1}, \boldsymbol{b_2})$ taking into account the presence of both systematic and disturbing factors. The model includes a sequential chain of $\boldsymbol{i}(\boldsymbol{i} = \overline{\boldsymbol{1}, \boldsymbol{\imath k}})$ blocks, each of which simulates a real source of information loss in the studied ergatic system in accordance with a given distribution law and its parameters. The output data for each block is determined on the basis of physical processes that generate measurement errors. At each model implementation, the entire chain of simulated sources is sequentially passed. The sequence of operations for each source is as follows. First, a random number $\boldsymbol{R_p}$ is generated (block 13), distributed according to a uniform law in the interval (0,1), which is then converted into a random number $\boldsymbol{R}$ in accordance with the law of distributions and parameters of the source in question (block 14). Then, it is determined whether this random value $\boldsymbol{R}$ falls within the interval of the area of permissible deviations $(\boldsymbol{b_1}, \boldsymbol{b_2})$. If so, then the counter of the number of hits $\Pi_{\boldsymbol{n}}$ is increased by one (blocks 15 - 17). After $\boldsymbol{P_3}$, the number of model realizations, the calculated number of random numbers falling inside the area of permissible deviations $\boldsymbol{D_\tau}$ is set in accordance with the total number of tests, which subsequently determines the probability of the aircraft entering the investigated area of the observation zone (block 35).

The set of quality indicators in the $\boldsymbol{\varepsilon}$ and $\boldsymbol{r}$ models is determined in a similar way. By combining the obtained characteristics in block 43, we obtain generalized probabilistic characteristics of the entire system and its quality indicator. The developed model has been tested using problems based on known statistical criteria, which confirmed the possibility of using it to study real systems.

4.3.1. Initial data

Currently, various CNS/ATM tools are used to support flights. To improve their performance, information fusion is used in various combinations of these tools. The following tools can be used as such:

a) means of navigation: DME, VOR, HHC, CBC, satellite system;

b) surveillance equipment: airfield and route radars of various classes.

Usually, the following means are combined:

a) DME/DME/INS;

b) DME/DME/*Air data*;

c) VOR/DME/INS;

d) VOR/DME/*Air data*;

e)VOR/VOR connected to the autopilot.

The listed surveillance and navigation aids were taken as the objects of study.

As a result of statistical modeling of navigation and surveillance tools, data on lateral deviations of aircraft along air routes and in the airfield area were obtained. The obtained statistical distributions were approximated by a normal distribution function based on the Kolmogorov-Smirnov criterion [65]. For the considered means in Figs. 4.2 and 4.3 show the approximated distribution density functions with their mathematical expectations m and variances for air routes and in the airfield area, respectively. The results of statistical modeling are almost reliably confirmed by experimental data obtained by a number of foreign countries [169,170].

The a priori probabilities specified in clause 2.5 of air situation situations when using any of the above navigation and surveillance systems were selected from the following conditions.

The routes were chosen in such a way that the probability of a catastrophe, according to ICAO standards, is equal to 2-10, and the probability of a normal situation is equal to 0.954. Based on this, other a priori probabilities of situations were obtained, which are equal to = 0.334, = 0.0094, = 0.0026. In addition, we considered the case of an equally probable position of the aircraft in any of the situations under consideration, i.e. = 0.2; k = .

4.3.2. Modeling of options for combining ANO means

The functional efficiency of the systems under consideration was studied by statistical tests on an IBM 386DX PC.The simulation of the lateral deviation of the aircraft was carried out using random number sensors built on the basis of approximation of the distribution laws.

The modeling results are presented in the form of histograms of probabilities of correct classification and false decisions in Fig. 4.2-4.5.

In Fig. 4.2 shows a comparison of the probabilities of correct and incorrect decisions generated by different ANS systems. The probability histograms show that the satellite system, Y0R/DME/CBC, airfield radar, and the assurance system provide classification according to the instrument flight rules with a probability of at least 0.6. All other means of flight support considered do not meet ICAO requirements for preventing catastrophic situations. In this case, a guaranteeing system is understood as a system that allows a given situation to be classified with a probability of at least 0.5. V0R/VOR, track radar and VOR have the largest probabilistic errors in ascending order. In this case, they classify a normal situation instead of ATC with a probability of more than 0.5.

In Fig. 4.3 shows histograms of probabilities of correct classification of the NPP and erroneous decisions by the spectrum of situations for different systems, which more clearly show the distribution of errors in the classification of the NPP situation for each system separately.

The error analysis shows that there is an increase in the probability of correct classification with an increase in the precise characteristics of the systems. In addition, Fig. 4.3 shows that the combination of VOR/VOR and VOR/DME/CBC information compared to VOR leads to an increase in the probability of correct classification and a decrease in the probability of confusion errors.

The results of the study showed that only the satellite system provides classification of the disaster mode with a probability of at least 0.5, while the classification of the disaster mode with a given probability by all other systems is very difficult.

However, in this case, the probability of an emergency increases, i.e., the emergency is classified with greater reliability. It should be emphasized that due to the large dispersion of lateral deviations of the aircraft caused by its dynamic characteristics, control system and characteristics of the measuring systems, the classification of ATC, CC and CS situations is greatly complicated by the navigation and radar means used.

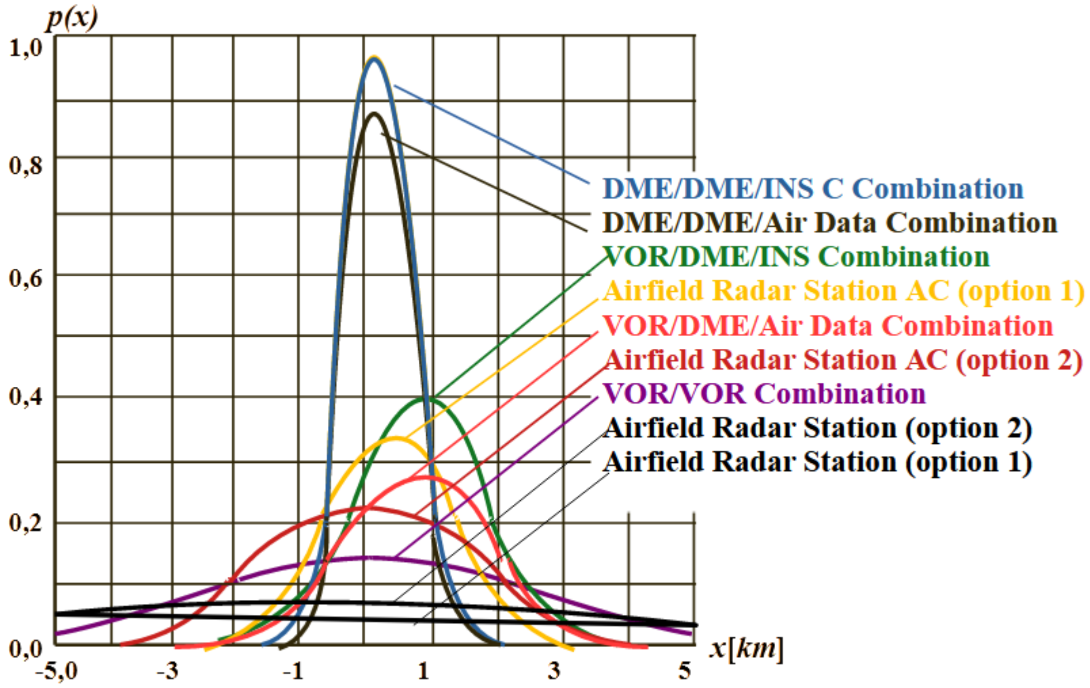


Fig. 4.2. Density of distribution of probabilities of lateral deviations of aircraft during flights in the airfield area using navigation or surveillance means

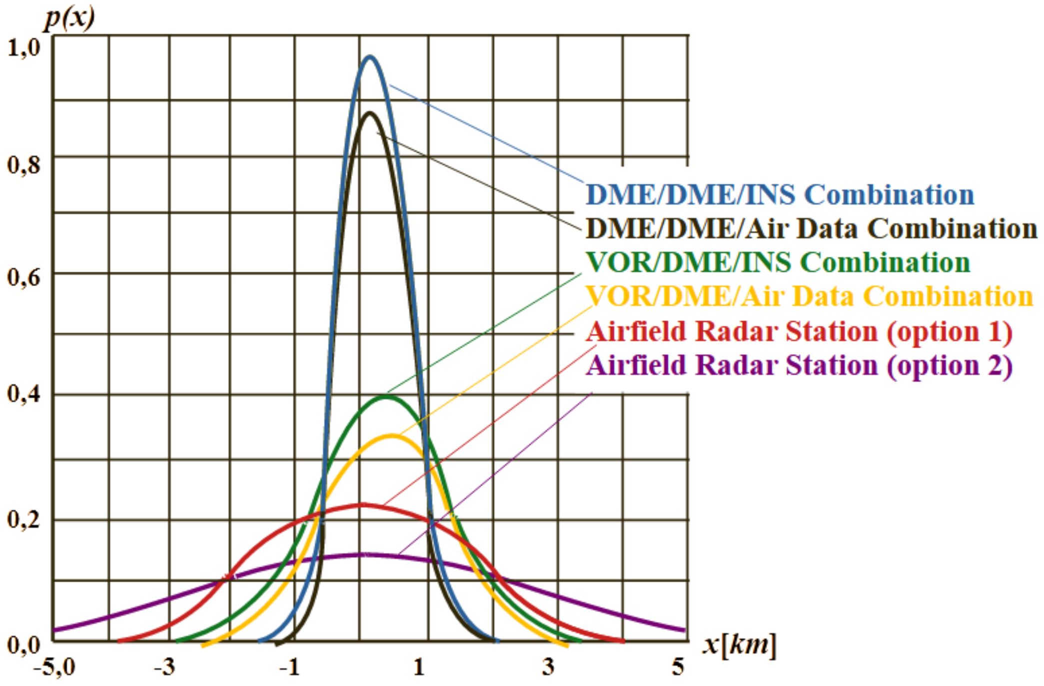


Fig. 4.3. Probability distribution density of lateral deviations of aircraft during flights in the airfield area with the use of navigation or surveillance means

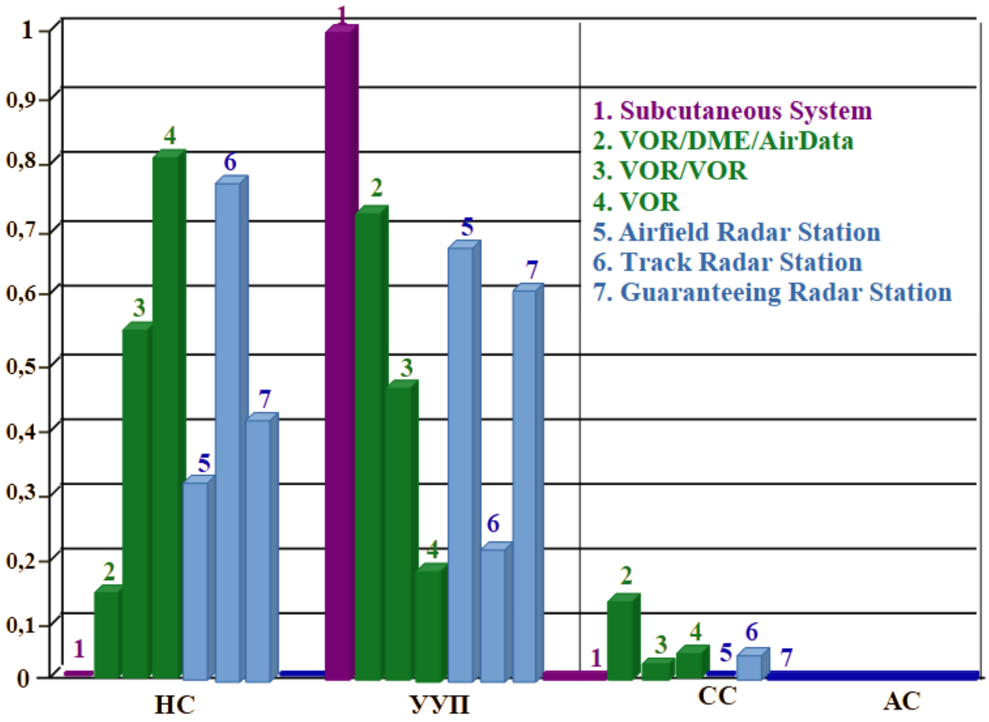


Fig. 4.4. Spectrum of air situations during the flight of an aircraft in difficult conditions with information from the SNA systems

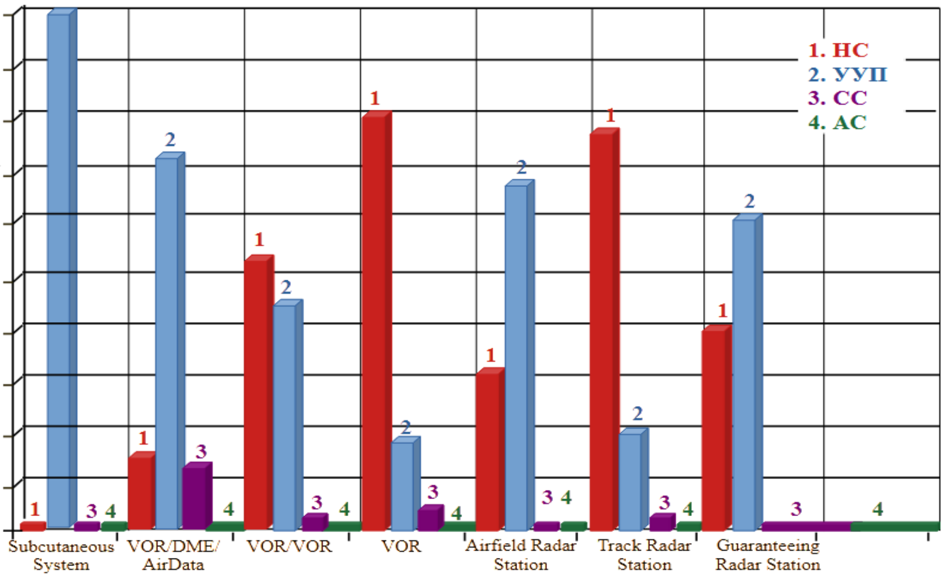


Fig. 4.5. Spectrum of the air situation when flying an aircraft in difficult conditions with the information of the SNA

4.3.3. Study Of Data Traffic In The Control And Communication Channels Of Bpl

The Integrated Space-Air-Ground Network (ISGN), including the Internet of Things and the stratospheric remotely piloted air system with artificial intelligence, is a powerful tool for next-generation communications. systems. Artificial intelligence systems are capable of processing huge amounts of information and demonstrate great potential in terms of cognition and decision-making. In this sense, AI systems can revolutionize the way we build ICT systems. The scope of artificial intelligence is rapidly expanding as computing performance increases and utilizes machine learning algorithms. There is a combination of networks and artificial intelligence algorithms to solve the problem of optimization based on big data and integration with blockchain.

In the actual process of training and testing, problems arise due to large amounts of data and, as a result, the loss of data packets in artificial intelligence systems. Even if training data is already available, it is difficult to test it in real networks. This is because hardware devices used in real networks are incompatible with artificial intelligence models. In addition, it is important to develop methods for assessing data loss when using artificial intelligence algorithms. It is important to study the impact of additional AI hardware on traffic losses.

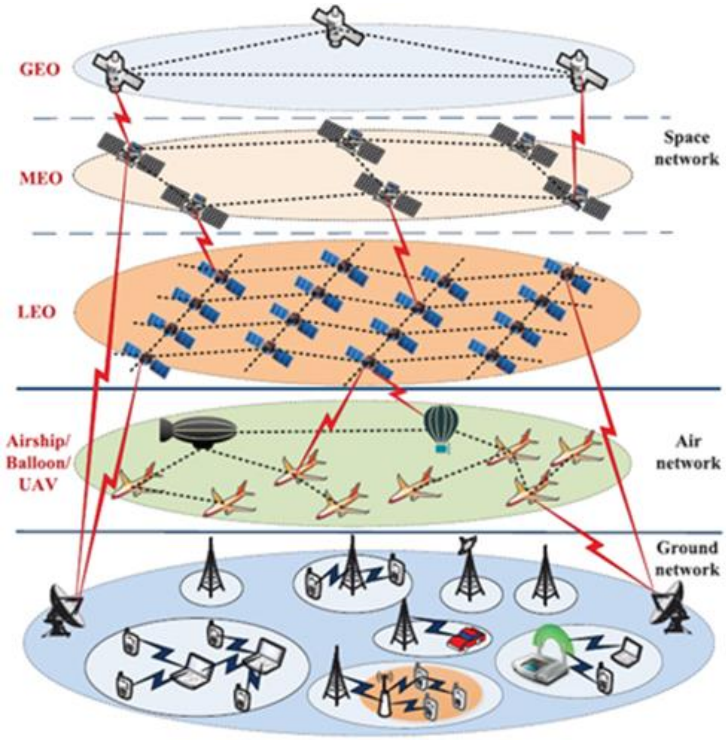


Fig.4.6. Architecture of SAGIN

The contribution of our work is as follows. The research is based on the paradigm of using stratospheric UAVs as high-altitude platforms with onboard artificial intelligence equipment to transmit data from ground-based Base Stations (BS) to cellular network users via low-orbit satellites and low-altitude UAVs. Reliable operation of the IMCS means minimal packet loss. However, there is currently no research in the field of packet loss estimation in AI augmentation, and there is no data in the literature on traffic and data loss during information exchange. We studied the centralized two-way communication channel of the IMCS. Data transmission and loss estimation were investigated with the help of an original model using NetCracker software. The influence of the main factors - data rate, transaction size, bit error rate (BER), bandwidth, packet error probability (PFC) in the AI system - was studied.

The literature does not address data loss in AI-enabled ICH systems and does not consider the necessary hardware requirements to minimize losses. At the same time, working with big data of artificial intelligence inevitably leads to data loss on hardware devices of real networks. To develop and test artificial intelligence algorithms, simulating their performance becomes important for further implementation in real networks.

When creating an AI-enabled IPCS and choosing data transmission modes, it is important to know when a critical situation may arise in terms of the number of bit errors and quality of service. When communication becomes unreliable or is completely interrupted, the transmission of useful data, especially commands and controls, can lead to the loss of drones and the failure of the mission objective. Therefore, when creating artificial intelligence-enabled IMCS, it is necessary to develop the theoretical foundations of such communication channels that are necessary to predict their behavior. This problem is relevant because it is associated with the inclusion of ground, air, and space networks in communication channels and the creation of integrated communication systems involving UAVs.

The aim of our study is to evaluate the dependence of packet loss on the transaction size (TS) and data rate for different PFCs in the system. In addition, it is important to obtain the dependence of the average BS uplink load and packet transit time on TS, as well as the dependence of BER on the average BS uplink load for different PFCs in an AI system. Quantitative information on the loss of two-way traffic for AI-enabled ICT communication channels is currently not available in the literature. In this paper, such information was obtained using the model in Fig. 4.2, and the calculated traffic characteristics are shown in Figures 4.2-4.5.

4.3.4. Model architecture

Since there are no studies of traffic in the IMCS with artificial intelligence systems, it is of interest to study this issue at least on the simplest models to understand the necessary hardware requirements for such systems. As the simplest model, we consider BS-SRPAS-AI-Sat-RPAS-CU (Fig. 4.7), which contains a BS, a stratospheric RPAS, an artificial intelligence system, a low-orbit satellite, a low-altitude RPAS, and a cellular user, developed using Professional NetCracker 4.1 software. The stratospheric RPAS is located at an altitude of 15 km and has a bandwidth of 1 Gbps. The low-orbit satellite is located at an altitude of 1000 km and has only two parameters that can be changed - packet delay and PFC, which are equal to zero. The low-altitude RPAS is located at an altitude of 500 meters and has a bandwidth of 1 Gbps. The base station and cellular network user servers have a bandwidth of 10 Mbps.

For simplicity, the artificial intelligence system is modeled as a cloud structure with the ability to change packet delay and PFC. The delay time was not taken into account, and the PFC was varied from zero to 0.08 in the simulation. All communication channels in the original models had a T1 data rate (1.544 Mbps) and BER=0.

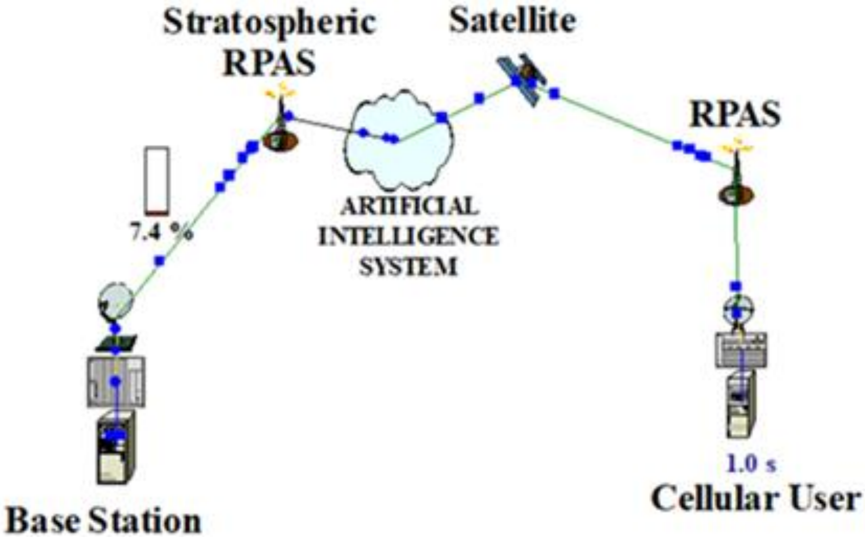


Fig.4.7. The IMPACT model BS-SRPAS-AI-Sat-RPAS-CU

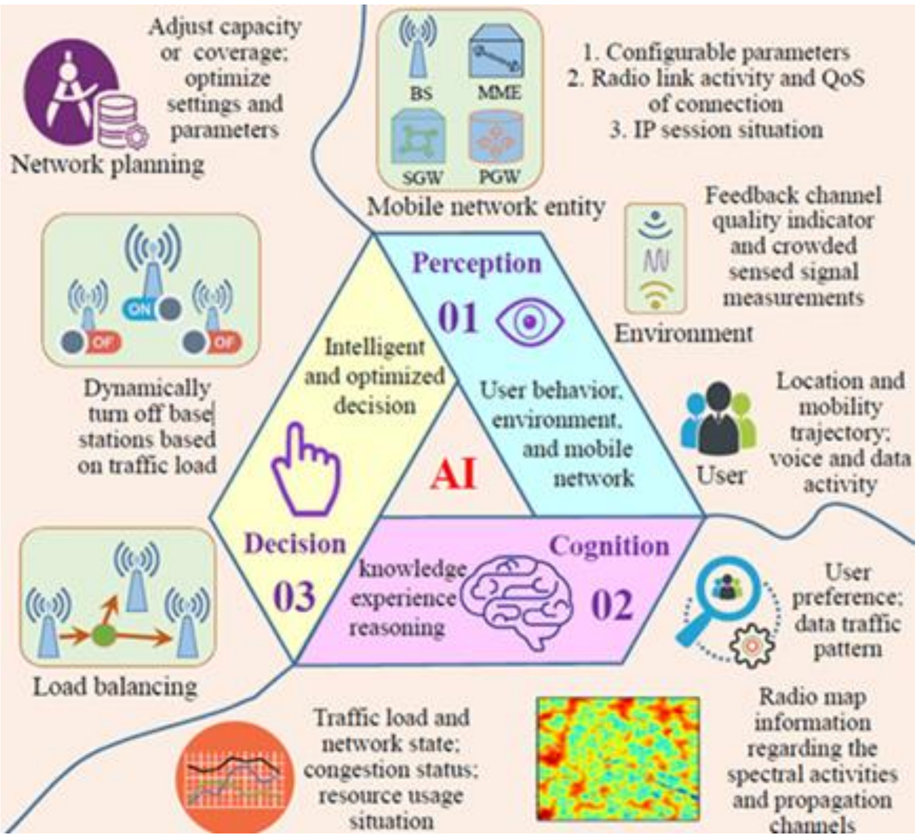


Fig. 4.8. Artificial intelligence system in the BS-SRPAS-AI-Sat-RPAS-CU model

A possible architecture of a mobile AI network was proposed earlier and consists of the processes of perception, cognition, and decision-making that form a control system (Fig. 4.8). In our model (Fig. 4.7), the artificial intelligence system is located in the stratospheric computing unit of the RPAS, which reduces the delay and load on the backbone network. This provides the necessary computing resources for processing big data and creates opportunities for developing analytical solutions in real time. The latter, in turn, leads to better customer service and lower operating costs.

4.3.5. Results

The results are shown in Figures 4.9-4.13 and contain the information necessary for network operators to ensure optimal operation of the IMCPC. During the simulation, we used TBT = 1 s and a peer-to-peer local area network protocol.

With intensive traffic in the IMCS, channel congestion may occur, and preventing it is one of the key tasks. To control network congestion, it is necessary to know the dependence of the average channel load on the transaction parameters. Here, the average load refers to the average traffic on a particular channel as a percentage of the total channel capacity..

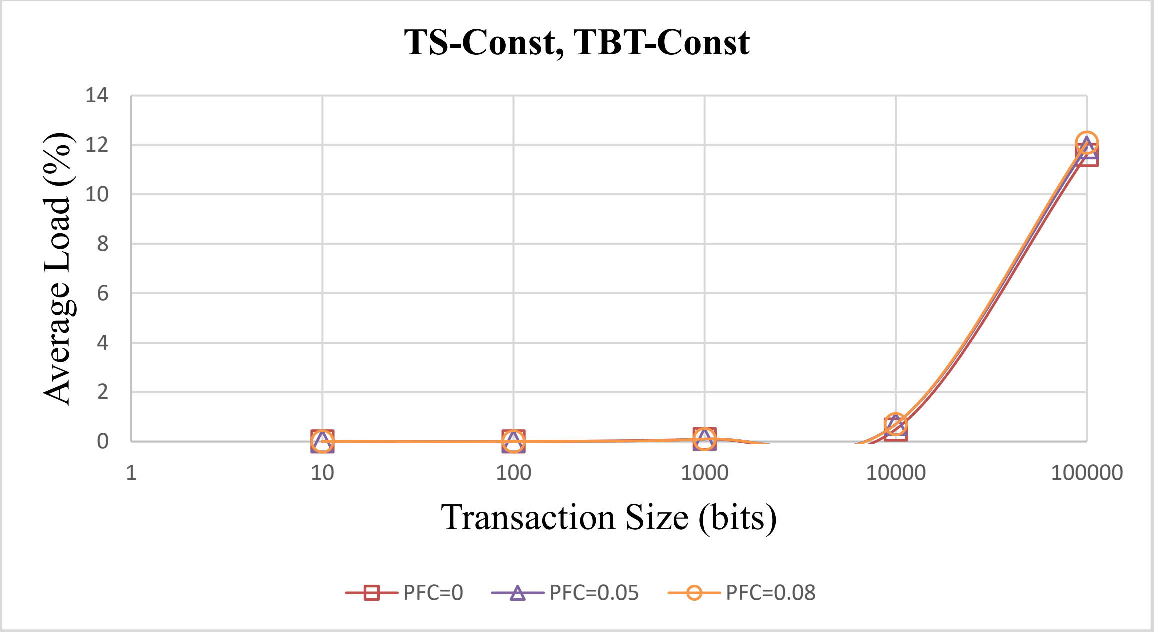


Fig.4.9. Dependence of average channel load on TS

Figure 4.9 shows the dependence of the average BS link load on the TS parameter. The graphs show that for TS values from 10 bits to 10 Kbit, the uplink load is almost zero for the considered packet loss probabilities, starting to increase only when TS > 10 Kbit. At the same time, increasing the transaction size to 100 Kbits leads to a sharp increase in network load. At TS > 100 Kbits, the channel closes and data transmission becomes impossible for the selected model parameters (data rate and server bandwidth).

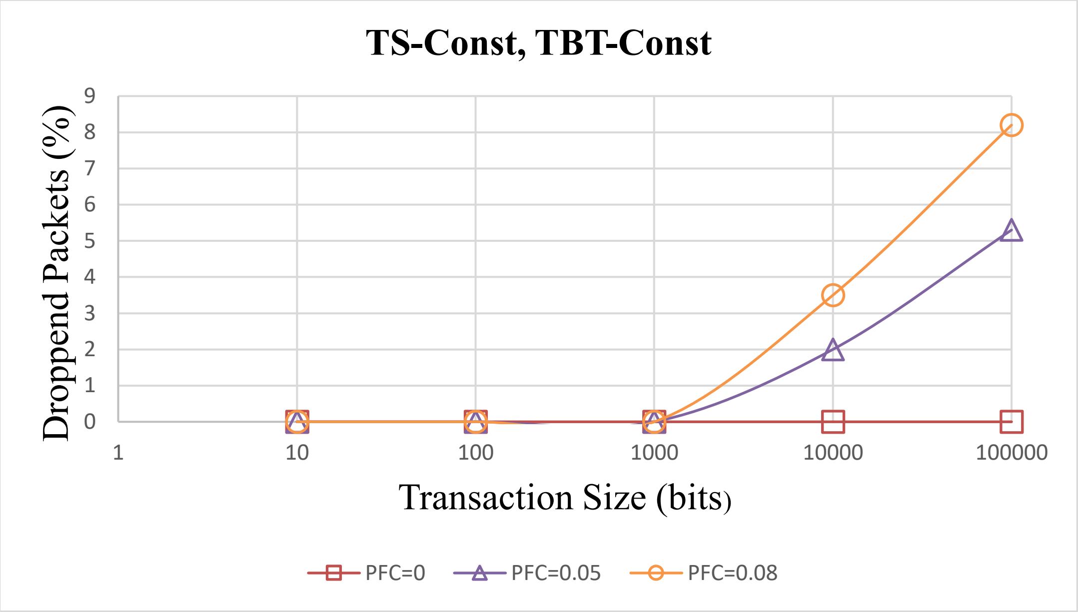


Fig.4.10. Dependencies of lost packets on TS

Figure 4.10 shows the dependence of lost packets on TS for the BS-SRPAS-AI-Sat-RPAS-CU model with different packet failure probabilities. It can be seen from the graphs that for TS values from 10 bits to 1 Kbit, the percentage of lost packets is zero and increases only for TS > 1 Kbit. This increase in loss is greater the larger the PFC parameter. When TS > 100 Kbps, the channel is closed.

The result seems to be trivial, namely that as the transaction size increases, the traffic increases and the number of lost packets increases. It is important to note that the graphs allow you to quantify the relative amount of losses and help you choose the right data transmission mode.

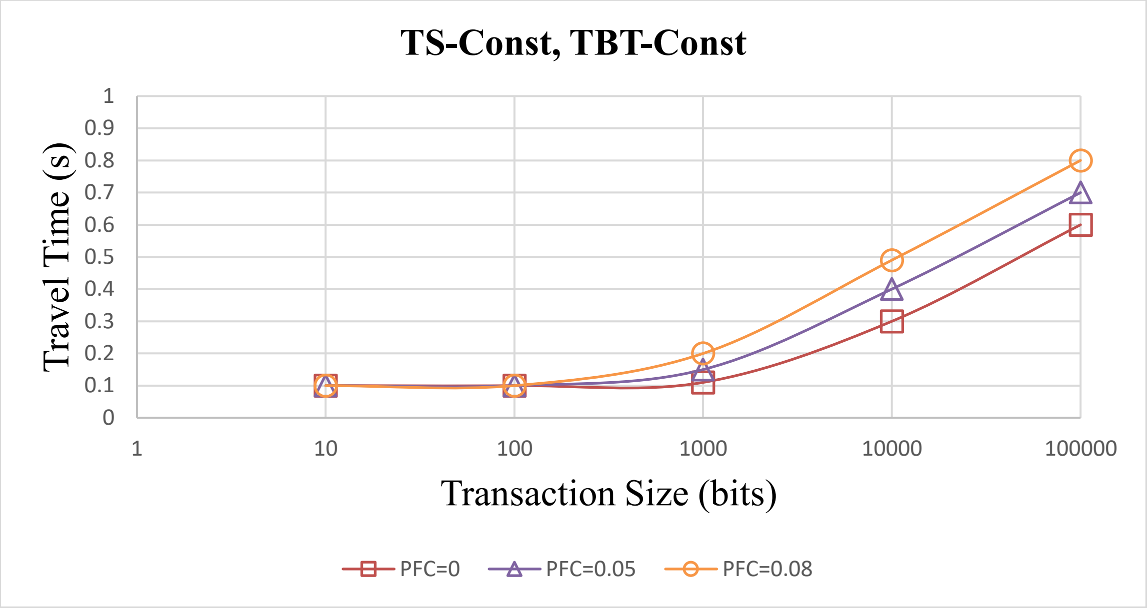


Fig.4.11. Dependencies of packet transit time on TS

Here, we study the impact of traffic parameters, namely transaction size and packet loss probability, on the time it takes for data packets to travel through the channel to the consumer. Calculations have shown (Fig. 4.11) that increasing the transaction size from 10 bits to 100 Kbit leads to an increase in message transit time by almost an order of magnitude, with slightly different values for all graphs. Knowledge of such dependencies is necessary when using real-time applications.

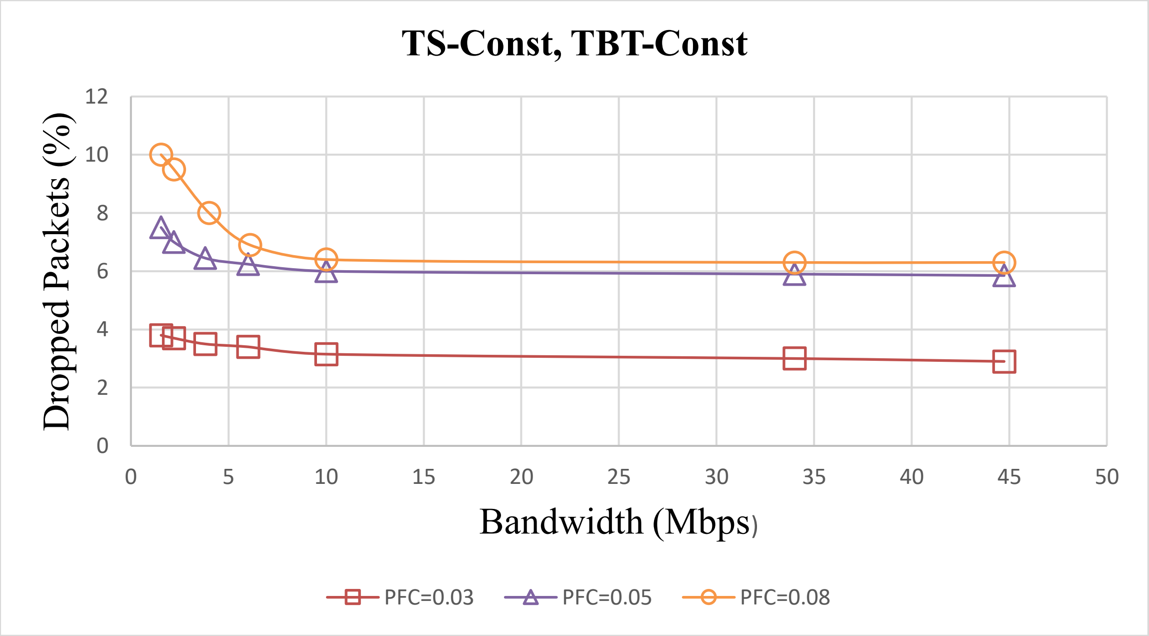


Fig.4.12. Packet dependencies on the BS-SRPAS channel bandwidth

It is necessary to ensure reliable direct communication between drones flying autonomously to prevent collisions and ensure the interaction of all components of the IMCS. Insufficient data rates in any of the channels can significantly degrade the performance of the entire integrated network. Figure 4.12 answers the question of how packet loss depends on the data rate in the uplink, which varies from T1 = 1.544 Mbps to T3 = 44.736 Mbps. The data from all graphs show that the percentage of lost packets increases with decreasing data rate and at T1 reaches ≈ 3.8% for PFC = 0.03, ≈ 7.5% for PFC = 0.05, and ≈ 10% for PFC = 0.08, respectively.

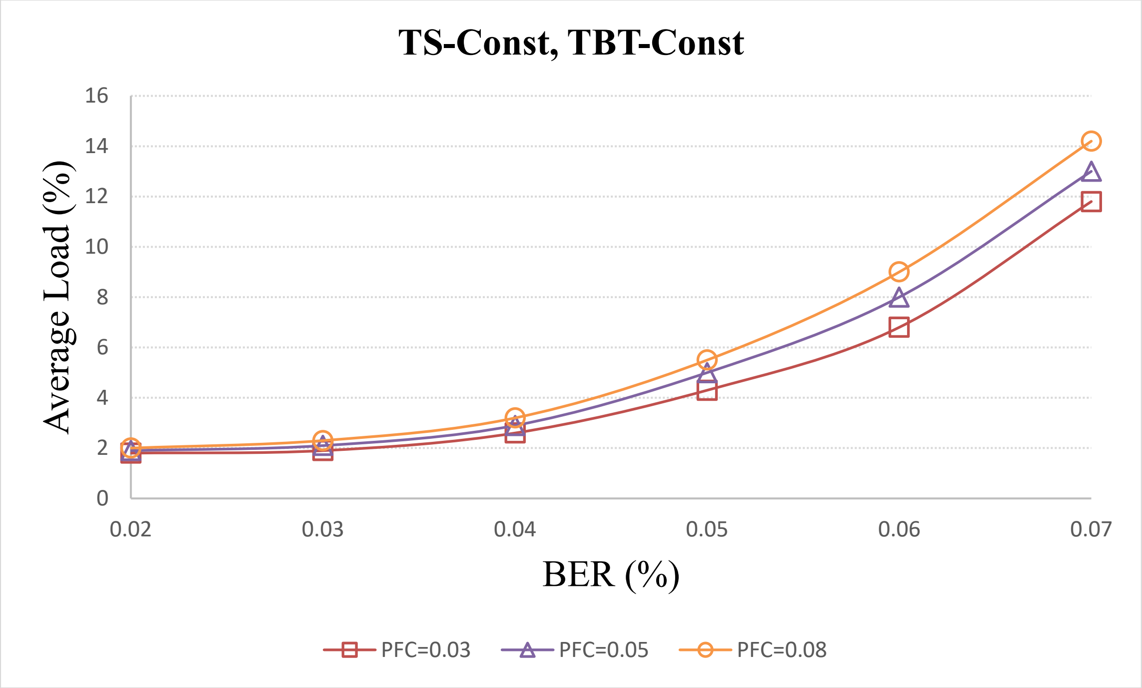


Fig.4.13. BER dependence on the average load of the BS channel

The relative distances between all the components in an IMCS are constantly changing, making it difficult to maintain quality of service. Data flow parameters are also constantly changing, which leads to an increase in the bit error rate. The BER parameter is used to evaluate the quality of service and noise immunity of the IMCS. Figure 4.13 shows the dependence of BER on the average load for an uplink BS with different packet loss probabilities. The results demonstrate the significant impact of bit errors on the quality of data transmission.

The practical value of these results lies in the fact that the obtained dependencies can be used to predict the behavior of the IMCPS when the length of transactions changes, to understand the effect of reducing bandwidth, as well as different levels of bit errors and packet loss probability. Knowing this information allows us to understand how data transmission modes affect channel utilization and quality of service.

This is the first study by the IMCI to calculate data packet loss in AI hardware. The communication channel includes a BS, a stratospheric AI-enabled UAS, a low-orbit satellite, a low-altitude UAS, and a terrestrial cellular network user. Traffic characteristics were calculated using NetCracker Professional 4.2 software. The AI system was modeled by a cloud structure with the ability to change the delay and probability of data packet loss. The obtained dependencies of losses on message size and data rate, the dependence of the average load for the uplink and packet transit time on the size of transactions, and the dependence of BER on the average load allow us to make practical recommendations for choosing the necessary data transmission modes.

Conclusions of Chapter 4

1. Mathematical methods for solving the formulated problems of navigation support for cargo drones are determined. A modification of these methods was created taking into account the specific features of large-dimensional problems with significant nonlinearity of variables and the complex nature of constraints on phase coordinates.

2. The computational algorithms for solving the problems are developed:

- calculation of system constraints of the landing system introduced by the aircraft as a controlled dynamic object (search for a global extremum taking into account constraints on variables in the form of equations and inequalities);
- predictive evaluation of a stochastic sequence of results (probabilistic analysis of the sequence tree of the set of flight situation predicates and its evaluation);

- construction of areas of permissible values of navigation support parameters (tracking the boundaries of closed sets by the method of forecast-correction, with correction by the gradient of boundary violation);
- combined study of the characteristics of navigation support (joint use of the results of analytical solution of simplified navigation problems and modeling by the method of simulation modeling).

3. Programs for quantitative studies of navigation support problems have been developed.

4. The need to provide reliable direct communication between drones flying autonomously to prevent collisions and ensure the interaction of all components of the Integrated Space-Air-Ground Network (ISGN) has been proven. Insufficient data transmission speed in any of the channels can significantly degrade the performance of the entire integrated network.

5. We modeled an AI artificial intelligence system with a cloud structure and the ability to change the delay and probability of data packet loss. The obtained dependencies of losses on message size and data rate, the dependence of the average load for the uplink and the packet transit time on the size of transactions, as well as the dependence of BER on the average load allow us to make practical recommendations for choosing the necessary data transmission modes in the communication channels of freight UAS.

CONCLUSIONS

This thesis presents a comprehensive study of the integration and optimization of unmanned aerial vehicle procedures in various application sectors, with a particular focus on logistics and supply chains, including a detailed review of the development and application of unmanned aerial vehicles (UAVs/drones) with regard to the needs for high mobility and autonomy. It also focuses on the importance of understanding and complying with the regulatory framework for drones in organizations such as ICAO, FAA, EASA, Eurocontrol and CAAC, and analyzes the differences in the approaches of these organizations to drones. The drone taxonomy is used to more fully understand how drones are used in real life to ensure aviation and human safety.

Any possibility of a reliable estimate of the global optimum in a multi-extreme problem is fundamentally based on the availability of certain a priori information that allows us to relate possible values of the minimization function to known values at points where measurements have already been made. It is proved that solving multidimensional problems using a simple search method on a uniform grid requires a significant number of iterations and, in fact, is possible only for small values of N and low solution accuracy.

The use of parsimonious sequential methods that create a non-uniform grid requires solving an additional multi-extreme problem at each iteration, which must also be solved using search methods (e.g., the brute force method), which dramatically increases the computational complexity of the iteration.

On the other hand, it is possible to build simple sequential search methods for a multi-extreme problem based either on a given value of a constant or on estimates calculated during the solution process, which create an economical non-uniform grid whose nodes are used for measurements. In this regard, it is worth considering the possibility of reducing multidimensional, multi-extreme problems to some equivalent one-dimensional problems.

It is proved that a targeted search for solutions to multi-extreme problems based on a priori assumptions about the boundedness of differences generally requires more measurements than a local search for solutions to unimodal problems, since in the first case measurements are made at the nodes of a (non-uniform) grid in a multidimensional search area, and in the second case - at nodes located on a certain one-dimensional descent path.

In general, the implementation of mathematical models for the delivery of goods by drones is an effective option for companies seeking to optimize their supply chains and reduce costs. By reducing delivery times, increasing efficiency, and saving costs, drone delivery can help businesses stay competitive in the market. It has been proven that the use of such algorithms increases delivery speed by 20% and reduces operating costs by 15%. Dynamic programming is used to optimize the sequential decision-making process in UAV operations for each stage of the delivery route, taking into account the current state and making decisions that will lead to the best overall result. This approach allows the company to increase throughput by 25% while maintaining an acceptable level of safety.

The developed method for evaluating the UAS efficiency is represented by the category of action during the system's operation at a certain time interval, which reflects the correspondence of the result obtained to the resources invested. The concept of evaluating the effectiveness of UAS is based on taking into account the social, economic and functional types of effect. For example, drones can help reduce carbon dioxide emissions from urban delivery by 40%, reducing dependence on traditional delivery vehicles.

Two approaches to assessing the effectiveness of UAS have been proposed and developed: with implicit and explicit systemic links between the means and a higher-order system. Evaluation of efficiency in the case of implicit links of UAS vehicles is based on the formation of the resulting quality indicator and the reduction of a multicriteria problem to a scalar one. An original algorithm for selecting the priority variant of the means is developed.

The subproblems that arise in the formulation of goals, criteria and performance evaluation with explicit systemic links are systematized. It is proved that evaluating the effectiveness of the UAS system is associated with the problem of performance management, which depends, in turn, on the controllability of situations.

The principles of determining the functional effect in the management of dynamic objects are formulated, based on the modified foundations of the theory of situational analysis of the air situation, which includes:

- principles of situation formation in the ANS;
- construction of a metric as a measure of situations;
- selection of a function that characterizes the danger of flight situations by the relevant coordinates;
- construction of a priori probability densities of the measured parameter;
- construction of a priori probabilities of situations;
- construction of conditional probability densities by zones;
- building a spectrum of situations.

This made it possible to develop and substantiate a generalized criterion for UAS efficiency. For the first time, it is possible to assess the real effectiveness of UAS in the air navigation system of ANO.

The mathematical methods for solving the formulated problems of navigation support for cargo drones are determined. A modification of these methods was created taking into account the specific features of large-dimensional problems with significant nonlinearity of variables and the complex nature of constraints on phase coordinates, and computational algorithms for solving problems were developed:

- calculation of system constraints of the landing system introduced by the aircraft as a controlled dynamic object (search for a global extremum taking into account constraints on variables in the form of equations and inequalities);
- predictive evaluation of a stochastic sequence of results (probabilistic analysis of the sequence tree of the set of flight situation predicates and its evaluation);
- construction of areas of permissible values of navigation support parameters (tracking the boundaries of closed sets by the method of forecast-correction, with correction by the gradient of boundary violation);
- combined study of navigation support characteristics (joint use of the results of analytical solution of simplified navigation problems and modeling based on

simulation modeling);

- programs for quantitative research of navigation support problems were developed.

The need to ensure reliable direct communication between drones flying autonomously to prevent collisions and ensure the interaction of all components of the Integrated Space-Air-Ground Network (ISGN) has been proved. Insufficient data transmission speed in any of the channels can significantly degrade the performance of the entire integrated network.

We modeled an AI artificial intelligence system with a cloud structure and the ability to change the delay and probability of data packet loss, obtained the dependence of losses on the size of messages and data rate, the dependence of the average load for the uplink and the packet transit time on the size of transactions. Parametric dependencies on the average load were constructed, which allow us to make practical recommendations for choosing the necessary data transmission modes in the communication channels of freight UAS and to evaluate the unmanned system as a whole.

All modeling results are supported by graphical and tabular material.

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Appendix

ALGORITHM FOR CALCULATING SYSTEM CONSTRAINTS

Most methods that allow solving multi-extreme problems are associated to some extent with random search [45, 51, 59, 78, 103, 106, 113, 151, 158]. With increased requirements for the extremum estimation algorithm, it is advisable to use random search methods in combination with other machine learning-based methods.

The first task to be solved when developing an algorithm is the formation of a basic ensemble of control realizations randomly distributed in a given region of the admissible set. This problem belongs to the class of random variable modeling problems and is considered in the relevant literature, and, depending on the conditions of the problem, this issue can be solved in different ways:

a) a random point is uniformly distributed in a $\boldsymbol{n}$-dimensional parallelepiped. Then:

$$F(x_1, x_2, \dots, x_n) = F(x_1) \cdot F(x_2) \cdot, \dots, F(x_n), \qquad (4.1)$$

where $\boldsymbol{F_i(x_1)} -$ distribution function of the coordinate $\boldsymbol{X_1}$.

In this case, each coordinate can be modeled independently and as a result, we get a simple formula for calculating coordinates:

$$x_1 = a_i + \xi_i(b_i - a_i),\ i = 1, n\,, \qquad (4.2)$$

where

$\boldsymbol{a_i}$ and $\boldsymbol{b_i}$ are the coordinates of the vertices of the $\boldsymbol{n}$-dimensional parallelepiped;

$\boldsymbol{\xi_i} -$ independent random numbers;

б) a random point obeys an $\boldsymbol{n}$-dimensional normal law with mathematical expectation:

$$M(x_1) = a_i \qquad (4.3)$$

and other issues:

$$M\big[(x_1 - a_i)\big(x_j - a_j\big)\big] = b_{ij}. \qquad (4.4)$$

In this case, we also get a simple formula for calculating the coordinates:

$$x = A\xi + a, \qquad (4.5)$$

where

ξ – independent random variables in the interval **(0, 1)** that follow the normal law;

A – transformation matrix, which is determined from the condition:

$$AA^T = B, \qquad (4.6)$$

where $B = |b_{ij}|, T$ – transportation index.

The calculation of system constraints imposed by dynamic objects includes the task of determining a random control implementation that satisfies the constraints on the phase coordinates. Finding the optimal control is reduced to determining the coordinates of a random point in an n- dimensional parallelepiped.

The second problem that needs to be solved when developing an algorithm is the choice of a condition for stopping the computational process due to the achievement of a given accuracy of solving the problem or due to the end of available computing resources. The stopping condition can be described by introducing an appropriate sequence of functions Φ_k:

$$f^k = \Phi_k(\omega_k), \quad k = 1, 2, \ldots \qquad (4.7)$$

such that if for some ω_k it is true that $f^k = 0$, then $f^{k+\gamma} = 0, \gamma = 1, 2, \ldots$, regardless of the values of ω_k, i.e. $(x^{k+1}, Z^{k+1}), \ldots, (x^{k+\gamma}, Z^{k+\gamma})$. Here:

$$Z^i = \Phi(x_i) + \varepsilon^i, \quad 1 \le i \le k, \qquad (4.8)$$

where ε^i is the error of the i- th trial.

In this case, the final estimate of the extremum is considered to be the estimate [120] e^T, which corresponds to the stopping step T. Then the ε – optimal solution is obtained:

$$\Phi[x_\varepsilon] \le \inf \Phi[x] + \varepsilon, \qquad (4.9)$$

where $\varepsilon > 0$.

Thus, it is practically necessary to set an acceptable degree of accuracy in terms of the deviation of the value of the functional obtained as a result of solving the problem from the minimum possible value and the number of steps to obtain it.

Let's take the best of the base points as the required solution of $\boldsymbol{\Phi}[\boldsymbol{x}_{\boldsymbol{\varepsilon}}]$ at the moment when, within a given number of iterations, the radius of the set of base points does not exceed a predetermined small value:

$$rad\, H \le \varepsilon,\ x_\varepsilon \in H\,. \qquad (4.10)$$

Now we can fully describe the algorithm for finding the optimal solution to the extreme problem 2.2.

$$Q = \int\limits_{\Omega(\tau)} f(\vec{Z})\ dF(\vec{Z}, \tau). \qquad \mathbf{(2.2)}$$

The task is to find a vector $\boldsymbol{u}^*$ that reports the largest (smallest) value of the functional $\boldsymbol{\Phi}[\boldsymbol{u}, \boldsymbol{x}, \boldsymbol{t}]$:

$$\Phi[u^*] = \sup_{u \in U} \Phi\ [u, x, t]. \qquad (4.11)$$

At the first step, a zero approximation is chosen for the control vector u in such a way that all the constraints imposed on this dynamic system are satisfied. The control function approximation system is chosen and the number of approximation nodes is determined for a given flight interval $\boldsymbol{J}_{\boldsymbol{\tau}} = [\boldsymbol{t}_{\boldsymbol{0}}, \boldsymbol{t}_{\boldsymbol{k}}]$ (the number and coordinates of the nodes can be chosen from the condition of optimal compensation of the approximation error at the ends of the intervals $[\boldsymbol{t}_{\boldsymbol{0}}, \boldsymbol{t}_{\boldsymbol{k}}]$ and in the inter-node subintervals for the expected classes of functions).

Let $\boldsymbol{H}(\boldsymbol{x}, \boldsymbol{t})$ – be the upper bound of the admissible set $\boldsymbol{U}$, abe the lower bound of this set. Then the values of the control function at the approximation nodes to obtain an ensemble of random control realizations of a dynamic system will be determined by the following formula:

$$u_{ij} = G(x_i, t_i) + \xi_{ij}[H(x_i, t_i) - G(x_i, t_i)], \qquad (4.12)$$

where

$\boldsymbol{i} = \overline{\boldsymbol{1}, \boldsymbol{L}}$ – index of the approximation node;

$\boldsymbol{j} = \boldsymbol{1}, \boldsymbol{k} - \boldsymbol{1}$ – index of the realization from the ensemble of basic controls;

$\boldsymbol{\xi}_{\boldsymbol{ij}}$ – random numbers $\boldsymbol{\xi}_{\boldsymbol{ij}} \in \boldsymbol{I} = [\boldsymbol{0}, \boldsymbol{1}]$.

For each realization from the ensemble of basic controls $\boldsymbol{u}_{\boldsymbol{i}} \in \{\boldsymbol{u}\}, \boldsymbol{i} = \overline{\boldsymbol{1}, \boldsymbol{k}}$, the value of the functional $\boldsymbol{\Phi}_{\boldsymbol{i}} \in \{\boldsymbol{\Phi}\}, \boldsymbol{i} = \overline{\boldsymbol{1}, \boldsymbol{k}}$ is calculated. At the same time, the constraints imposed on the phase variables $(\boldsymbol{x} \in \boldsymbol{X})$, as well as implicit type constraints, are checked.

If implicit constraints are violated for some realization $\boldsymbol{u_j}$, then a correction of this control is introduced. The new control $\boldsymbol{u_j^*}$ is obtained as follows.

1. First of all, the reflection is performed [151], which results in the vertex of the polyhedron:

$$\vec{u}^* = (1 + \eta_1)A - \eta_1\vec{u}_r\,, \qquad (4.13)$$

where

$\boldsymbol{A}$ – the coordinate matrix of the center of the simplex excluding the worst vertex;

$\vec{\boldsymbol{u}}_{\boldsymbol{r}}$ – ontrol, which corresponds to $\boldsymbol{\Phi_r = \max\{\Phi\}}$;

$\boldsymbol{\eta_1}$ – reflection coefficient $(\boldsymbol{\eta = 1})$.

If, as a result of reflection, $\boldsymbol{\Phi[u_1] < \Phi[u^*] < \Phi < \Phi[u_r]}$, then $\boldsymbol{u_r}$ is changed to $\boldsymbol{u^*}$. The resulting new simplex is used as the initial one for the first stage.

If $\boldsymbol{\Phi[u^*] < \Phi[u_1]}$, the stretching takes place, transforming the vector $\boldsymbol{u^*}$ to $\boldsymbol{\widetilde{u}^*}$ за using the ratio:

$$\tilde{u}^* = \eta_2 u^* + (1 - \eta_2)A, \qquad (4.14)$$

where $\boldsymbol{\eta_2}$ – the stretching factor $(\boldsymbol{\eta_2 = 2})$.

If $\boldsymbol{\Phi[u^*] > \Phi_i}$, $\forall_i \neq \boldsymbol{r}$, i.e. $\boldsymbol{u^*}$ corresponds to the point that provides the maximum of $\boldsymbol{\Phi}$, then a new vector u_r is determined, which is equal to the previous vector $\boldsymbol{u_r}$ or equal to the control $\boldsymbol{u^*}$, which provides a smaller value of the functional $\boldsymbol{\Phi}$. Then, compression is performed, transforming the vector $\boldsymbol{u}$ into $\boldsymbol{\widetilde{u}^*}$ according to the formula:

$$\tilde{u}^* = \eta_3 u + (1 - \eta_3)A, \qquad (4.15)$$

where $\boldsymbol{\eta_3}$ – compression ratio, $\boldsymbol{0 \leq \eta_3 \leq 1}$, $(\boldsymbol{\eta_3 = 0,5})$.

The vector $\boldsymbol{u}$ is changed to $\boldsymbol{\widetilde{u}^*}$ and the first stage is repeated, provided that the vertex of the compression does not lead to a worse result than $\boldsymbol{\max\{\Phi[u], \Phi[u^*]\}}$, i.e., if $\boldsymbol{\Phi[\widetilde{u}^*] > min\{\Phi[u], \Phi[u^*]\}}$. In the latter case, all vectors $\boldsymbol{u_i}$ are changed by $\frac{u_i + u_l}{2}$ i and returned to the first stage.

In this case, it corresponds to the $\boldsymbol{u_l}$:

$$\Phi[u_l] = min\{\Phi[u_i]\}. \qquad (4.16)$$

If an extreme value of the functional $\boldsymbol{\Phi}[\boldsymbol{u}^*]$ exists, then the algorithm ensures that the condition is met:

$$|\max\{\Phi[x_j]\} - \min\{\Phi[x_i]\}| \leq \varepsilon; \;\; i,j = \overline{1,k}, \qquad (4.17)$$

where $\boldsymbol{\varepsilon} -$ a small value that defines the accuracy of the solution. The counting process stops if the inequality (4.17) is true for several iterations.

Based on the proposed algorithm, a program for calculating system constraints, which are determined using the dynamic characteristics of the aircraft as a controlled object, was developed.

The implementation of the considered algorithm allows us to construct the domain $\boldsymbol{D_\tau}$, which is used below to predict the sequence of event outcomes in the control system of such dynamic objects as UAVs.

Appendix

LIST OF THE PHD STUDENT PUBLICATIONS

1. Li Haoyang. Classifications of unmanned aerial systems adopted in international organizations. *«XV International Scientific and Technical Conference "AVIA-2021" » of the National Aviation University.* April 20 - 22, 2021, pp. 6.65 - 6.71.

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