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Факультет систем управління літальними апаратами

Кафедра систем управління літальних апаратів

# Пояснювальна записка

до дипломної роботи
____________магістра____________
(освітньо-кваліфікаційний рівень)

на тему: «Розробка системи управління БПЛА та її дослідження в режимі виходу на заданий маршрут»
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Виконав: студент 6 курсу, групи 3-96ав(і)
зі спеціальності
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Освітня програма «Системи автономної навігаціїї та адаптивного управління ЛА»

_Орхан Ібрахімлі
(прізвище та ініціали)

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Кафедра Систем управління літальних апаратів

Освітньо-кваліфікаційний рівень магістр

(бакалавр, спеціаліст, магістр)

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(назва)

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Завідувач кафедри
систем управління ЛА
к.т.н.,доцент________К.Ю.Дергачев
"____" _____________2022 року

**З А В Д А Н Н Я**

**НА ВИПУСКНУ РОБОТУ СТУДЕНТУ**

_Орхан Ібрахімлі

(прізвище, ім'я, по батькові)

1. Тема роботи: Розробка системи управління БПЛА та її дослідження в режимі виходу на заданий маршрут
2. керівник роботи: Джулгаков В. Г

(прізвище, ім'я, по батькові, науковий ступінь, вчене звання)

затверджена наказом по університету від «17» __11____2022 р, № _1602 уч._

2. Строк подання студентом роботи: _10 грудня 2022 року

3. Вихідні дані до роботи автоматичний режим роботи, характер використання мікроелектромеханічних вимірювальних пристроїв

4. Зміст розрахунково-пояснювальної записки (перелік питань, які потрібно розробити)

а) аналіз питання моніторингу за допомогою БПЛА;

б) синтез математичних моделей;

в) проектування системи;

г) реалізація системи;

д) експериментально-практична частина.

5. Перелік графічного матеріалу (з точним зазначенням обов'язкових креслень)
___10 плакатів (у формі презентаційних слайдів)

6. Консультанти розділів роботи

| Розділ | Прізвище, ініціали та посада консультанта | Підпис, дата | |
|---|---|---|---|
| | | завдання видав | завдання прийняв |
| Стан проблеми | Джулгаков В. Г. | **22.11.2022** | **29.11.2022** |
| Аналіз і синтез СУ | Джулгаков В. Г. | **22.11.2022** | **29.11.2022** |
| Конструктор. частина | Джулгаков В. Г. | **29.11.2022** | **04.12.2022** |
| Дослідницька частина | Джулгаков В. Г. | **05.12.2022** | **12.12.2022** |
| Експ.-практ. частина | Джулгаков В. Г. | **12.12.2022** | **19.12.2022** |
| Економічне обґрунтування | Попов О.А. | **12.12.2022** | **19.12.2022** |

7. Дата видачі завдання 22.12.2022

**КАЛЕНДАРНИЙ ПЛАН**

| № з/п | Назва етапів випускної роботи | Строк виконання етапів роботи | Примітка |
|---|---|---|---|
| 1. | Формулювання теми проекту. | 16.11.2022 | |
| 2. | Розробка технічного завдання | 20.11.2022 | |
| 3. | Огляд стану проблеми і патентний пошук. Математичний опис системи управління. Аналіз і синтез системи управління | 23.11.2022 | |
| 4. | Конструкторська частина роботи. Дослідницька частина роботи. Економічне обґрунтування розробки. Розробка питань охорони праці і безпеки в надзвичайних ситуаціях | 01.12.2022 | |
| 5. | Експериментально-практична частина | 04.12.2022 | |
| 6. | Оформлення розрахунково-пояснювальної записки і графічного матеріалу. Попередній захист роботи | 10.12.2022 | |
| 7. | Рецензування проекту. Захист проекту в ДЕК | 22.12.2022 | |

**Студент** О.ІБРАХІМЛІ
( підпис ) (прізвище та ініціали)

**Керівник роботи** __Джулгаков В. Г.
( підпис ) (прізвище та ініціали)

Міністерство освіти і науки України
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«Харківський авіаційний інститут»

Кафедра 301

**ЗАТВЕРДЖУЮ**

Завідувач кафедри
систем управління ЛА
к.т.н.,доцент________К.Ю.Дергачев
“____” _____________20__ року

ТЕХНІЧНЕ ЗАВДАННЯ
на дипломне проектування
Орхан Ібрахімлі

1. Тема роботи: Розробка системи управління БПЛА та її дослідження в режимі виходу на заданий маршрут

затверджена наказом по університету від « 17 » 11 2022 р. № 1602 уч.

2. Строк здачі студентом закінченої роботи «_20.12_ » 2022 р.

3. Область застосування розробки: Дослідження системи управління БПЛА при виході на заданий маршрут.

4. Початкові дані для розроблювальної системи

4.1. Призначення і мета створення системи: розробити систему керування безпілотним літальним апаратом призначеним для моніторингу зон підвищеної небезпеки та рекогностування місцевості

4.2 Загальні відомості : проблеми дослідження місцевості при проведенні рекогностування та зон надзвичайних ситуа

5. Технічні вимоги до каналів системи управління

5.1. Питання, що підлягають розробці: розробка системи управління різними режимами польоту БПЛА при виконанні задач моніторингу рекогностування та зон надзвичайних ситуацій___________________________________________

5.2. Режим роботи системи (безперервний, циклічний, одноразової дії): циклічний

5.3. Показники якості системи управління: коливальність ≤ 1.02%, час перехідного процесу – 5с, перерегулювання – ≤5%, запас по амплітуді ≥10dB запас по фазі ≥60 град.

5.4. Вимоги до приладового складу системи: прилади систем керування повинні забезпечити виконання режимів стабілізації положення центра мас у просторі, відповідно до вимог точності кутів крену, тангажу, рискання з точністю не менше ніж 1 градус, кутової швидкості не менше 0.01 градусів і точності стабілізації швидкості лінійного переміщення центра мас не більше ніж 0.3 метра за секунду.

5.5. Вимоги до взаємозамінності блоків: при відказі одного з функціональних блоків що входить до системи керування останній повинен бути заміненим з аналогічними тактико-технічними характеристиками

6. Умови експлуатації системи

6.1. Кліматичні вимоги до експлуатації (температура середовища, у якій буде працювати система управління, її вологість, вміст хімічно активних компонентів і т.ін.):

а) від – 5С до +35С

б) від 5% до 15% вологості

в) всі хімічно активні компоненти повинні бути відсутні

6.2. Механічні вимоги (вібрація, тряска, можливі перекоси, удари, нахили і т.ін.): транспортування БПЛА дозволяється тільки у захисному кейсі

6.3. Наявність перешкод (електричні наведення радіоперешкоди, магнітні впливи): можливі радіоперешкоди

6.4. Електричні параметри системи (напруга джерел живлення, потужність, стабільність, частота): 14В постійної напруги, ємність акумуляторних батареї не менше ніж 5 000 мАг

7. Додаткові функції, реалізовані системою (сигналізація про несправності, реєстрація необхідної інформації, самоконтроль самої системи і т.ін.): наявність самоконтролю функціональних блоків системи керування

8. Обсяг виконуваних розроблювачем робіт

8.1. Етапи проведення роботи: аналіз технічного завдання, постановка задач на розробку системи керування з урахуванням різних режимів польоту, розробка функціональних схем, здобуття математичних моделей окремих функціональних елементів та об’єкту керування, вибір та обгрунтування законів керування БПЛА, проведення моделювання у часовій та частотній областях, аналіз здобутих результатів, синтез корегувального пристрою, розробка спецрозділу системи. Керування на базі ПД регулятора, розробка економічної і конструкторської частин.

8.2 Обсяг розробки по кожному етапу:

1. Стан проблеми та постановка завдання системи моніторингу зон надзвичайної ситуації і рекогностування ( 1 лист)

2. Розробка системи управління квадрокоптера (4 листи)

3. Конструкторська частина (1 лист)

4. Дослідницька частина (1 лист)

5. Експериментально практична частина (2 листи)

6. Економічне обгрунтування розробки (1 лист)

9. Параметри устаткування системи: відеокамера UHD 60 кадрів за секунду, тепловізор, GPS приймач, пульт керування з LCD монітором, комплект запасних акумуляторних батарей

10. Вимоги безпеки: згідно з вимогами нормативно технічної документації.

11. Дослідницька частина: провести дослідження модального регулятора технологій у відповідності до заданих показників якості системи керування БПЛА у відповідності до вимог безвідмовного функціонування.

12. Експериментально-практична частина: розробити методику проведення дослідження системи керування БПЛА на базі модального регулювання.

13. Економічна частина

13.1. Розробити (розрахувати, одержати): оцінити собівартість і ціну обладнання БПЛА, побудувати точку безбитковості.

13.2. Умови і вимоги: розрахунково пояснювальна записка та графічний матеріал повинні відповідати вимогам ЄСКД та вимогам технічного завдання відповідно до вмісту.

13.3. Очікуваний результат: розробити систему автоматичного управління квадрокоптеру для вирішення задач моніторингу зон надзвичайних ситуацій і рекогностування у відповідності до технічного завдання.

14. Перелік графічних матеріалів із зазначенням форматів: 10 листів А1:

1. Стан проблеми та постановка завдання системи моніторингу зон надзвичайної ситуації і рекогностування ( 1 лист)

2. Обґрунтування вибору БПЛА (1 лист)

3. Математична модель БПЛА (1 лист)

4. Лінеризація системи (1 лист)

5. Фільтрація даних МЕМС (1 лист)

6. Модель ПД регулятора та ДПС (1 лист)

7. Аналіз ефективності конструкції квадрокоптера (1лист)

8.Синтез модального регулятора (1 лист)

9. Розробка конструктороської частини (1 лист)
10. Розробка економічної частини (1лист)

Керівник роботи
__________________ Джулгаков В. Г
(П.І.Б.)
___________________________________
« 22 » __11___ 2022 р.

Прийняв до виконання
_________________Орхан Ібрахімлі
(П.І.Б. студента)
___________________________________
« 22 » __11____ 2022 р.

Погоджено з питань: конструкції
__________________ Джулгаков В. Г
(П.І.Б.)
___________________________________
« 29 » 11 2022 р.

дослідницької частини
_______________Джулгаков В. Г
(П.І.Б.)
___________________________________
« 29 » 11 2022 р.

Єкономіки
____________________Попов О.А
(П.І.Б.)
___________________________________
« 29 » 11 2022 р.

# ABSTRACT

108 pages, 60 figures, 17 tables, __ sources, 1 appendices.

The thesis is devoted to the research and synthesis of the control system of an unmanned aerial vehicle, which is used for aerial photography of terrain in conditions of increased danger and in remote places. The work presents a general description of the problem of reconnaissance and monitoring of emergency zones, an analysis and synthesis of the control system is performed. With the help of the calculated system, the control of the unmanned aerial vehicle was performed according to the technical task.

In the design part of the work, the choice of the equipment of the unmanned aerial vehicle - the flight controller, direct current motors, attachment equipment for the unmanned aerial vehicle, and other parts of the general system of the unmanned aerial vehicle - is substantiated.

In the research part, a synthesis of modal control was carried out and research results were obtained, a controller algorithm was developed for a computer model made in the Matlab/Simulink environment.

The experimental part displays the developed UAV control system in the Matlab/Simulink software environment, as well as an analysis of the system's efficiency using the eCalc environment.

In the economic part, the cost and price of the equipment were calculated, the break-even point graph was drawn, and the profitability of the development was investigated.

UNMANNED AIRCRAFT, RECONNAISSANCE, AUTOMATIC CONTROL SYSTEM, MODAL REGULATION.


## LIST OF TERMS AND ABBREVIATIONS

UAV - unmanned aerial vehicle;

LA - aircraft;

SU - management system;

DPS DC motor;

PID - proportional integral - differential (regulator);

PD - flagging and differential (regulator);

OU - object of management;

FPV (English First Person View) - view from the first person;

OSD - (English On Screen Display) - a module for superimposing information on the image;

ECS - (eng.Electronic Controller Speed) – engine speed controller;

IMU - (English Inertial Measurement Unit) - inertial measuring unit;

LC – flight controller;

AKB - rechargeable battery;

OZP - total salary;

DZP - additional salary.

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## INTRODUCTION

Man's desire to soar into the sky, resembling a bird, forced him to learn and expand a whole complex of aviation sciences. Starting from simple gliders that allowed a person to hang in the air for some time, ending with complex systems of huge space aircraft or, conversely, small drones, we see how far engineering thought and creative impulse can go.

Unmanned aerial vehicles (UAVs), which are controlled without the participation of a pilot on board, deserve special attention. There are two types of such devices: remotely piloted UAVs and automatic UAVs that are programmed for a specific flight route.

One of the most important advantages of drones is the preservation of the lives of the flight crew. In addition, they have such positive qualities as compactness, efficiency, low cost, low operating costs, and in some cases have a long flight range and the possibility of multi-purpose use.

According to the textbook [3], the development of modern technologies in the field of aerodynamics, electronics, computer technologies, achievements in the field of satellite navigation systems, allowed to reach a qualitatively new level in the creation of unmanned aerial systems (UAS). Unmanned aerial vehicles as part of UAS have already found their place in modern activity. Among the priority directions are defense and rescue operations, law enforcement and environmental protection activities, scientific research and environmental monitoring. The development of the Arctic, work on environmental protection is becoming more and more relevant.

Unmanned flying robots enter emergency nuclear reactors, climb into the upper atmosphere, descend into volcano vents, effectively patrol land and sea borders. In other words, the development of technologies, new opportunities in the field of security allow people to increasingly actively send unmanned work devices instead of themselves to hard-to-reach places.

The aim of the thesis is research and development of the UAV control system when entering a given route. As a simulated situation, a UAV is considered to be dropped from a carrier aircraft and fly along a given trajectory to solve the problems of emergency zone monitoring and terrain reconnaissance.

The paper argues for the choice of a rotor-wing four-rotor type UAV - a quadrocopter to solve the given problem. The synthesis of the control system and selected attachment equipment for the aircraft was carried out. The design efficiency and economic efficiency of the developed system were also investigated.

# 1. ANALYSIS OF THE SPHERE OF USE OF UNMANNED AIRCRAFT

## 1.1. Use of unmanned aerial vehicles for civil purposes.

The use of UAVs in the civil sector is currently awaiting the resolution of some technical and organizational issues. These are primarily administrative problems of the integration of unmanned aerial vehicles into the national and international airspace, the allocation of a frequency range for the control of UAVs and the transmission of information from the board to the ground and vice versa. In addition, it is necessary to obtain the status of an aircraft (aircraft) by unmanned aerial vehicles, because they are not subject to registration in the aircraft register and do not have a certificate of registration and suitability for use, according to the classification, they are a radio-controlled model [10].

In public use, UAVs primarily have control functions. With the help of unmanned systems, it is possible to control both the technical condition of objects, as well as their safety and functioning, while the controlled objects can be at a great distance and have a long length. For example, monitoring of gas and oil pipelines, traffic control, investigation of damage in power transmission lines. The field of potential application of UAVs is quite large, which makes it possible to use them also during environmental research (pollution monitoring, weather observation and solving scientific problems), forest fire monitoring, ensuring national security, border patrols, preventing the importation of drugs, aerial reconnaissance and mapping , precision farming, disaster relief,

Commercial use of unmanned aerial vehicles (UAVs) is not yet well developed, although it is rapidly gaining momentum. The development of the civil service market is in its infancy. Among such services are

delivery of goods, photo-video recording for mass media, advertising and even Internet broadcasting.

In order to ensure the necessary level of solving many of the above-mentioned tasks, it is necessary to increase the reliability of unmanned aircraft systems (UAVs), further develop the potential of UAVs, increase the ease of operation and reduce the cost of such systems.

Below are some types of UAVs used in the public sphere.


Figure 1.1 - Yamaha RMAX UAV - for field spraying.


Fig. 1. 2 - Lancaster UAV – for scientific research work.

## 1.2. Use of unmanned aerial vehicles during military operations.

UAVs used for military purposes deserve special attention. It was military clashes that prompted the creation of an unmanned aerial vehicle that would save the pilot's life.

Around the world, unmanned aerial vehicles (UAVs) are playing an increasingly important role in defense programs and defense strategy. As recent military conflicts have shown, there are many military applications for unmanned aerial vehicles, including terrain reconnaissance, surveillance, battle damage assessment, communications relaying, urban operations and other special operations support, as well as convoy support and unit protection .

The methods of using UAVs and their effectiveness in carrying out military operations largely depend on the conditions associated with the technical potential implementation of the considered solutions and the emergence of new, more accessible technologies. In addition, the ratio of the cost of the device to its efficiency and the problem of training time for operators controlling UAVs remain relevant.

Drawing. 1.3 - UAV Orbiter - for conducting military intelligence. It is equipped with a silent electric motor, electro-optical and infrared cameras, means of communication and data exchange.

In the case of using this monitoring method during military reconnaissance, it is necessary to assess the expediency of the operation. Below is a table for evaluation.

Table 1.1. Factors affecting the expediency of using UAVs for the logistical support of troops.

Thus, the further implementation of unmanned aerial vehicles will significantly contribute to the filling of information gaps regarding the dynamics of emergency situations and data for engineering-geological and military reconnaissance. This method of using unmanned aerial vehicles can be quite effective and timely for the introduction of the necessary forces and means. At the same time, in combination with data obtained from other space-based, land-based or surface-based technical means, the

| | Factors | Use is appropriate | Use is inappropriate |
|---|---|---|---|
| 1 | The cost of LA | Miniature UAVs of the Scan Eagle type and smaller | Large UAVs of the Predator type, capable of carrying missiles |
| 2 | Location, character performed operation | Difficult, mountainous terrain, line-of-sight operations, large-scale operations where the use of fixed surveillance cameras is not possible | Open, lightly cut area, small scale of the operation |
| 3 | Technical and tactical arsenal of the enemy | Mass accumulations of manpower, holding positions | Short sorties, small accumulations of manpower, refusal to hold positions |
| 4 | The amount of damage that can be avoided in the case of the use of UAVs | Significant damage due to enemy actions | Accidental damage due to enemy actions |
| 5 | Weather conditions | Conditions conducive to the flight of UAVs and the normal operation of sensors | Conditions that prevent the flight of the UAV and / or the normal operation of the sensors |
| 6 | Bandwidth of communication channels | Low bandwidth makes better point-to-point connection of UAV operators | excess bandwidth is sufficient to support robust communication networks |

real picture of future events, as well as the nature and pace of their development, can be presented in detail.

# 2. UAV SYSTEM DEVELOPMENT

## 2.1. Selection and justification of the type of UAV to solve the given task

Based on the importance of the use of drones in various spheres of life, the thesis proposes the consideration of monitoring large areas with the help of UAVs. These can be large-scale emergencies, such as forest fires, massive floods, snow avalanches, etc.; search operations conducted in large and remote areas, or engineering-geological and military reconnaissance. For such tasks, several aircraft units are often used, which has high economic costs and is a threat to the health and life of several crew members at once. Therefore, it is advisable to use robotic systems that are able to transmit information about their condition to the relevant management bodies in real time for taking prompt and adequate measures.

One of the innovative methods of launching a UAV is to launch a drone from a carrier patch. For fairly remote areas, it is suggested to use one carrier plane or helicopter, which would be able to transport several UAVs to drop them in the necessary places, for the purpose of monitoring.

The use of this technique has the following advantages:

- Cost-effectiveness of large-scale operations;
- Possibility of simultaneous inspection of a large area;
- Monitoring of remote areas;
- Development of an alternative method of launching a UAV and its use in various areas of science and military technology.

To solve the monitoring tasks, it is necessary to choose the appropriate type of UAV. The selection will be based on four main features: aircraft type, engine type, compactness for transportation and the possibility of installing special equipment.

There are three main types of drones:

1. aircraft type (fixed wing);
2. rotor type;
3. convertibles

They are classified according to the type of design, depending on the elements and their number, which determine the method of flight of the device. The last type of UAV is more difficult to operate, control and has a higher cost, so we exclude it from the selection.

An aircraft-type UAV creates lift thanks to the wing surface itself. This type of device has the characteristics of a glider and is more resistant to piloting errors or technical malfunctions.

It has the following advantages compared to a rotorcraft UAV:

- more payload;
- range and flight time.

Disadvantages:

- little maneuverability;
- lack of vertical take-off and landing;
- impossibility of long-term monitoring in one stream.

Rotor-type UAV - flight is carried out due to the lifting force created by the propellers. This type of drone can have several main rotors and is called a multicopter, which makes it more stable and more controllable. Multicopters have the following most popular configurations:

- 3 screws - tricopter;
- 4 screws - quadcopter;
- 6 screws - hexacopter;
- 8 screws - octocopter.

Compared to aircraft-type UAVs, it has the following advantages:

- wide maneuvering range;
- presence of vertical take-off and landing;
- great stability during photo-video fixation.

Disadvantages:

- relatively short range and flight time.

According to the type of engine, UAVs are: electric or internal combustion piston engines (ICE).

Electric engines have the following advantages in contrast to internal combustion engines:

- low noise level;
- ease of maintenance and ease of management;
- relatively low weight.

Disadvantages:

- low battery capacity, as a result - short flight range.

Equally important when choosing a UAV for monitoring tasks is the ability to install photo-video equipment, thermal imagers, and a GPS receiver. Therefore, the selected aircraft must have a payload for transporting equipment.

The tasks of monitoring emergency zones and reconnaissance require the possibility of long-term hovering from the UAV for spot observation of the necessary areas. If necessary, the drone must quickly change its flight path and have great maneuverability. Since it is necessary to transport this type of UAV by helicopter or airplane, the drone must be compact and light. Mini UAV engines are more often used electric type. In addition, the electric motor does not have a thermal trace, which makes the aircraft invisible to the means of thermal guidance, in case of its use during military reconnaissance.

Having evaluated all the advantages and disadvantages, the cost and compactness of the existing types of UAVs, a four-rotor rotor type - a quadrocopter - was chosen.

A quadrocopter is an unmanned flying machine designed according to the rotorcraft scheme. The lift of this device is created with the help of four motors with propellers located at the ends of the cross-shaped frame. The frame can be made of both metal and polymer materials, which simplifies and lowers their production. Motors are rigidly fixed.A microcontroller control system is used. The controller (on-board computer), power supplies, navigation devices, sensors and other peripheral devices are located, if possible, in the center of the frame. The quadcopter has 6 degrees of freedom. Control is carried out using a remote control, where the operator sets the orientation of the quadcopter and its height, or by indicating the route using a GPS receiver. Options for independent operation are also possible, for example, based on video data from the on-board camera. Payload usually reaches 5 kilograms.


Drawing. 2.1. The appearance of some quadcopter.

## 2.2. Analytical modeling of the flight trajectory.

Analyzing the review of patents and literature in the first chapter of the thesis, it can be seen that the problem of launching unmanned aerial vehicles from a carrier aircraft is quite relevant and has been considered for a long time. Inventions can be used for military intelligence, various combat tasks, aerial photography and terrain mapping, targeted delivery of small cargo to hard-to-reach areas, search and other military and civilian tasks. An acute issue is the return of expensive aircraft to a neutral landing place, which is not always possible, for example, due to the topography of the area or due to the tactical situation.

The system for returning the UAV to the aircraft or to neutral territory requires extensive consideration, but is not the main task. The aim of the thesis is research and development of a UAV stabilization system when entering a given route after diving from a carrier aircraft or helicopter. However, the general concepts of this issue are proposed to be solved in the following way: dropping one or more UAVs in the necessary monitoring zone, barrage it for the maximum possible time in the reconnaissance territory, and return the drone to a neutral territory, where the gathering group or the the helicopter itself - the carrier will be able to pick it up.

The analysis of the flight path according to the monitoring task can be imagined as follows:

Figure 2.2. - The flight path of the drone after being dropped from the aircraft - the carrier

Of course, such an approach to solving a flight mission must meet the following criteria:

- the possibility of technological application
- expediency of use and scale of the operation.
- the possibility of returning the UAV "home"
- damage analysis in case of drone loss

## 2.3. System of automatic control of UAV flight height.

The consideration of vertical movement is based on a patent for a useful model []. When the carrier aircraft reaches the required territory, all systems of the quadcopter are reset.

The moment of separation of the quadcopter from the carrier aircraft is characterized by point 1, which corresponds to the height H1. Before separating the quadcopter on its board, the time relay is activated. This is necessary so that according to the formula

$$H_2 = \frac{gt^2}{2}, \tag{2.1}$$

determine the quadcopter's achievement of point 2 of the diving trajectory, where t is the specified time to reach the height.

Point 2 (H2) is the height at which the stabilization system is activated.

In the mode of diving from a heightH1 to height H2 UAV movement is described as follows:

$$m\alpha = F + G - X_{on} \tag{2.2}$$

where$\alpha$– vertical acceleration,

F is the thrust of the engine,

$G = mg$ - the force of gravity,

$X_{on}$ - frontal drag force.

To use the formula (2.1) with high accuracy, it is necessary that the condition is fulfilled

$$m\alpha = mg \quad (2.3)$$

$$\text{i.e}\alpha = g \quad (2.4)$$

As can be seen from the expression (2.2), this condition can be fulfilled if

$$F=Xon \quad (2.5)$$

which corresponds to the need to compensate for resistance forces that act in the form of air impact on the drone body, due to the production of thrust F by the engines.

Since the accelerometer of linear accelerations does not measure the acceleration of free fall - g. Thus, the violation of condition (2.4) means the presence of uncompensated resistance forces $X_{on}$ and the presence of the output signal of the first linear acceleration accelerometer A1. At the same time, a signal is taken from the first linear acceleration accelerometer A1 and fed to the input of the thrust control system of the UAV engines.

The roll channel control signal is formed on the basis of the output signals of the roll angle sensor and the roll angular speed sensor:

$$F\gamma = K\gamma(\gamma - \gamma_{ass}) + K\dot{\gamma} \cdot \Delta\dot{\gamma} \quad (2.6)$$

where $K\gamma$, $K\dot{\gamma}$– conversion coefficients;

$F\gamma$– the total thrust of the engines for roll control.

$\gamma, \gamma_{зад}$– respectively, the signal from the roll angle sensor and the signal of the set value of the roll angle;

$\dot{\gamma}$– the output signal of the roll angular velocity sensor.

The pitch channel control signal is formed similarly, since the design of the quadcopter is symmetrical.

The control signal of the yaw channel is formed on the basis of the output signals of the yaw angle sensor and the yaw angular velocity sensor:

$$F\psi = K\psi (\psi - \psi_{ass}) + K\psi'\dot{\psi}, \quad (2.7)$$

where $K\psi$, $K\psi'$ are conversion coefficients;

$F\gamma$– angle of deviation of the rudder direction;

$\psi, \psi_{зад}$– respectively, the signal from the yaw angle sensor and the signal of the specified value of the yaw angle;

$\dot{\psi}$– the output signal of the yaw angular velocity sensor.

Since the chosen UAV is a quadcopter, it has advantages in comparison with the shape of a glider, such that the flight between points 3 and 4 is characterized by the curvature of the turn with a radius of r, the angular velocity of the turn by the pitch angle $\omega_P$ for a glider. This causes such UAVs to be overloaded along the normal (OY) and longitudinal (OX) axes.

In order to avoid unacceptable overloads, it is necessary that the condition is fulfilled

$$\omega_P \leq \omega_{Z\ \partial on},$$

where $\omega_{Z\ \partial on}$ is the permissible value of the angular speed of reversal relative to the OZ axis.

Therefore, multirotors have another advantage.

Thanks to the functioning of all channels (yaw, pitch and roll) when performing a dive mode from the height of leaving the carrier aircraft to the height of the start of stabilization, the accuracy of determining the location of the quadcopter in space increases, since its position can be affected by wind disturbances and changes in air density. In addition, the presence of sensors of permissible overloads relative to the longitudinal and transverse axes protects the UAV body when performing a dive mode and entering a given route at a given height.

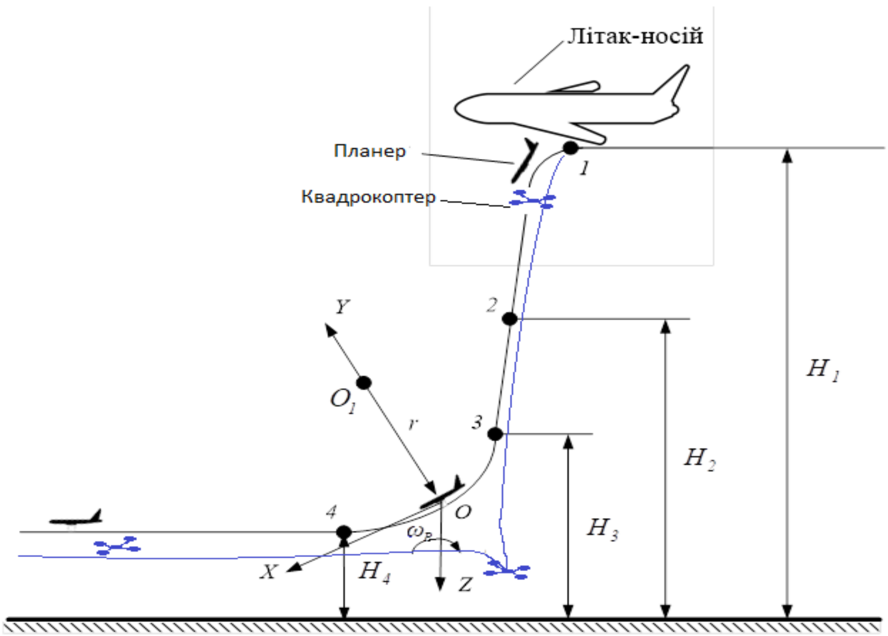



Figure 2.3. – A comparative flight diagram of a quadcopter and a glider from a carrier aircraft.

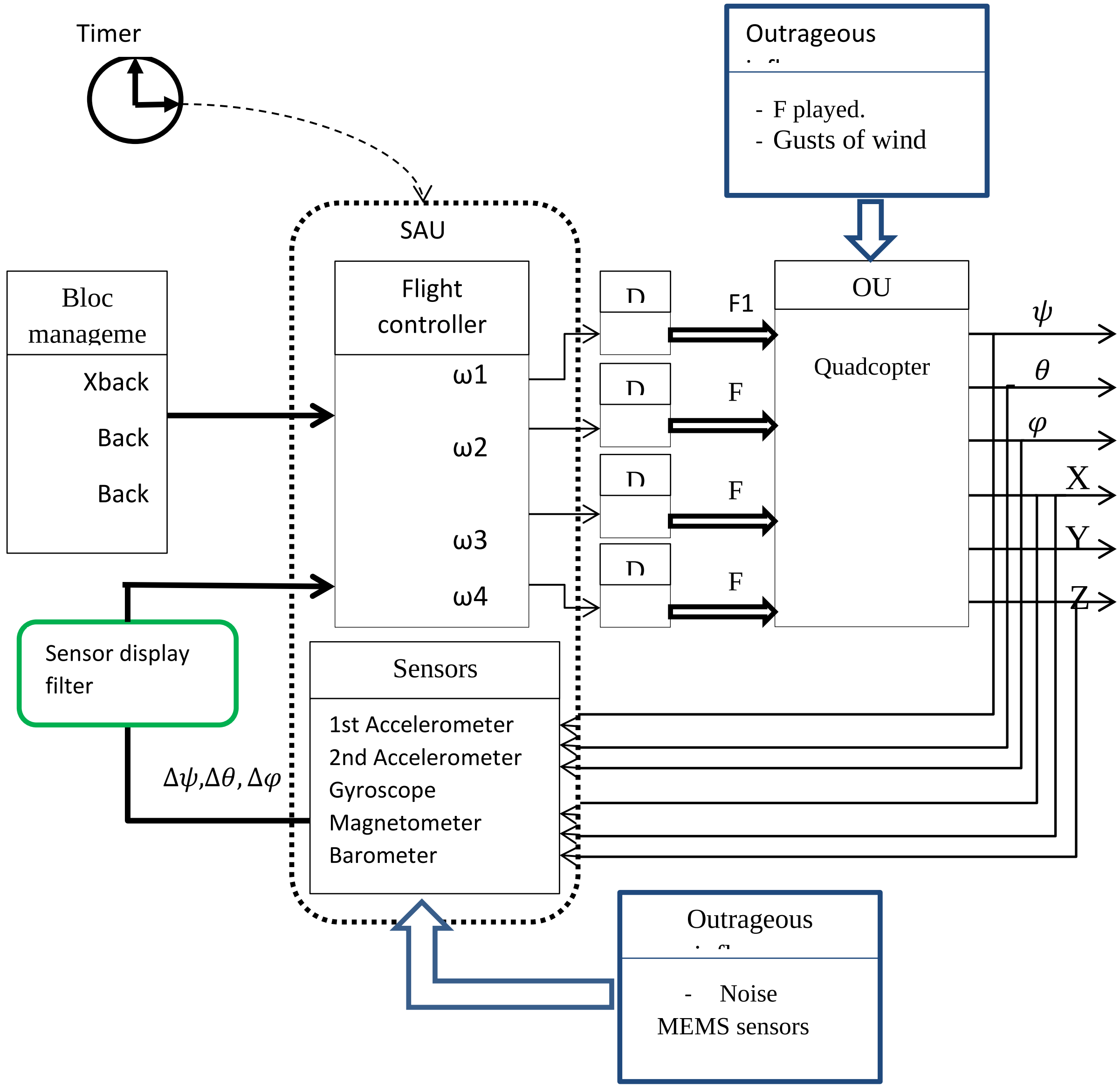
## 2.4. Functional diagram of the quadcopter.

Automatic control systems (ACS) are designed to automatically change one or more parameters of the control object in order to establish the necessary mode of its operation. Automatic control systems ensure the stability of set values of regulated parameters or their change according to a set law, and also optimize certain criteria of control quality. Such a system includes a quadcopter flight stabilization system. Regarding the theory of automatic control (ATC), a functional diagram of the quadcopter was created, which is given below:

Figure 2.4. -Functional diagram of the quadrocopter UAV under development.

The control unit is a coordinate setter. Modern quadcopters can fly in several modes. Usually, a radio-controlled drone has 3 flight modes, but there may be more. Including:

1. Manual flight mode (Manual mode). Control of the quadcopter depends on the operator. Control is set from the control panel.



2. Stable flight mode or orientation mode in space (Attitude mode). This mode uses an accelerometer to help stabilize the UAV. Semi-automatic mode.

3. Stabilization using the GPS system. Automatic mode according to the given flight coordinates.

The control effect is given by changing the speed of rotation of the motors. The scheme of movements is presented below:

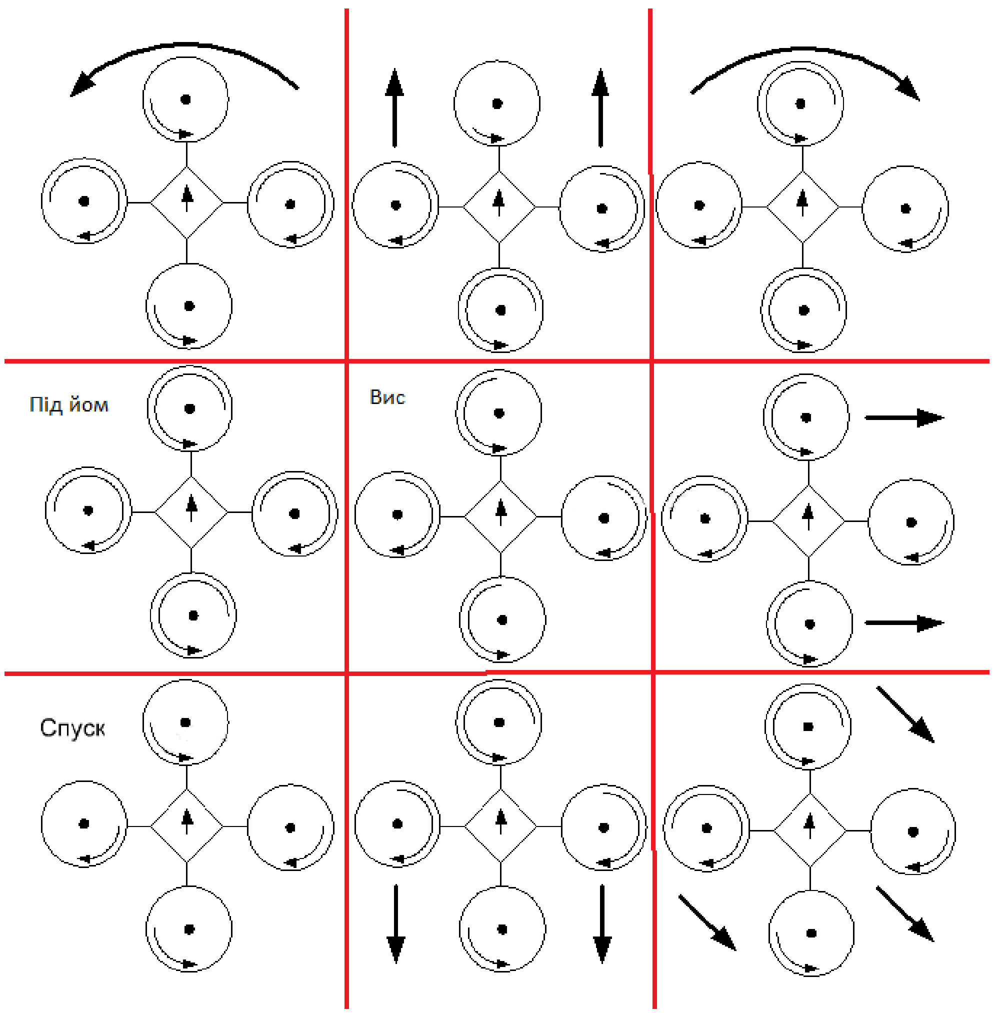



Figure 2.5 - Diagram of quadcopter movements.

The ACS system includes a flight controller based on an STM32 microprocessor (see the design part), and sensors in the feedback channel to ensure flight stabilization. The need to stabilize the flight of the quadcopter follows from the principle of its unstable operation. If the flight stability of a glider or airplane is due to the ability to restore the kinematic parameters of undisturbed motion without the intervention of the pilot and return to the original flight mode after the disturbance has stopped, then the quadcopter does not have such capabilities and at the slightest external influence, an unauthorized descent begins.

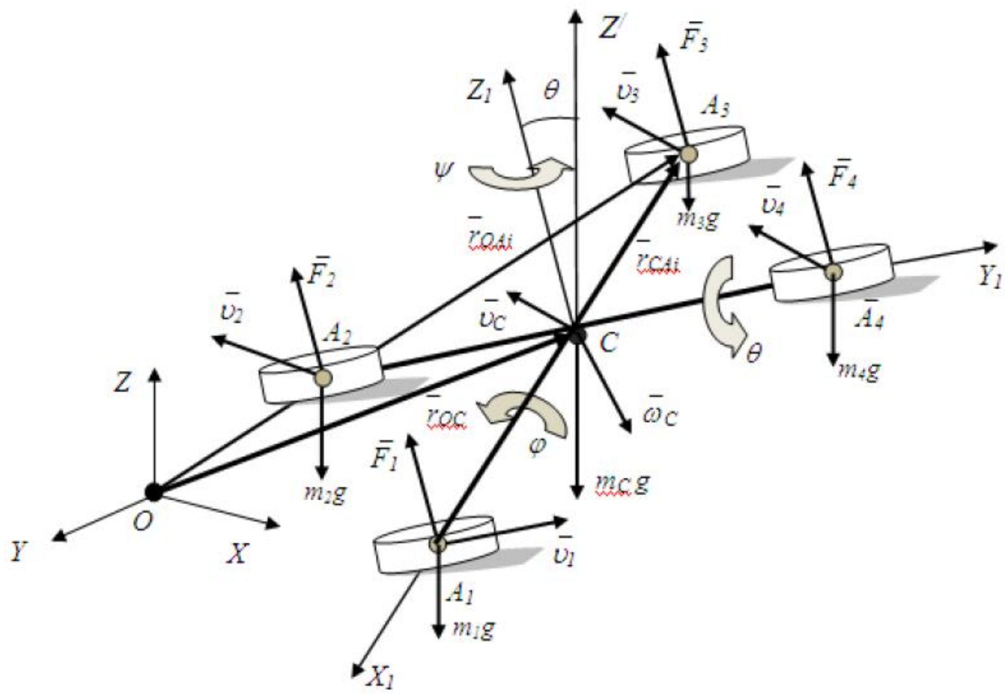
In order to effectively stabilize the quadcopter in flight, it is necessary:

1. Be able to determine the current state of the system.
2. Have the ability to provide controlling influence on the system.
3. Know in what state the system will be maintained.

**2.3. Mathematical model of UAV.**

The mathematical model is used from the source [2]. For this reason, it is necessary to create a theoretical basis that describes the researched object of management and in the future will reduce both the risk of injuries when working with it and the probability of its destruction. One of the most generalized approaches to the theoretical description of a dynamic system is the compilation of a mathematical description of the system. Below is a sequential derivation of a simplified mathematical model of the object for practical work with it.

Let the position of the center of mass of the quadcopter coincide with the beginning of the moving coordinate system CX1Y1Z1, and in the stationary Cartesian coordinate system it is described by the coordinates X, Y, Z (OXYZ system) (Figure 2.6.).




Drawing. 2.6. Calculation diagram of a quadcopter.

Orientation in space is determined by the Euler-Krylov angles, which are usually used in aviation engineering to describe the movement of the aircraft and make up the so-called angles: roll, pitch and yaw. They correspond to the following sequence of turns:

1. Turn the corner$\psi$relative to the vertical axis OZ (R z,$\psi$) - yawning.
2. Turn the corner$\theta$relative to the main transverse axis of inertia OY (R y, $\theta$) is pitch.
3. Turn the corner$\varphi$around the longitudinal axis OX (R x, $\varphi$) is a roll.

When the quadcopter flies, it is affected by the aerodynamic forces of the main rotors$\bar{F}_1$,$\bar{F}_2$,$\bar{F}_3$,$\bar{F}_4$, applied to their centers of mass of the rotors A1, A2, A3, A4, respectively, and the gravity forces of the body mCg and screws mig (Fig. 2.6.), and the forces$\bar{F}_i$, parallel to the CZ1 axis. The position of the center of mass of the quadcopter is determined by the coordinates of the vector rOS = [X, Y, Z]T. In the future, we will agree to understand the OXYZ and CX1Y1Z1 coordinate systems under the symbols (0) and (1), respectively. Then the force vectors:

$$\vec{F}_{\text{and }(0)}=T10\cdot \vec{F}_{i(1)} \quad (2.8)$$

$$T10= (\psi, \theta, \varphi)= R(z,\psi) \times R(y, \theta) \times R(x, \varphi)=$$

$$= \begin{bmatrix} \cos\psi\cos\theta & \cos\psi\sin\varphi\sin\theta - \cos\varphi\sin\psi & \sin\psi\sin\varphi + \cos\psi\cos\varphi\sin\theta \\ \sin\psi\cos\theta & \cos\psi\cos\varphi + \sin\psi\sin\varphi\sin\theta & \cos\varphi\sin\psi\sin\theta - \cos\psi\sin\varphi \\ -\sin\theta & \cos\theta\sin\varphi & \cos\varphi\cos\theta \end{bmatrix}$$

Let's write down the obvious equality:

$$r_{OAi}^{(0)} = \overline{r_{OC}^{(0)}} + \overline{r_{CAi}^{(0)}} \quad (2.9)$$

where

$$\overline{r_{CAi}^{(0)}} = T10 \cdot \overline{r_{CAi}^{(1)}}$$

Vectors $r_{CAi}^{(1)}$ for points Ai have the form:

$$\overline{r_{CA1}^{(1)}} = \begin{bmatrix} l \\ 0 \\ 0 \end{bmatrix}; \overline{r_{CA2}^{(1)}} = \begin{bmatrix} 0 \\ -l \\ 0 \end{bmatrix}; \overline{r_{CA3}^{(1)}} = \begin{bmatrix} -l \\ 0 \\ 0 \end{bmatrix}; \overline{r_{CA4}^{(1)}} = \begin{bmatrix} 0 \\ l \\ 0 \end{bmatrix}.$$

where l is the distance from the center of mass of the quadcopter C to the center of mass of the rotors Ai.

We determine the velocities of points Ai by differentiating equality (2.9) in time:

$$\bar{\upsilon}A_i = \frac{\overline{r_{OAi}^{(0)}}}{dt} = \frac{\overline{r_{OCi}^{(0)}}}{dt} + \frac{\overline{r_{CAi}^{(0)}}}{dt}$$

Taking equality into account, we get:

$$\bar{\upsilon}A_i = \bar{\upsilon}c + \dot{T}_{10} \cdot \overline{r_{CAi}^{(1)}}$$

where $\bar{\upsilon}c = \bar{\iota}\dot{X} + \bar{\jmath}\dot{Y} + \bar{k}\dot{Z}$ - speed of the center of mass of the quadcopter.

The amount of movement and mass is determined by the formula:

$$\bar{q}_i = \text{mi}\,\bar{\upsilon}A_i = \text{mi}\,(\bar{\upsilon}c + \dot{T}_{10} \cdot \overline{r_{CA1}^{(1)}}) \quad (2.10)$$

We determine the change in the amount of movement from the expression:

$$\frac{d\bar{q}_i}{dt} = \text{mi}\,(\frac{d\bar{\upsilon}c}{dt} + \ddot{T}_{10} \cdot \overline{r_{CAi}^{(1)}}) = T10\bar{F}_{i(1)} \quad (2.11)$$

The vector of the amount of movement of the considered system, which consists of a body and 4 screws, is determined by the formula:

$$\bar{Q} = m_c\bar{v}c+\sum_{i=1}^{4} m_{Ai}\bar{v}_{Ai} \quad (2.12)$$

The theorem on the change in the amount of movement of a mechanical system in differential form has the following form:

$$\frac{d\bar{Q}}{dt}=m_c\frac{d\bar{v}c}{dt}+\sum m_i\left(\frac{d\bar{v}c}{dt}+\ddot{T}_{10}\cdot \overline{r_{CAi}^{(1)}}\right) =(m_c+\sum m_i)\frac{d\bar{v}c}{dt}+\ddot{T}_{10}\sum m_i\overline{r_{CAi}^{(1)}} = T10\bar{F}_{i(1)} \quad (2.13)$$

In the projections onto the coordinate axes, equation (2.13) will take the form:

$$\begin{cases}(m_C+\sum m_i)\dfrac{d\bar{\upsilon}_C^X}{dt}=\sum F_{ix}^{(0)}\\(m_C+\sum m_i)\dfrac{d\bar{\upsilon}_C^Y}{dt}=\sum F_{iy}^{(0)}\\(m_C+\sum m_i)\dfrac{d\bar{\upsilon}_C^Z}{dt}=\sum F_{iz}^{(0)}\end{cases}$$

Here

$$\sum\overline{F_i}^{(0)}=T_{10}\sum\overline{F_i}^{(1)}=\left|T_{10}\right|\begin{vmatrix}\sum F_{ix}^{(1)}\\\sum F_{iy}^{(1)}\\\sum F_{iz}^{(1)}\end{vmatrix}=\begin{vmatrix}(\sin\psi\sin\varphi+\cos\psi\cos\varphi\sin\theta)\cdot\sum F_i\\(\cos\varphi\sin\psi\sin\theta-\cos\psi\sin)\cdot\sum F_i\\\cos\varphi\cos\theta\cdot\sum F_i\end{vmatrix} \quad (2.14)$$

where

$$\bar{F}_{1(0)}=\begin{bmatrix}0\\0\\\bar{F}1\end{bmatrix},\quad \bar{F}_{2(0)}=\begin{bmatrix}0\\0\\\bar{F}2\end{bmatrix}, \bar{F}_{3(0)}=\begin{bmatrix}0\\0\\\bar{F}3\end{bmatrix}, \bar{F}_{4(0)}=\begin{bmatrix}0\\0\\\bar{F}4\end{bmatrix}, \quad (2.15)$$

$$\sum\bar{F}i^{(1)}=\begin{bmatrix}0\\0\\\bar{F}1+\bar{F}2+\bar{F}3+\bar{F}4\end{bmatrix}=\begin{bmatrix}0\\0\\\sum_{i=1}^{4}Fi\end{bmatrix}$$

Then equation (2.14) taking into account (2.15) will have the form:

$$\begin{cases} (m_C + \sum m_i)\dfrac{d\upsilon_C^X}{dt} = (\sin\psi\sin\varphi + \cos\psi\cos\varphi\sin\theta)\cdot\sum F_i \\ (m_C + \sum m_i)\dfrac{d\upsilon_C^Y}{dt} = (\cos\varphi\sin\psi\sin\theta - \cos\psi\sin)\cdot\sum F_i \\ (m_C + \sum m_i)\dfrac{d\upsilon_C^Z}{dt} = \cos\varphi\cos\theta\cdot\sum F_i \end{cases}$$

$$\begin{cases} m\ddot{X} = (\sin\psi\sin\varphi + \cos\psi\cos\varphi\sin\theta)\cdot\sum F_i \\ m\ddot{Y} = (\cos\varphi\sin\psi\sin\theta - \cos\psi\sin)\cdot\sum F_i \\ m\ddot{Z} = \cos\varphi\cos\theta\cdot\sum F_i \end{cases} \qquad (2.16)$$

The presented system of differential equations describes the change in the generalized X, Y, Z coordinates of the quadcopter.

This system must be supplemented with the force of aerodynamic resistance.

$$\text{Ax}=\text{Cx}\frac{pv^2}{2}S.$$

where Cx is the coefficient of aerodynamic force, p is air density, kg/m3; v - velocity of the oncoming air flow, m/s; S is the surface area of the apparatus on which the oncoming flow acts, m2.

## 2.4. Angular speeds of rotation of the rotors.

The next task will be to calculate the rotation of the rotors of the quadcopter in the local coordinate system CX1Y1Z1 (Figure 2.7, 2.8). To do this, we introduce the Aixyizi coordinate system, which coincides with the center of mass mi of the rotors.

$$\bar{\Omega}_i = \overline{\omega_\iota} + \overline{\omega_c}, i = 1 \ldots 4;$$

$$\overline{\omega_\iota} = \bar{\iota}_i\omega_{ix} + \bar{J}_i\omega_{iy} + \overline{k_\iota}\omega_{iz};$$

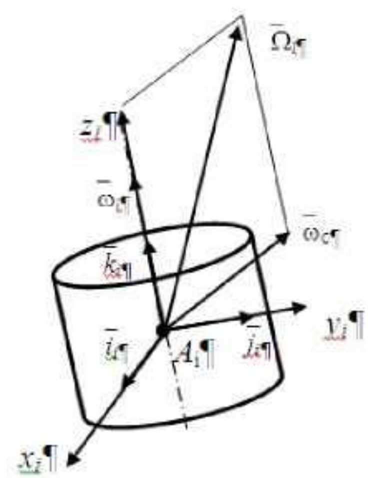
$$\overline{\omega_c} = \bar{\iota}_i\omega_{CX1} + \bar{J}_i\omega_{CY1} + \overline{k_\iota}\omega_{CZ1}; \qquad (2.17)$$

where i1, j1, k1 and ii, ji, ki are unit vectors of the CX1Y1Z1 coordinate system and Aixyiyi is the absolute angular speed of rotation of the ith rotor in the CX1Y1Z1 coordinate system;$\overline{\omega_c}$,$\overline{\omega_\iota}$- the vectors of angular velocities of the housing and i-th rotor in the CX1Y1Z1 and Aixyizi coordinate system are defined as:

$$\overline{\omega_c}=\begin{bmatrix}\omega_{x1}\\ \omega_{y1}\\ \omega_{z1}\end{bmatrix}, \overline{\omega_c}=\begin{bmatrix}0\\ 0\\ \omega_i\end{bmatrix}, \bar{\Omega}_i = \begin{bmatrix}\omega_{x1}\\ \omega_{y1}\\ \omega_i+\omega_{z1}\end{bmatrix} (2.18)$$

Or

$$\bar{\Omega}_i = \bar{\iota_1}\Omega_x + \bar{\jmath_1}\Omega_y + \overline{k_1}\Omega_z (2.19)$$




Drawing. 2.7 - Scheme of determining the angular velocity of the rotor of complex motion.

Let's determine the moment of the amount of movement of the rotor in the Aixyizi coordinate system

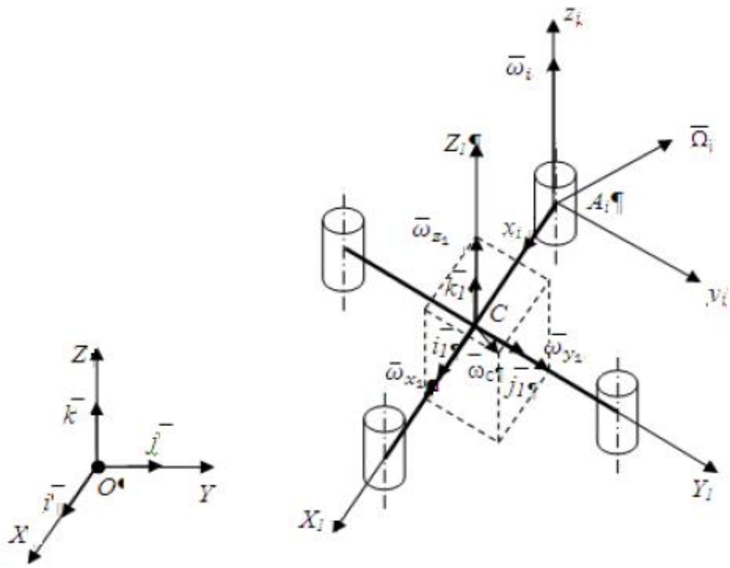
$$\bar{L}_{iAi} = \int_{mi}(\bar{r}_i \times \bar{v})\, dm_i or \bar{L}_{iAi} = I_{Ai}\bar{\Omega}_i$$

where

- $$I_{iA_i} = \begin{vmatrix} J_{Ai}^x & 0 & 0 \\ 0 & J_{Ai}^y & 0 \\ 0 & 0 & J_{Ai}^z \end{vmatrix}$$ rotor inertia tensor.

Then the kinetic moment is equal to:

$$\bar{L}_{iA_i} = \begin{vmatrix} J_{Ai}^x & 0 & 0 \\ 0 & J_{Ai}^y & 0 \\ 0 & 0 & J_{Ai}^z \end{vmatrix} \begin{vmatrix} \omega_{X_1} \\ \omega_{Y_1} \\ \omega_i + \omega_{Z_1} \end{vmatrix} = \begin{vmatrix} J_{Ai}^x \omega_{X_1} \\ J_{Ai}^y \omega_{Y_1} \\ J_{Ai}^z (\omega_i + \omega_{Z_1}) \end{vmatrix}$$



Drawing. 2.8. - Calculation scheme for determining the kinetic moment of the quadcopter.

Let's determine the moment of the amount of movement in the system:

$$\bar{L} = \bar{L}_c + \sum \bar{L}_i \quad (2.20)$$

where

$\bar{L}_c = I_c\overline{\omega_c}$-kinetic moment relative to the center of mass of the quadcopter.

$\bar{L}_i = I_i\overline{\Omega}_i = (I_{A_i} + ml^2)\,\overline{\Omega}_i$ - the kinetic moment of the ith rotor relative to the center of mass of the quadcopter in the CX1Y1Z1 coordinate system (according to Huygens' theorem).

The tensors of inertia of the case IC and the i-th rotor Ii, taking into account that the main axes of inertia of the mechanical system are the main central axes of inertia (all centrifugal moments of inertia are equal to zero) are equal to:

$$I_C = \begin{vmatrix} J_C^{X_1} & 0 & 0 \\ 0 & J_C^{Y_1} & 0 \\ 0 & 0 & J_C^{Z_1} \end{vmatrix}; \quad I_i = \begin{vmatrix} J_{A_i}^{x} + m_i l^2 & 0 & 0 \\ 0 & J_{Ai}^{y} + m_i l^2 & 0 \\ 0 & 0 & J_{Ai}^{z} + m_i l^2 \end{vmatrix}$$

Then

$$\overline{L}_i = \begin{vmatrix} J_{A_i}^x + m_i l^2 & 0 & 0 \\ 0 & J_{Ai}^y + m_i l^2 & 0 \\ 0 & 0 & J_{Ai}^z + m_i l^2 \end{vmatrix} \begin{vmatrix} \omega_{X_1} \\ \omega_{Y_1} \\ \omega_i + \omega_{Z_1} \end{vmatrix} = \begin{vmatrix} (J_{A_i}^x + m_i l^2)\omega_{X_1} \\ (J_{Ai}^y + m_i l^2)\omega_{Y_1} \\ (J_{Ai}^z + m_i l^2)(\omega_i + \omega_{Z_1}) \end{vmatrix}$$

$$\overline{L}_C = \begin{vmatrix} J_C^{X_1} & 0 & 0 \\ 0 & J_C^{Y_1} & 0 \\ 0 & 0 & J_{Ai}^{Z_1} \end{vmatrix} \begin{vmatrix} \omega_{X_1} \\ \omega_{Y_1} \\ \omega_{Z_1} \end{vmatrix} = \begin{vmatrix} J_C^{X_1}\omega_{X_1} \\ J_C^{Y_1}\omega_{Y_1} \\ J_C^{Z_1}\omega_{Z_1} \end{vmatrix} \quad (2.21)(2.22)$$

Taking into account (2.21), (2.22), expression (2.20) will have the form:

$$L = \begin{vmatrix} (J_C^{X_1} + \sum J_{A_i}^x + \sum m_i l^2)\omega_{X_1} \\ (J_C^{Y_1} + \sum J_{Ai}^y + \sum m_i l^2)\omega_{Y_1} \\ (J_C^{Z_1} + \sum J_{Ai}^z + \sum m_i l^2)\omega_{Z_1} + (\sum J_{Ai}^z + \sum m_i l^2)\omega_i \end{vmatrix} = \begin{vmatrix} J^{X_1}\omega_{X_1} \\ J^{Y_1}\omega_{Y_1} \\ J^{Z_1}\omega_{Z_1} + \sum J_i^z \omega_i \end{vmatrix} \quad (2.23)$$

where $J^{X1} = J_C^{X1} + \sum J_{Ai}^X + \sum m_i \; l^2$, $J^{Y1} = J_C^{Y1} + \sum J_{Ai}^Y + \sum m_i \; l^2$,

$J^{Z1} = J_C^{Z1} + \sum J_{Ai}^Z + \sum m_i \; l^2$.

$\sum J_i^Z = J_{Ai}^Z + \sum m_i \; l^2$- the axial moments of inertia are given.

Theorem on the change of the kinetic moment of a mechanical system:

$$\frac{d\overline{L}}{dt} = \frac{d\overline{L}}{dt} + \left(\overline{\omega}_C \times \overline{L}\right) = \sum \overline{M}_C^e$$

$$\frac{d\overline{L}}{dt} = \begin{vmatrix} J^{X_1}\dot{\omega}_{X_1} + \omega_{Y_1}\omega_{Z_1}\left(J_i^{Z_1} - J^{Y_1}\right) + \omega_{Y_1}\sum J_i^z \omega_i \\ J^{Y_1}\dot{\omega}_{Y_1} + \omega_{X_1}\omega_{Z_1}\left(J^{X_1} - J_i^{Z_1}\right) - \omega_{X_1}\sum J_i^z \omega_i \\ J^{Z_1}\dot{\omega}_{Z_1} + J_i^z \dot{\omega}_i + \omega_{X_1}\omega_{Y_1}\left(J^{Y_1} - J^{X_1}\right) \end{vmatrix} = \begin{matrix} M_{X_1}^e \\ M_{Y_1}^e \\ M_{Z_1}^e \end{matrix} \quad (2.24)$$

As a result, on the basis of (2.16) and (2.24), a system of differential equations describing the movement of the quadcopter was obtained:

$$\begin{cases} m\ddot{X} = (\sin\psi\sin\varphi + \cos\psi\cos\varphi\sin\theta)\cdot\sum F_i \\ m\ddot{Y} = (\cos\varphi\sin\psi\sin\theta - \cos\psi\sin)\cdot\sum F_i \\ m\ddot{Z} = \cos\varphi\cos\theta\cdot\sum F_i \\ J^{X_1}\dot{\omega}_{X_1} + \omega_{Y_1}\omega_{Z_1}\left(J_i^{Z_1} - J^{Y_1}\right) + \omega_{Y_1}\sum J_i^z\omega_i = M_{X_1}^e \\ J^{Y_1}\dot{\omega}_{Y_1} + \omega_{X_1}\omega_{Z_1}\left(J^{X_1} - J_i^{Z_1}\right) - \omega_{X_1}\sum J_i^z\omega_i = M_{Y_1}^e \\ J^{Z_1}\dot{\omega}_{Z_1} + J_i^z\dot{\omega}_i + \omega_{X_1}\omega_{Y_1}\left(J^{Y_1} - J^{X_1}\right) = M_{Z_1}^e \end{cases}$$

This system (2.25) must be solved with kinematic relationships that will express the projections of the angular velocity of the body on the axis of the bound coordinate system through the angular velocities of the pitch and roll angles:

$$\begin{cases} \omega_{X_1} = \dot{\varphi} + \psi\sin\theta \\ \omega_{Y_1} = \dot{\psi}\cos\theta\cos\varphi + \dot{\theta}\sin\varphi \\ \omega_{Z_1} = \dot{\theta}\cos\varphi - \dot{\psi}\cos\theta\sin\varphi \end{cases} \tag{2.26}$$

Or

$$\begin{cases} \dot{\phi} = \omega_{X_1} - (\omega_{Z_1}\cos\phi - \omega_{Y_1}\sin\phi)\, ctg\ \theta \\ \dot{\theta} = \omega_{Z_1}\sin\phi + \omega_{Y_1}\cos\phi \\ \dot{\psi} = \dfrac{1}{\cos\theta}(\omega_{Z_1}\cos\phi - \omega_{Y_1}\sin\phi) \end{cases} \tag{2.27}$$

## 2.5. Linearization of the UAV mathematical model

When studying an automatic control system (ACS), it is more convenient to use the theory of conventional linear systems as the simplest. Linearization involves the creation of a linear approximation of a nonlinear system that operates in a small neighborhood of the operating point. Linearization is necessary for the development of control systems using classical design methods, using Bode diagrams (LAFCH) and root hodograph methods. Linearization also allows analyzing the behavior of the control system, determining its stability and other qualities.

To do this, we linearize the differential equations describingdescribes the change in the generalized coordinates of the quadcopter X, Y, Z. – longitudinal, lateral and vertical movement, and we will get transfer functions on three control channels.

Differential equations for longitudinal motion taking into account aerodynamic resistance ($\boldsymbol{\varphi}$=$\boldsymbol{\psi}$=0).

$m\ddot{x} = (sin\boldsymbol{\psi}\ sin\boldsymbol{\varphi}$+cos$\boldsymbol{\psi}$cos$\boldsymbol{\varphi}$sin$\boldsymbol{\Theta}$)$\sum Fi$- Ah

$$\text{Ax=Cx}\frac{pv^2}{2}S.$$

where Cx is the coefficient of aerodynamic force, p is air density, kg/m3; v - velocity of the oncoming air flow, m/s; S is the surface area of the apparatus on which the oncoming flow acts, m2.

$$\ddot{x} = (sin\boldsymbol{\psi}\ sin\boldsymbol{\varphi}+\cos\boldsymbol{\psi}\cos\boldsymbol{\varphi}\sin\boldsymbol{\Theta})\frac{\sum Fi}{m}-\text{Ah} \quad (2.28)$$

$$\begin{cases} x = x_0 + \Delta x_0 \\ \theta = \theta_0 + \Delta\theta_0 \end{cases}$$

$$\begin{cases} \ddot{x} = \dot{v} \\ sin\theta = cos\theta\dot{\theta} \end{cases}$$

$$V^2 = 2Vx\Delta x$$

$$\dot{V}= cos\theta\dot{\theta}\ \frac{\sum F}{m}–\text{Cx}\frac{pV^2\Delta x}{2}S \quad (2.29)$$

We will write the points of view of the theory of automatic control$cos\theta$andCx$\frac{pV^2}{2}S$as K1 and K2, respectively. $\frac{\sum Fi}{m}$ let's write U as the controlling influence. Then the formula will look like:

$$\ddot{x}+\text{K2}\Delta x=\text{K1}\dot{\theta}U \quad (2.30)$$

Next, it is necessary to perform the Laplace transformation.

V(t)≑ V(s);

X(t) ≑X (s);

U(t) ≑ U(s);

Equation (2.30) will have the form:

$$S^2\text{x(s)+K2x(s)=K1}\dot{\theta}U(s) \quad (2.31)$$

We obtain the transfer function of the longitudinal movement channel:

$$\frac{x(s)}{U(s)} = \frac{K_1\dot{\theta}}{(S^2+K_2S)} = \frac{K_1\dot{\theta}}{S(S+K_2)} = \frac{K_1\dot{\theta}}{K_2S(1/K_2S+K_2)} = \frac{K_1\dot{\theta}}{K_2S(TS+K_2)}. \quad (2.32)$$

Next, according to the transfer function, we will build a structural diagram of the longitudinal movement of the quadcopter.

Drawing. 2.9 - Structural diagram of the longitudinal control channel of the quadcopter.

where DKSH is an angular velocity sensor (accelerometer);

DK- angle sensor (gyroscope);

Ass. - pitch angle encoder θ (microprocessor calculator);

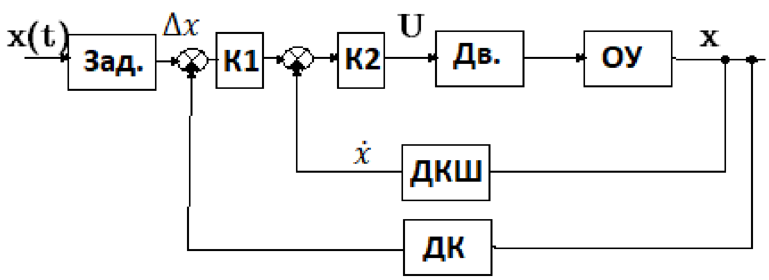
K1, K2 - calculated coefficients;

Dv. - engine or total thrust of four rotors;

OU is a management object.

Differential equation for bullish motion taking into account aerodynamic resistance ($\theta$=$\boldsymbol{\psi}$=0).

$$m\ddot{y} = (cos\varphi\ sin\psi\ \sin\Theta - \cos\ \sin\boldsymbol{\varphi})\sum Fi - Ah \quad (2.33)$$




whereAy=Cy$\frac{pv^2}{2}S$.

$$\begin{cases} y = y_0 + \Delta y_0 \\ \varphi = \varphi_0 + \Delta\varphi_0 \end{cases}$$

$$\begin{cases} \ddot{y} = \dot{v} \\ -sin\varphi = -cos\varphi \end{cases}$$

$$V^2 = 2Vy\Delta y$$

$$\dot{V} = -cos\varphi\frac{\sum F}{m} - Cx\frac{pV^2\Delta y}{2}S \quad (2.34)$$

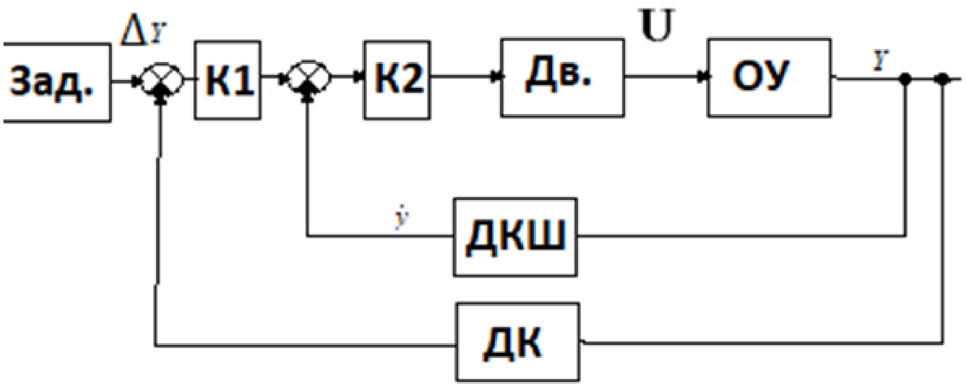
The equation will look like this:

$$S^2y(s) + K2y(s) = -K1\dot{\varphi}U(s) \quad (2.35)$$

We obtain the transfer function of the longitudinal movement channel:

$$\frac{x(s)}{U(s)} = -\frac{K_1\dot{\varphi}}{(S^2+K_2S)} = -\frac{K_1\dot{\varphi}}{S(S+K_2)} = -\frac{K_1\dot{\varphi}}{K_2S\left(\frac{1}{K_2S}+K_2\right)} = -\frac{K_1\dot{\varphi}}{K_2S(TS+K_2)}. \quad (2.36)$$

It should be noted that the contours of the position along the angles φ and θ are identical in terms of parameters and structure, since the parameters of the moment of inertia, taking into account the symmetry of the quadcopter, have equal values.




Drawing. 2.10. Structural diagram of the side control channel of the quadcopter.

When calculating the longitudinal and lateral movement of the quadcopter, the forces of gravity g were not taken into account, since they are quite insignificant. When studying vertical motion, the differential will have additional resistance to gravitational forces. We linearize the equation of vertical motion. (θ =***φ***=***ψ***=0).

$m\ddot{z} = (cos\varphi\ cos\Theta - \text{g})\sum Fi$- Ah (2.37)

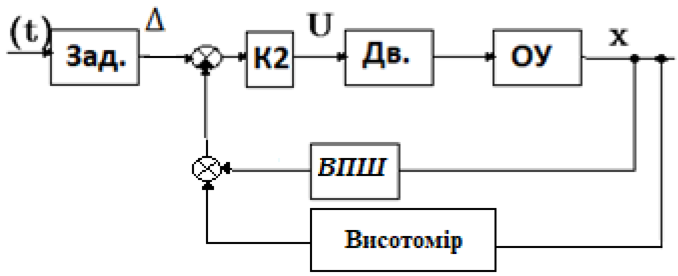
$\ddot{z} = \sum Fi - g/m$- Ah

The equation will look like this:

$S^2 z$(s)+K2z(s)=$U(s)$(2.38)

Transfer function of vertical movement:

$$\frac{Z(s)}{U(s)} = -\frac{1}{(S^2+K_2S)} = \frac{1}{S(S+K_2)} = \frac{1}{K_2S\left(\frac{1}{K_2S}+K_2\right)} = \frac{1}{K_2S(TS+K_2)}. \quad (2.39)$$




Drawing. 2.11. Structural diagram of the vertical control channel of the quadcopter.

where VPSh is an air speed meter

Ur (t) - regulator signal, V; IN; ωi (t) - angular velocity of the BDPTi, rad/sec; h (t) - flight height, m; Ua (t) - the output signal of the height corrector, V; Uв (t) - the output signal of the altimeter, V; hz (t) - control signal of the system, m; Uz (t) - control voltage, V; ε (t) is an error signal.

## 2.6. PD Regulator

In the automatic control system, the main element is the regulator, which is a device that monitors the state of the control object and ensures the necessary control law. The control process includes: calculation of the control error or mismatch signal e(t) as the difference between the desired setting (g) and the current value of the process (y), after which the regulator produces a control signal (U) .

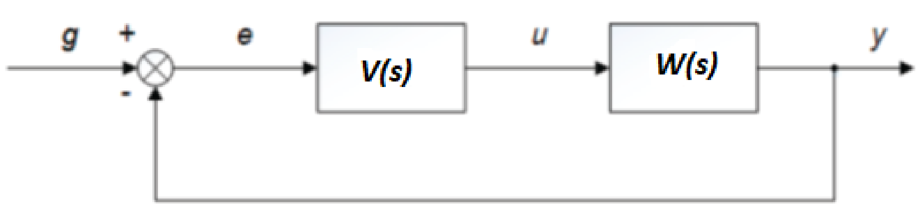



Figure 2.12 - Classical scheme of the ACS regulator.

One of the types of regulators is the use of classic PID regulators.However, to control the movement of the quadcopter, we will use PD-regulators, since the P-regulator will make the angle control system oscillating, when using the PI-regulator, there will also be two complex roots in the angle control system, and with the PID-regulator, the order of the system increases to the third.

(PD) regulator that forms a control signal that is the sum of two components: proportional and differential.

The transmission PD of the regulator has the form:

V(S) = Kp+KdS (2.40)

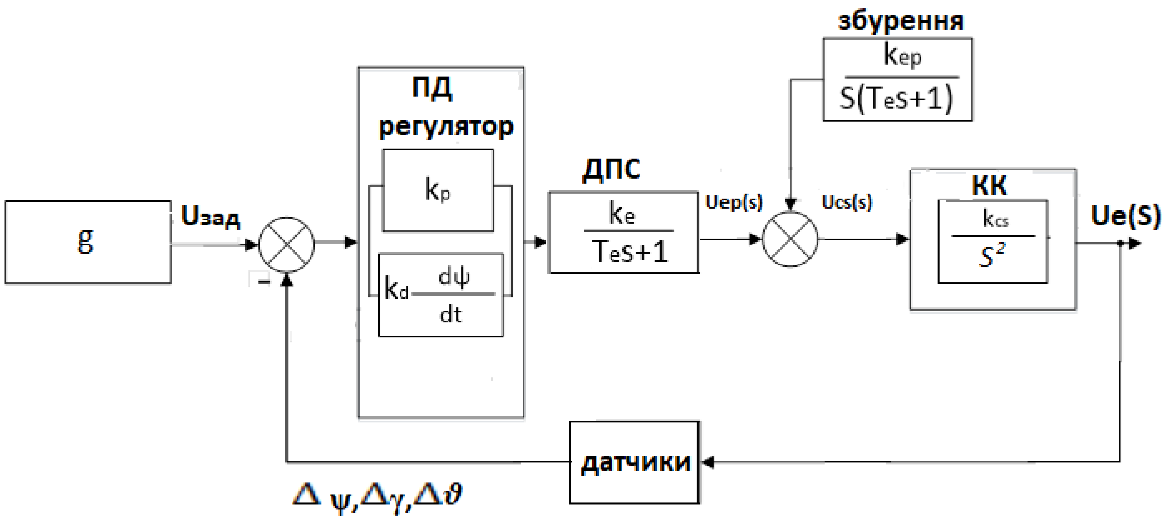



Figure 2.13 – PD scheme of the regulator in the ACS of the quadcopter.

Adjustment of the movement of the quadcopter occurs by using PD-regulators. Since during the flight we need to ensure stabilization along all axes of the aircraft's movement. In this way, we get that we need to implement four PD regulators. The first will stabilize roll, the second will stabilize pitch, the third will stabilize yaw, and the fourth is responsible for stabilizing the quadcopter in height. In this study, the main task was to consider the stabilization of the UAV at a given height. The main problem of accidents is a sharp decrease in altitude and the occurrence of disturbing effects in the form of wind gusts, different air density, and errors in measuring the battery charge during flight. Therefore, when adjusting the PD of the regulators, the main focus was on the regulators responsible for maintaining the height.

## 2.7. MEMS data filtering

Determining real readings requires accurate precision meters, the use of which is impossible for implementation in "micro" and "mini" UAVs, therefore, obtaining measurements is limited to obtaining information from microelectromechanical (MEMS) sensors, which have a larger spread of output parameters and measurement noise. The solution to this problem is the use of a discrete Kalman filter. Compared to other low-pass filters, Kalman filtering takes the leading place. This methodis used in many radio engineering areas, including filtering noisy signals, generating unobserved states, and predicting future system states.

This filter is designed for recursive re-estimation of the state vector of an a priori known dynamic system, in other words, to calculate the current state of the system, it is necessary to know the current measurement, as well as the previous state of the filter itself. The Kalman filter, similar to other recursive filters, is implemented in a time rather than a frequency representation, but unlike other similar filters, it operates not only with state estimates, but also with uncertainty estimates (distribution density) of the state vector, based on the Bayes formula conditional probability.

There are two stages of the filtering algorithm. At the stage of forecasting, the Kalman filter extrapolates the values of the state variables, as well as their uncertainties. At the second stage, based on the measurement data (obtained with some error), the extrapolation result is refined. Due to the step-by-step nature of the algorithm, it can track the state of the object in real time, as shown below:

Figure 2.14. – Kalman filter algorithm.

Figure 2.15. - Correlation stage

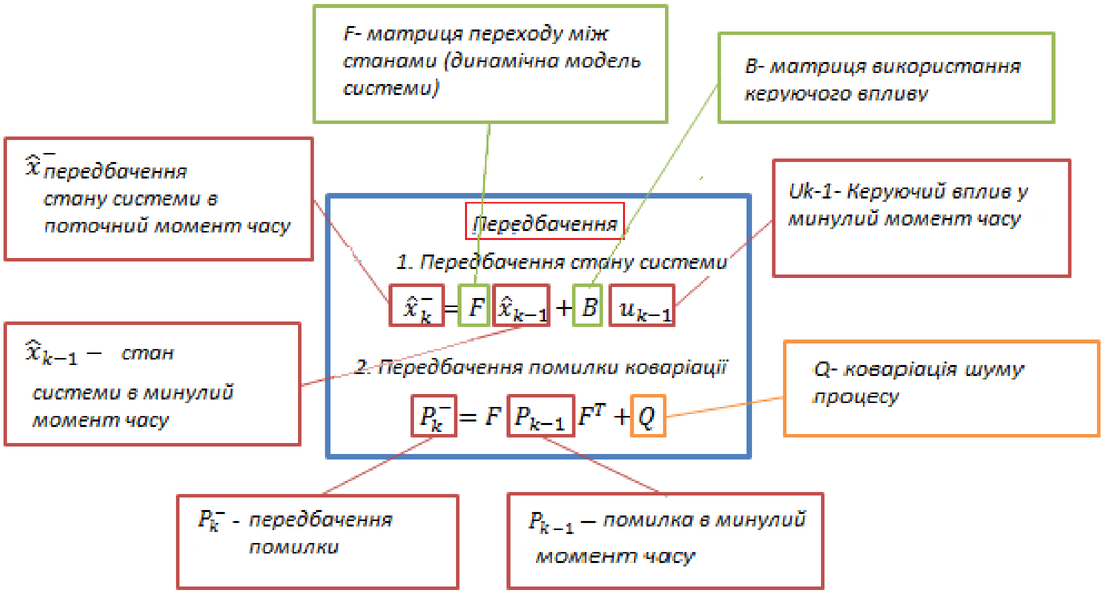




Figure 2.16 - Extrapolation stage

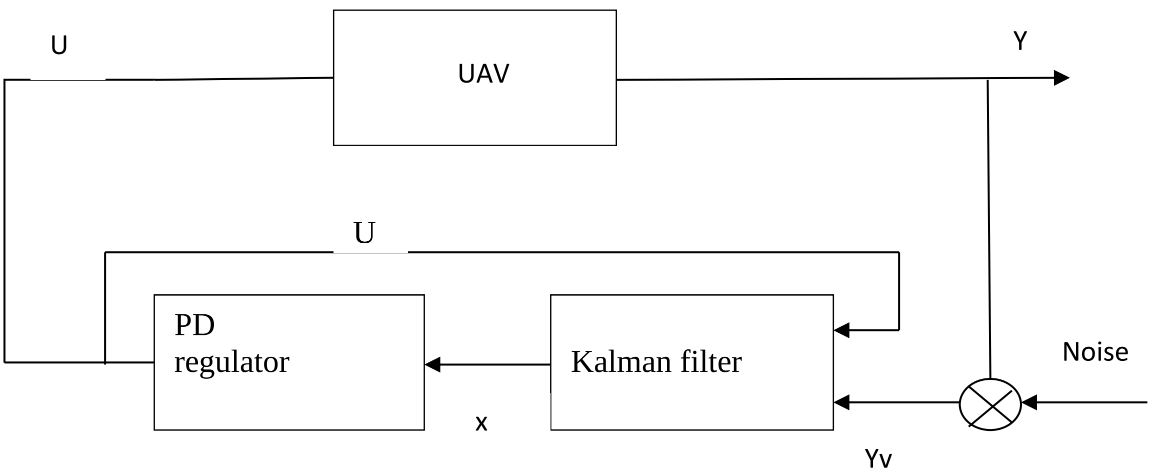



Figure 2.17 - Using the Kalman filter in the control circuit

## 2.8. Quadcopter drive model.

The thesis examines the model of DC motors. The engine equations, taking into account moments, have the following form:

$$\begin{cases} (J_p + J_v)\dfrac{d\omega}{dt} = M_{\partial e}(t) - d \cdot \omega^2, \\ c_M \cdot i(t) = M_{\partial e}(t), \\ L_Я \dfrac{di(t)}{dt} + R \cdot i(t) + c_e\omega = U_П. \end{cases} \tag{2.41}$$

Next, a specific engine is selected in the design partT-Motor MN3510-15 with parameters to perform the required flight.

From the system of differential equations (2.41), having specific values of all quantities included in the description of the DPS, a computer model for the DPS will be designed in the Matlab/Simulink software package.

The DPS scheme can be represented as follows:

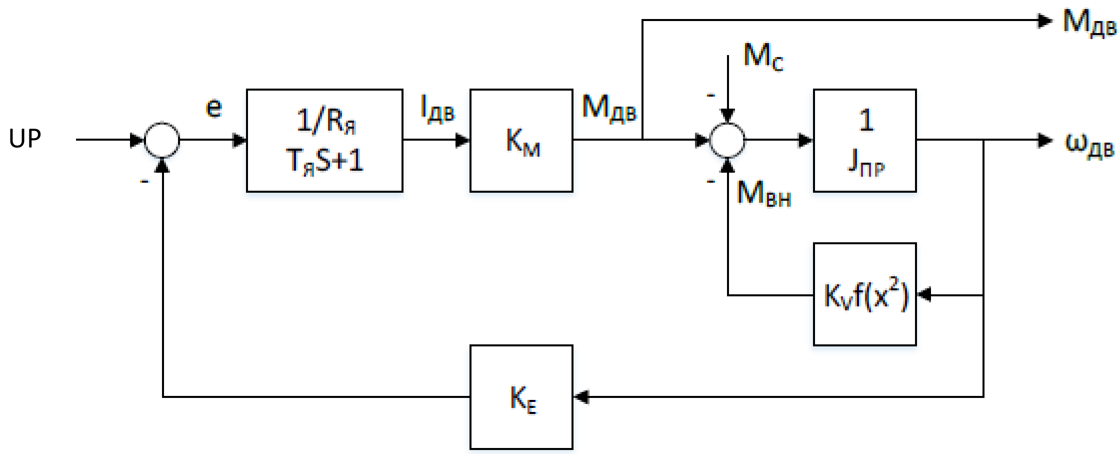



Figure 2.18 - Structural diagram of a direct current motor.

where$R_I$- active resistance of motor windings;

$T_I$- engine time constant;

$K_m$- coefficient of connection of the current in the windings of the motor and the torque on the shaft;

$K_{IS}$- coefficient of connection of shaft speed and EMF;

$J_{Ave}$- the given moment of inertia of the drive taking into account the screw.

The input of the model is the voltage from the ECS speed controllers, which is included in the drive speed control loop, as well as the external load torque. The outputs are the angular velocity of the motor shaft and the dynamic torque.

# 3. DESIGN PART

## 3.1 Mechanical part

### 3.1.1. Frame selection

The frame is the basis on which all the elements of the quadcopter are attached - motors, controllers, batteries, camera and other devices. Since the frame is a supporting structure consisting of a combination of linear elements, it must withstand the load, ensure the strength and stability of the UAV.

Plastics and their combination with various materials, glass fiber, aluminum and carbon are usually used as materials. Carbon frames are the strongest, lightest and most expensive.

The main parameter according to which the frame is selected is its size. This size is the distance between diagonally located engines. Depending on this distance, quadcopters can be conditionally divided into "classes", which determine the possibilities of their use.

Table 3.1. - Classes of quadcopter frames

| Size | Payload | Appointment | Flight range (depends on the equipment) |
|---|---|---|---|
| ≤ 200 mm | --- | toys | ≤ 30 m |

| | | | |
|---|---|---|---|
| ≥ 250 mm | entry-level video camera, GPS | sports, for mastering professional equipment | ≤ 50 m |
| ≥ 350 mm | mid-level video camera, GPS | Commercial use, entertainment | ≤ 1000 m |
| ≥ 550 mm | High-quality photo/video camera, GPS | Geological exploration, monitoring | ≥ 5000 m |

For the tasks of long-term monitoring of the terrain, it is necessary to select a frame of the latest class, which will have high strength with a relatively small mass, and will have the possibility of installing high-quality equipment for video recording on it.

The Tarot FY650 "IRON MAN" TL65B01 carbon frame was chosen. This design can be folded for transportation and provides high mobility. Small dimensions and high strength allow you to fly in the wilderness, which is important for aerial photography, mapping, and terrain reconnaissance. The center of gravity of the device can be adjusted depending on the weight of the installed photo or video camera (it is carried out by moving the power battery or suspension).

Figure 3.1. - Quadcopter frame.

Features:

- The frame diameter is 650 mm

- Beam diameter: 16mm
- Weight of the empty frame: 476g

### 3.1.2. Choice of engine and propellers.

The electric motor for the UAV is selected taking into account the mass, speed and duration of the flight, energy consumption and dimensions determined by the design of the UAV. The quadcopter can be equipped with two types of electric motors - collector-type or collector-less. Collector engines are used on small and cheap models. Since the developed system must have high wear resistance, it is necessary to choose a DC motor without a collector.

The use of BDPS in comparison with a collector engine is due to a number of reasons:

- simpler design, smaller weight and size;
- higher efficiency and power index per kilogram of own weight;
- a wider range of screw rotation speed;
- less wear due to the absence of a brush-collector assembly;
- BDPS practically do not create radio interference.

The only drawback of BDPS is considered to be a complex and expensive electronic control unit (electronic regulator), due to which the number of engine revolutions is controlled.

When choosing engines, you should be guided by the following most important parameters:

- consumed current (measured in amperes [A]);
- Kv-rating (motor axis revolutions per minute (RPM) at a certain voltage);
- lifting force (measured in Newtons [N] or kilograms [Kg]);
- efficiency

Speed index:

RPM = Kv·U (3.1)

Minimum lifting force of motors:

$$F_{\text{під}} = \frac{m_{kk} \cdot 2}{4} (3.2)$$

where$m_{kk}$- the mass of the quadcopter

The T-Motor MN3510-15 engine was chosen with its parameters and characteristics, which allows computer modeling to get closer to the actual object.


Figure 3.2. - Quadcopter engineT-Motor MN3510-15.

Table 3.2 - Engine characteristicsT-Motor MN3510-15.

| | |
|---|---|
| Producer | T-Motor |
| Model | MN3510-15 |
| Class | Collectorless |
| Kind | outrunner |
| Configuration | 12N14P |
| Number of poles | 14 |
| KV | 630 |
| Max. traction | 1250 — 1850 |
| Nutrition | 11.1 — 14.8 V |
| Nominal current | 12.3 A |
| No-load current | 0.5 A |
| Max. continuous current | 22 A |
| Max. lasting power | 495 W |
| Resistance | 65 mΩ |
| shaft | Smooth shaft |

| | |
|---|---|
| Shaft diameter | 4 mm |
| Motor mounting | 25x25 mm |
| Dimensions | 28.5x41.8x41.8 mm |
| Weight | 97 g (without wires) |

### 3.2.3. Choice of propellers

Since engines cannot create lift by themselves, they must be supplemented with propellers. Propellers convert the rotational energy of the engine shaft into lifting force.

Important characteristics of the propeller are its size and the angle of inclination of the blades or the pitch of the blades, which indicates how much the propeller would rise in one revolution around its axis with a given inclination of the blade, when moving in a dense substance. The dimensions of these quantities are usually indicated in inches. With an increase in the size of the propeller, the lifting force increases, but the moment on the motor shaft increases and the consumer current increases. Flight stability is important for the quadcopter being developed, which is achieved by installing large propellers with a large pitch while reducing their rotation speed. The following carbon propellers were selected:

Figure 3.3- Propellers1540 Carbon Fiber Propeller CW&CCW

## 3.2.Electrical part

### 3.2.1. Battery selection.

The battery is the power source for all UAV systems and DC motors.

When choosing a battery, the following criteria must be taken into account:

- Battery capacity;
- Current output;
- Battery structure;
- Weight and dimensions;

The most optimal characteristics are lithium-polymer batteries (LiPo batteries), which have a low self-discharge, no memory effect, a wide range of operating temperatures and a small voltage drop during discharge. Disadvantages include not the highest charge density, a relatively small number of operating cycles (800-900) and an increased fire hazard.

LiPo - batteries consist of one or more compartments ("cans") connected in series. Each structural element provides a nominal voltage of 3.7 V, and corresponds to the 1S marking. Accordingly, the more compartments, the greater the voltage. Therefore, the designation of the voltage level 1S = 3.7 V, 2S = 7.4 V, 3S = 11.1 V, 4S = 14.8 V, etc. The output voltage level directly affects the angular speed of the installed electric motors.

Since the duration of the quadcopter's stay in the air increases not only due to the increase in battery capacity, but also due to a decrease in the level of output current, when performing a similar amount of work. The current output (marked with the index "C") indicates the permissible discharge rate of the battery. Too low current output can damage the battery, and too large "C" index can reduce flight time.

The Dinogy Li-Pol 11000mAh 4S 25C 40x61x179mm T-Plug battery with the following characteristics was chosen as the battery:

Table 3.3 - Characteristics of the selected battery

| | |
|---|---|
| Type | Li-Po |
| Capacity | 11000 mAh |
| High-voltage | 14.8 V |
| Configuration | 4S |
| Dimensions | 190x59x38 mm |
| Current output | 25 C |
| Charge current | 5 S |
| Connector | T-Plug |
| Balancing connector | JST-XH |
| Weight | 879 g |


Figure 3.4- Battery Dinogy Li-Pol 11000mAh 4S 25C.

Connectors.

All LiPo flight batteries (except 1S batteries, which have a special design) come with a set of wires and connectors. The battery is connected to the quadcopter or the output of the charger through the power cable. The choice of the connector for the power wire depends on the maximum output current of the battery. The most popular types of power connectors are XT30, XT60, XT90, which can withstand a current of 30, 60, 90 A, respectively. JST-XH connectors are usually used as connectors for the balancing wire.

Figure 3.5 - Types of battery connectors

A power module was selected for switching the battery with ECS APM BEC 3A XT60 plug

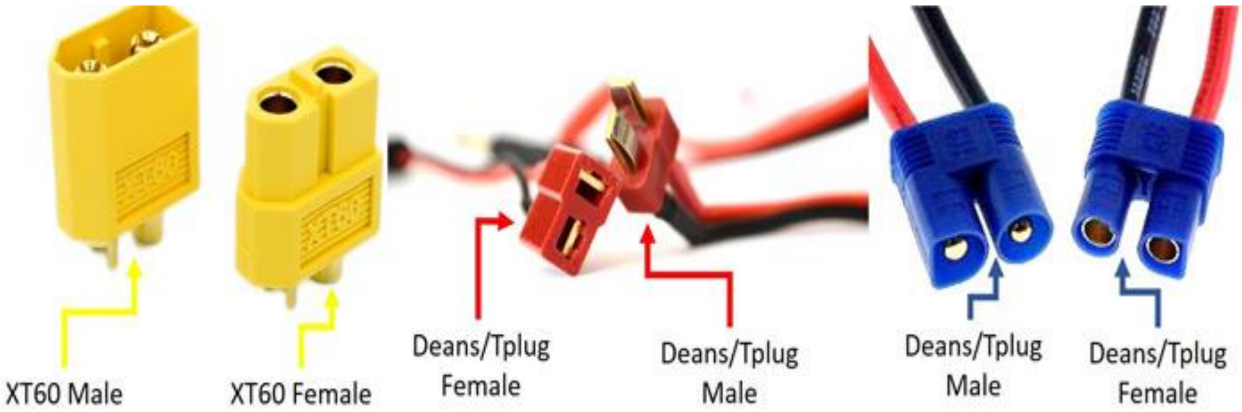


Figure 3.6 - Power module APM BEC 3A XT60 plug

### 3.2.2 Speed controller selection (ESC)

When choosing a speed controller, it is necessary to take into account: the maximum current consumed by the engine, as well as battery voltage. You should choose a battery with a maximum passing current 10-20% higher than the current consumed by the engines. The nominal voltage must be equal to or greater than the battery voltage.

Since the maximum consumer current of the engine is 22 A, and the battery voltage is 14.8V (4S), ESC HOBBYWING SKYWALKER Quattro 25A was chosen.

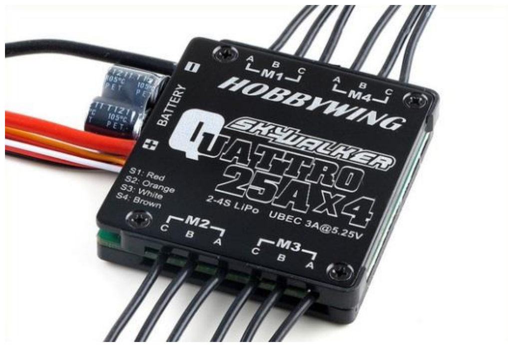



Figure 3. 7- Cruise control (ECS)

Table 3.4 - Characteristics of the chosen onespeed controller

| | |
|---|---|
| High-voltage | 7.4 — 14.8 V |
| Nominal current | 25 A |
| Peak current | 30 A |
| PWM frequency | 50-432 Hz |
| Cooling | passive |
| Size | 70x62x11 mm |
| Weight | 112 g |
| Output voltage | 5B |
| Output current | 3A |

## 3.3 Flight controller

### 3.3.1 PixHawk flight controller description.

A flight controller (FC) is an electronic device consisting of a board with a processor and built-in sensors that control the flight of a UAV.

The following sensors are used for multicopters carrying a payload:

- 3-axis accelerometer
- 3-axis gyroscope
- Magnetometer
- Barometer

The purpose of the work is to build a UAV capable of performing the main flight modes indicated in the table:

Table 3.5- Quadcopter flight modes

| No | Function | Description |
|---|---|---|
| 1. | Stabilize | Takeoff and landing. A gyroscope and accelerometer are used to maintain the horizon. The compass is used additionally for control and correction. |
| 2. | AltHold | Altitude hold mode. In this mode, the use of a barometer is added, which helps to maintain altitude according to air pressure. |
| 3. | Land | Automatic landing mode in the current position. A barometer is used to control altitude. |
| 4. | Simple | A mode that allows you to "forget" about the orientation of the UAV in relation to the pilot. In this mode, the most important thing is the compass. |
| 5. | Loiter | Point holding mode (by coordinate and height). Uses GPS. The mode is well suited for photo and video shooting. |
| 6. | Auto | Flight to the planned points. A path can be created manually through ground station software before flight. |
| 7. | Failsafe | Rescue mode, which sends the UAV home (to the point where the engines are started - Arming or another planned point). For example, in case of loss of communication with the ground station. |

A new generation PixHawk flight controller based on a 32-bit STM32 processor developed by the ArduPilot open source PX4 project was chosen. Due to a more productive processor core, PixHawk has greater efficiency compared to ArduPilot 2.5. -2.8. and a number of new functions: "black box" (recording of flight information on an SD card), adaptive filters and self-learning flight.

Characteristics:

- Size: 81x44x15mm
- Weight: 33.1g

Microprocessor:

- 32-bit STM32F427 Cortex M4 core with FPU
- 168 MHz / 256 KB RAM / 2 MB Flash
- 32 bit STM32F103 failsafe co-processor

Sensors:

- ST Micro L3GD20 3-axis, 16-bit gyroscope
- ST Micro LSM303D 3-axis, 14-bit accelerometer / magnetometer
- Invensense MPU 6000 accelerometer / gyroscope with 3 axes
- Barometer MEAS MS5611

Interfaces:

- 5x UART (serial ports)
- 2x CAN
- Spektrum DSM / DSM2 / Satellite DSM-X® compatible input to DX8
- Futaba S.BUS® compatible input and output
- PPM signal
- RSSI (PWM or voltage) input
- I2C
- SPI
- 3.3 and 6.6-volt ADC inputs
- External mUSB port

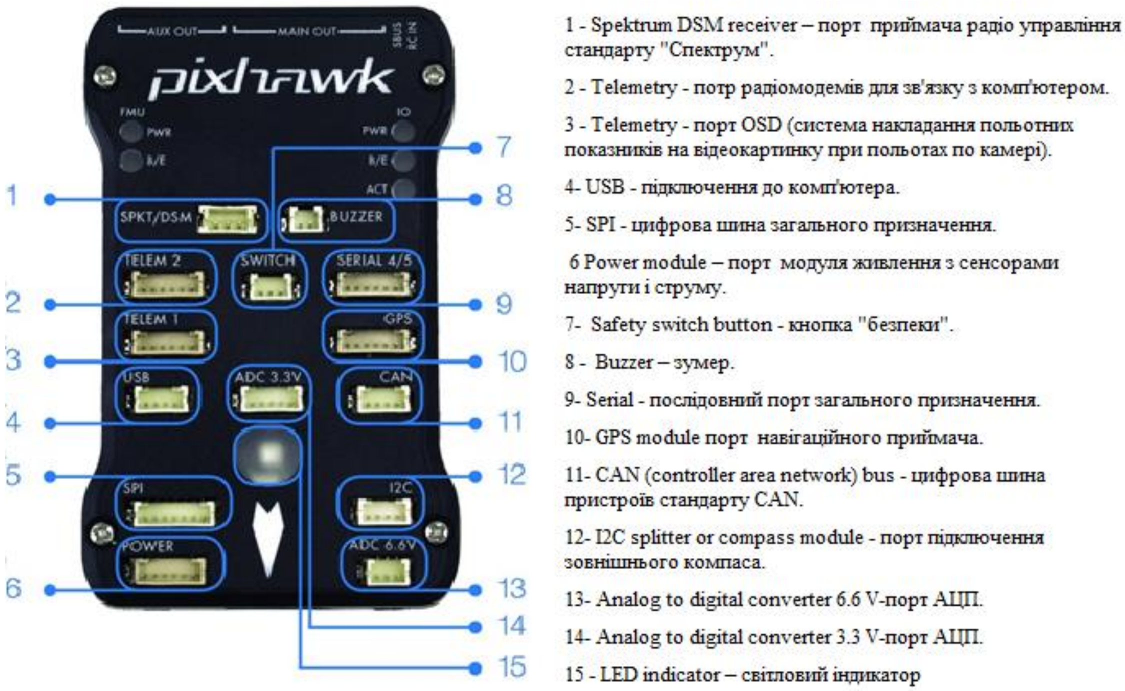
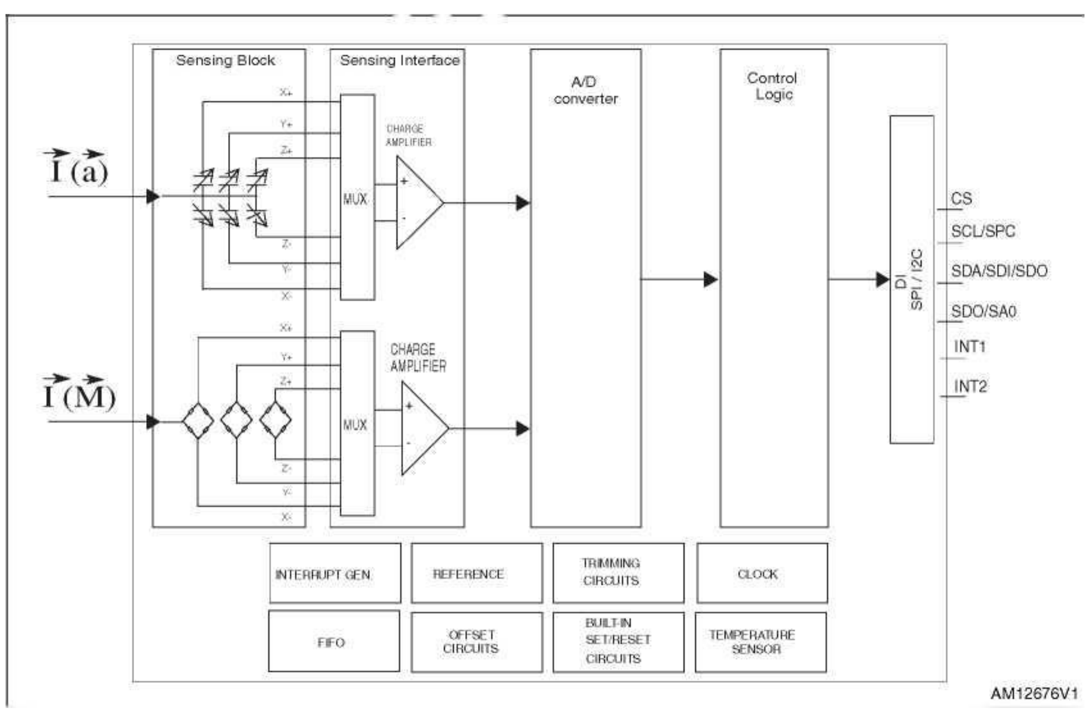



Figure 3.8- Flight controllerPixHawk

Below are the functional diagrams according to the technical documentation [_] of the ST Micro L3GD20 gyroscope, the ST Micro LSM303D accelerometer and magnetometer, the MEAS MS5611 barometer, which are equipped with the




PixHawk flight controller.

Figure 3.9- ST Micro LSM303D accelerometer and magnetometer

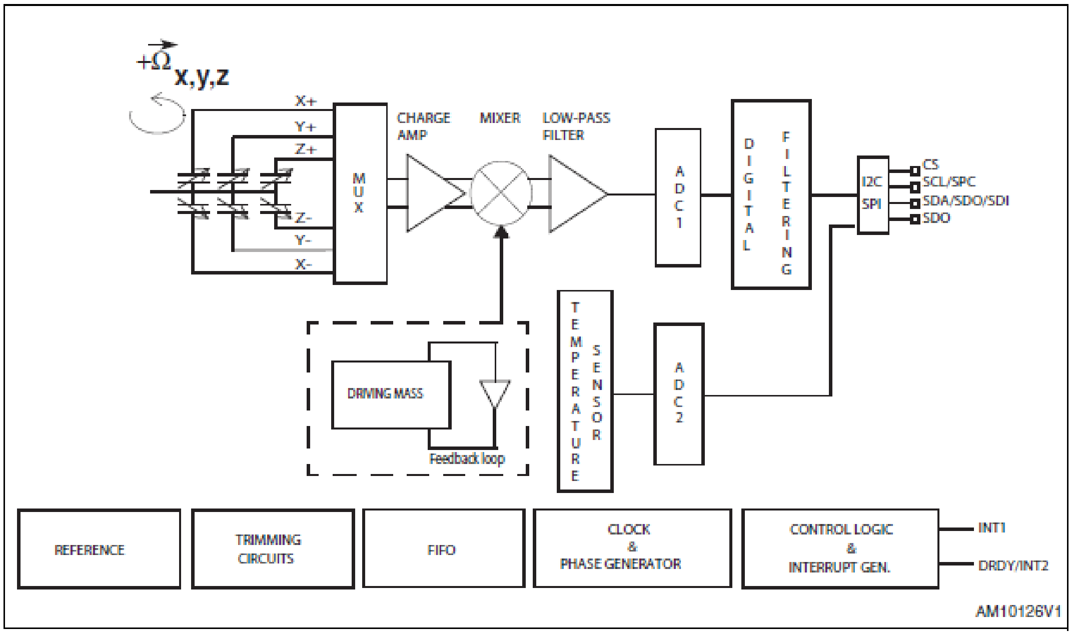



Figure 3.10 - ST Micro L3GD20 gyroscope

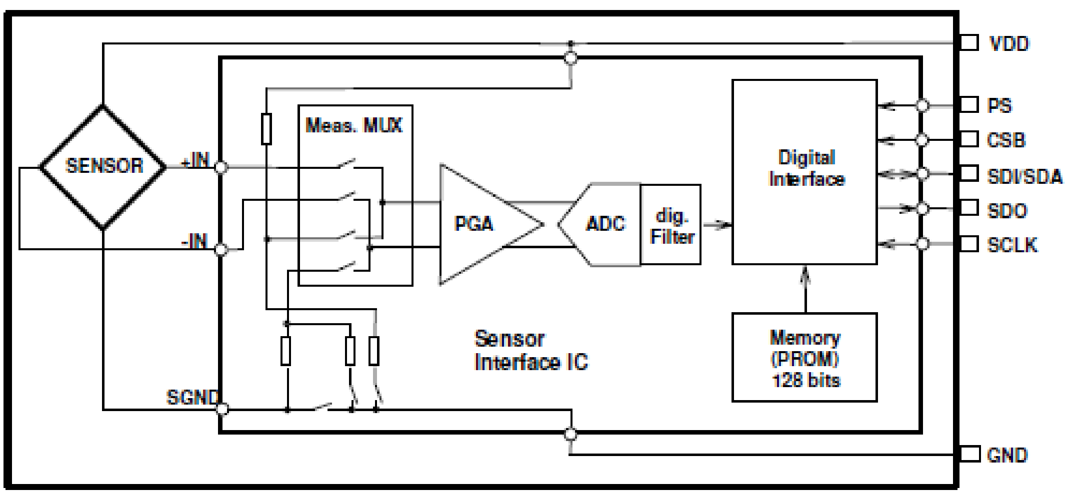



Figure 3.11- Barometer MEAS MS5611

### 3.3.2 Flight controller architecture.

The PX4 project develops a series of hardware modules used to control vehicles. This is manual and automatic control of unmanned aerial vehicles, motor boats, rovers and some other automatic control systems. All PX4-based aircraft share the same code base.

The PX4 architecture consists of two main levels:

- The upper middleware is a common level of robotics that can support any type of autonomous robot.
- The bottom part, the flight stack, is a flight evaluation and control system.

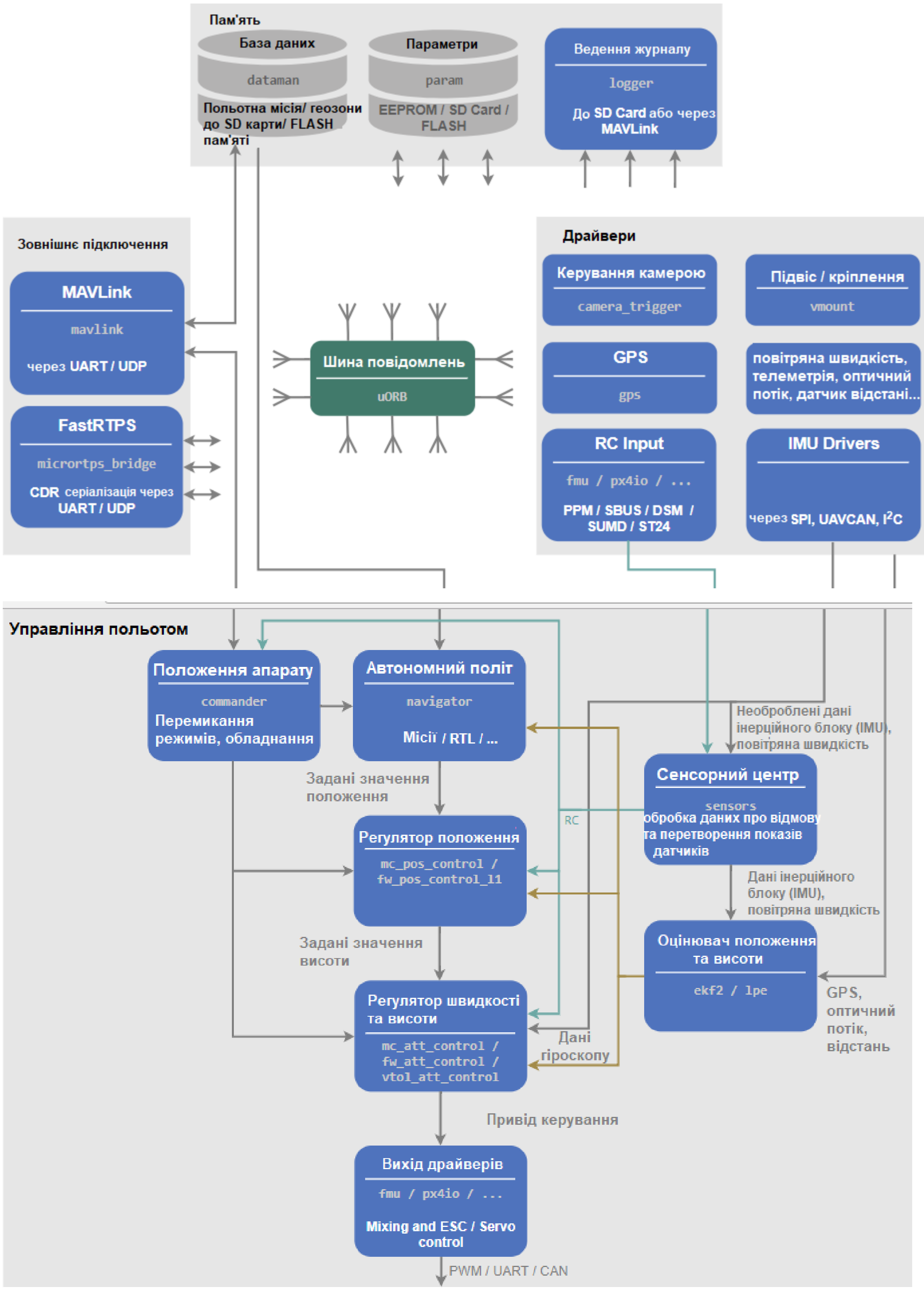



Figure 3.12 - High-level software architecture diagram.

The flight stack is a set of guidance, navigation and control algorithms for autonomous unmanned aerial vehicles. It includes controllers for fixed-wing or multi-rotor drones, as well as a position estimator.

The following diagram shows a general view of the flight stack blocks. It contains communication from sensors, RC input and autonomous flight control (navigator), all the way to the actuator.


Figure 3.13 - Flight stack diagram.

The estimator takes one or more sensor inputs, combines them, and calculates the state of the vehicle (for example, the position of the quadcopter from the IMU sensors).

A controller is a component that accepts a given value and measurement or estimated state (process variable) as input data. Its purpose is to adjust the value of a process variable so that it corresponds to a given point. The output signal is the correction to ultimately achieve this setpoint. For example, a position controller takes set position values as inputs, the process variable is the current estimated position, and the output is a set position and thrust value that moves the drone to the desired position.

The mixer takes power commands (eg turn right) and translates them into individual motor commands, within some limitations. This transition is specific to the type of UAV and depends on various factors, such as the location of the engine relative to the center of gravity or the rotational inertia of the engines.

## 3.4 **Selection of attachments.**

### 3.4.1 Selecting a GPS receiver.

The satellite navigation receiver in the quadcopter equipment is needed in order to:

- perform an automatic flight along a given route;

- determine the current distance to the take-off point, the speed and altitude of the flight when flying on FPV;

- to ensure automatic return to the take-off point in case of loss of the control signal.

Ublox Neo m8n 8N GPS was chosen.


Figure 3.14. - GPS Ublox Neo m8n 8N.

### 3.4.2 Selection of video equipment.

Video equipment of a quadcopter generally consists of the following components:

- video cameras, course and main;
- video switcher;
- stabilized camera suspension;
- the module for overlaying information on the image (OSD);
- video transmitters;
- omnidirectional antenna;
- video equipment power supply.

The terrestrial part of the video channel also consists of several components:

- video receivers;
- antennas, omnidirectional and directional;
- antenna position control system (tracker);
- video glasses or monitor;
- video recorder;
- power supply.

Usually, two cameras are used in professional filming for FPV flights: course and main. FPV - (English "First Person View" - a view from the first person) a way of controlling an unmanned aircraft using a video camera on board. The real-time video is transmitted to the pilot of the drone and allows him to control it outside the field of view. The course camera is light, uncomplicated and gives an image of average quality. It is mounted on the frame of the copter in a fixed position convenient for the operator and is directed slightly at an angle to the ground. Such a camera simulates the view from the cockpit and gives a clear idea of where and at what angle the copter is flying, and whether there are obstacles on the way. As a rule, telemetry information (OSD) is superimposed on the image from this camera [4]. However, for the developed system, a decision was made to choose one camera mounted on a controlled, stabilized suspension. This approach is more economical, also eliminates the need for a video switcher and frees up one of the radio channels. Thus, the Xiaomi Yi Sport Black camera was chosen. The Tarot T4-3D three-axis gimbal was chosen as the camera stabilization system.

Figure 3.15- Camera Xiaomi Yi Spor )

Tabl s.

| | | | |
|---|---|---|---|
| Ce | | | |
| Ma | , Sony | | |
| Viewing angle | 155° | | ° |
| Video shooting mode | 1080p 60 fps<br>1080p 30 fps<br>720p 120 fps<br>480p 240 fps | | |
| Photo shooting mode | 16 MP (4608x3456) | Working temperature | -20°C ~ 50°C |
| Nutrition | Replacement, Li-Po, 1010 mAh | Supply voltage | 2S ~ 6S LiPo |

| | | | |
|---|---|---|---|
| PZP | microSD (up to 64 GB) | Size | 99mm × 88.5mm × 105.6mm |
| Weight | 72 g | Weight | 178 g. |

The FPV system uses video data receivers and transmitters. For antennas, the following frequencies used in this system should be operated:

- 900 MHz;
- 1.2 GHz;
- 1.3 GHz;
- 2.4 GHz;
- 5.8 GHz.

The lower the frequency, the greater the penetrating ability, but the greater the geometric dimensions of the antenna. The most optimal option will be antennas operating at a frequency of 2.4 GHz.

Power is one of the important indicators. More power means more range. To double the range, the power must be quadrupled. But you should take into account the legality of using the selected FPV frequency and power in the country or region.

The telemetry system (OSD) is designed to transmit important technical information from the board in real time, as well as, if necessary, record this information in memory for further study. The composition of this information depends on the purpose of the system and the needs of the operator. This is usually the following information:

- battery voltage;
- consumed current;
- battery temperature;
- operation mode of the flight controller;
- flight time;
- height;
- linear velocity;

- vertical acceleration;
- readings of accelerometers (roll);
- compass readings;
- engine revolutions;
- current GPS coordinates;
- number of available satellites;
- distance to the starting point.

The telemetry implementation scheme using OSD is shown below:


Figure 3.16 - Block diagram of telemetry application with OSD.

External data to the OSD module (Figure 3.17.) can come from the flight controller through a serial interface, directly from external sensors, or simultaneously from different sources.

The module's own microcontroller (MCU) processes data and loads it into a special chip - a video mixer (V-MIX), which superimposes alphanumeric and graphic information on the image.

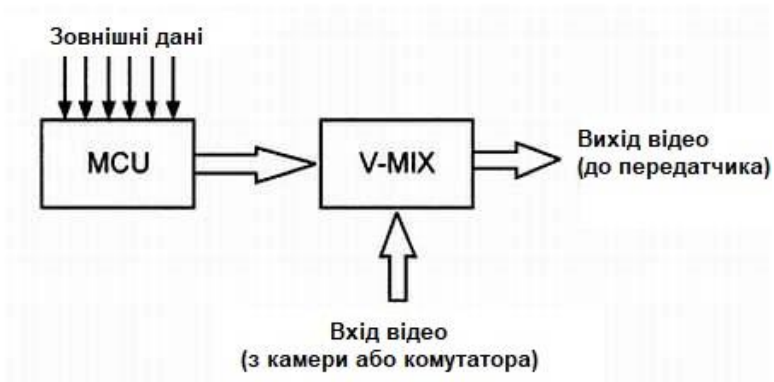



Figure 3.17 - Structural diagram of the OSD module

Based on the selection of design elements of the quadcopter mentioned above, a connection diagram was built.

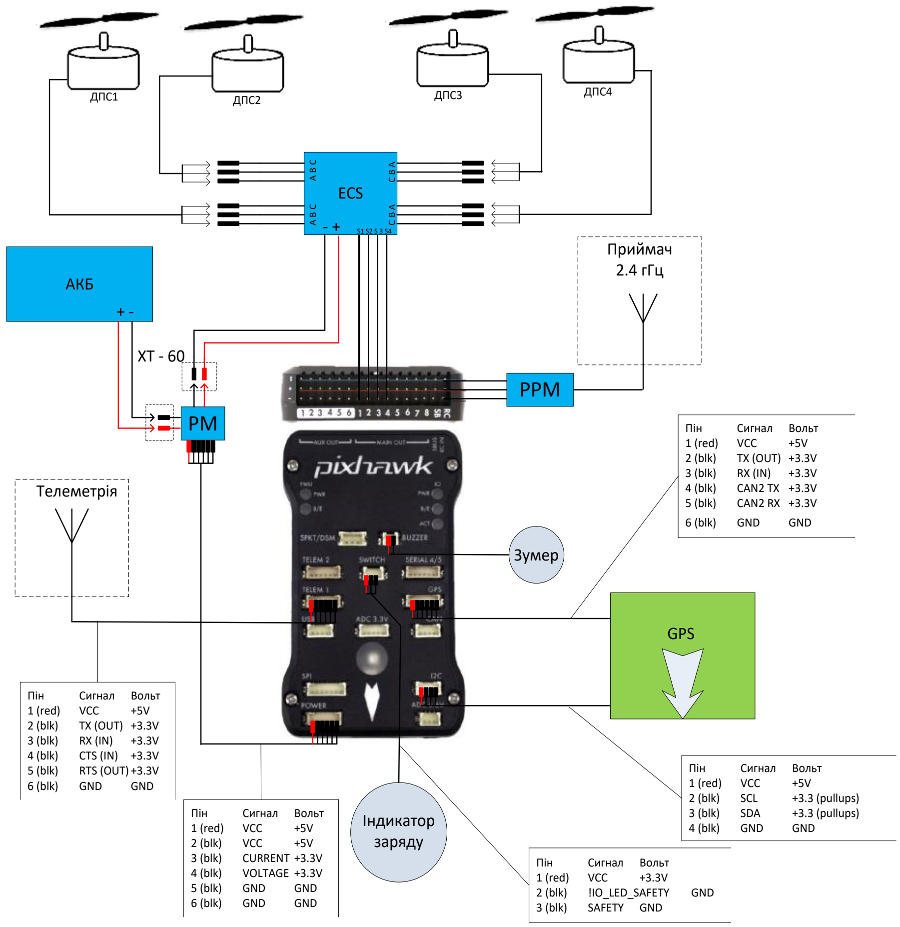



Figure 3.18 - Connection diagram of quadcopter elements.

## 3.5 Conclusion to the chapter

Thus, in this part of the thesis, a synthesis of the design parts of the UAV was carried out. The elements of the quadcopter are offered to be purchased as separate modules from the many options available on the market. Reasoned selection of the mechanical part of the quadcopter - frame and engines, a flight controller with a high-performance microprocessor was selected as the control device, the power supply system and attached monitoring equipment were selected.

# 4. RESEARCH PART

## 4.1. The purpose of the research part

The task of the research part of the control system of the quadcopter is the synthesis of the regulator, that is, the determination of its structure and parameters.

The regulator is designed in such a way that by its action it:

- compensated for the effect of the link of the object falling into this circuit;
- ensured astatism of the system in terms of controlling influence
- ensured the optimization of regulation processes according to the selected criterion.

There are a large number of methods of synthesizing regulators for various types of objects. The main methods are the synthesis of PID controllers, the method of modal regulation, the frequency method, the synthesis of controllers according to the desired transfer function, and the interpolation method. With such a variety of methods, the developer often faces the question of which of the above methods to use when synthesizing a particular control object.

The real interpolation method for unstable objects is poorly formalized. To solve the problem, it is necessary to attract additional information, so this is a type of compensatory methods.

The frequency method when working with unstable objects is quite time-consuming, therefore it is not used in practice.

The method of synthesizing regulators according to the type of desired transfer function of the system is well formalized, it allows quite simply to ensure the desired quality of the closed system in combination with its roughness.

In part 2.6. diploma thesis, PD regulator was used. Such a system has either zero roots or is on the limit of stability. Therefore, the modal method was chosen for the synthesis of the regulator, which seems to be the most optimal, since it is possible to build a regulator of the minimum order using it, providing good indicators of the quality of the synthesized system. The synthesis of the minimum order observer can present some difficulty.

## 4.2. The theory of the synthesis of the modal regulator

Modal control allows you to obtain the desired transient process by ensuring the necessary position of the roots of the characteristic polynomial on the complex plane. At the same time, the task is to find the feedback coefficients based on the state of the object, and not due to the use of corrective links in the direct chain of the ACS.

According to [11], the synthesis of the regulator is carried out on the basis of state space equations. In vector-matrix form, these equations are written as follows:

$$\begin{cases} \frac{dX(t)}{dt} = AX(t) + BU(t); \\ Y(t) = CX(t), \end{cases} \quad (4.1)$$

where A, B, C are matrices of dimensionality coefficients (n×n), (n×m), (r×n), (r×m) respectively; (matrix A characterizes the dynamic properties of the system, B is the control matrix, it determines the nature of the influence of the input variables U (t) on the state variables X (t), C is the matrix of the connection between the output changes Y (t) and the state variables X (t) ).

m - number of inputs; r - the number of outputs; U (t) - control vector function, dimensions m; X (t) is a vector-function of state variables of dimension n; Y (t) is a vector function of the initial coordinates of dimension n.

For the synthesis of the modal controller, the object described by equations (4.1) must be fully controlled and monitored.

Full controllability is the ability to transfer the object from the initial state Xq to any predetermined state X with limited control action. Observability - the ability to determine the state vector X (t) from the output vector Y (t).

The Kalman criterion allows us to investigate observability and controllability. For this, it is necessary to check the ranks of controllability matrices U and observation V:

U= [B AB A2B A3B…An-1B];

V= [C CA CA2 CA3...CAn-1], (4.2)

The system is fully controlled when the rank of the matrix U is equal to the order of the system (n). The system is fully converged when the rank of the matrix V is equal to the order of the system (n).

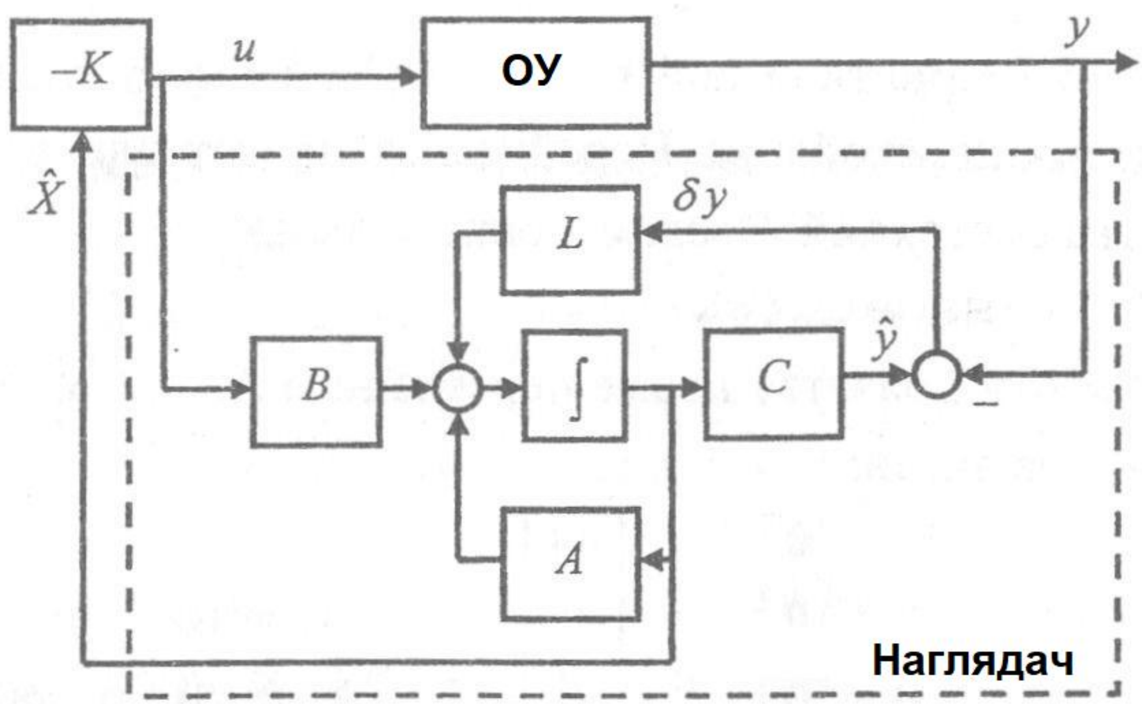



Figure 4.1 - The control system is closed by the supervisor and the regulator.

Figure (4.1) shows a control system with a supervisor and a regulator.

The state regulator is a negativeandthe reverse link for all components of the state vector. It should be noted that the order of the regulator is equal to the order of the system:

(4.3)

A closed system includes an object and a state controller:

$$u(t) = -KX(t) = -(k_1,\ k_2,\ \dots,\ k_n)X(t) = -(k_1x_1,\ k_2x_2,\ \dots,\ k_nx_n).$$

$$\frac{dX(t)}{dt} = AX(t) + B(-KX(t)) = (A - BK)X(t) = A_3 X(t), \quad (4.4)$$

where Az = A-VK is the state matrix of the closed system.

The matrix Aj must have the desired eigenvalues

$$\lambda_i, \quad i = 1, \ \ldots, \ n. \quad (4.5)$$

The coefficients of the matrix A3 are from the characteristic polynomial constructed according to the desired eigenvalues of A:

$$W_{ж}(p) = \prod_{i}^{n}(p - \lambda_i) = p^n + \overset{*}{a}_{n-1} p^{n-1} + \ldots + \overset{*}{a}_1 p + \overset{*}{a}_0,$$

$$A_3 = \begin{bmatrix} 0 & 1 & 0 & \ldots & 0 \\ 0 & 0 & 1 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & 0 & \ldots & 1 \\ -\overset{*}{a}_0 & -\overset{*}{a}_1 & -\overset{*}{a}_2 & \ldots & -\overset{*}{a}_{n-1} \end{bmatrix}. \quad (4.6)$$

The coefficients of the feedback matrix by state K are from equation (**).

The selection of the desired roots is carried out according to the Butterward distribution table.

Table 4.1 - Distribution of roots according to Butterworth

| No | Roots | | | | |
|---|---|---|---|---|---|
| 2 | - 0.7071+0.7071i | - 0.7071-0.7071i | | | |
| 3 | -1,000 | -0.5000+0.8660i | -0.5000-0.8660i | | |
| 4 | -0.3827+0.9239i | -0.3827-0.9239i | -0.9239+0.3827i | -0.9239-0.3827i | |
| 5 | -0.3090+0.9511i | -0.3090-0.9511i | -1,000 | -0.8090+0.5878i | -0.8090-0.5878i |

If the object is fully observable, then the current state of the object X (t) can be calculated from the measured values of the output variable y (t). In this case, the controlling influence will have the form:

$$u(t) = -K\hat{X}(t). \quad (4.7)$$

A state monitor is a model of the object covered by feedback on the deviation of the outputs of the model and the object. The estimate X (t) with an appropriate choice of the observer's feedback matrix

L should asymptotically tend to the state of the object. The definition of the L matrix is dual to the K matrix. Instead of A, B, let's substitute AT, CT.

In the case of a system specified in the canonical observable basis, first the desired values of the closed supervisor: λн and (и=1...,n), then the polynomial Wn(p) is written by the desired roots, then the matrix of the closed supervisor is constructed:

$$a_{\text{Н}\ i}\ (i=0,\ \dots,\ n-1)$$

$$(A_{\text{Н. З}})^{\text{T}} = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & 1 \\ -a_{\text{Н}\ 0} & -a_{\text{Н}\ 1} & -a_{\text{Н}\ 2} & \dots & -a_{\text{Н}\ n-1} \end{bmatrix} \quad (4.8)$$

where a is not (i =0, ..., n-1)

$$(A_{\text{Н. З}})^{\text{T}} = A^{\text{T}} - C^{\text{T}} L. \quad (4.9)$$

The eigenvalues specified during the synthesis of the state observer must provide greater speed than the eigenvalues specified during the synthesis of the regulator.

Figure 4. 2 – Block diagram of the algorithm for finding the feedback coefficients of the modal ACS by the classical method.

## 4.3. Synthesis of the modal controller in Matlab.

It is possible to find the transfer function of the observer of the system by the method of the root solution of polynomial equations. It is necessary to use the Euclid algorithm. At the same time, the modal controller provides a given distribution of poles and part of the zeros of the closed circuit transfer function of the quadcopter model.

The general Euclid algorithm can have the following form:

$$A(S) = B(S)P_0(S) + Z_1(S);$$

$$B(S) = Z_1(S)P_1(p) + Z_2(S);$$

$$Z_1(S) = Z_2(S)P_2(S) + Z_3(S);$$

$$Zb(S) = \beta. \quad (4.10)$$

The quadcopter has four flight modes: roll, pitch, yaw, and vertical movement or takeoff.

The roll contour is the contour of the position of the quadcopter along the OzXz axis. This contour is responsible for rotational and translational movement along the roll axis. The contour consists of two cascades: external - translational movement X and internal - angle of rotation φ. The values of the X positions allow tracking of the input, and the angle φ must be zero to prevent overshoot with respect to the X position.

Adjustment of the roll angle contour φ. Its transfer function has the form:

$$W\varphi = \frac{B(S)}{A(S)} = \frac{1}{S^2}.$$

Order B(S) = 0, order A(S) = 2.

Then $a=2$, $b=0$.

The transfer functions of the regulator and the closed circuit are realized if

$$\deg B(S) \leq deg A(S),$$

$$\text{i.e. } b \leq a.$$

$$W \text{ year}\varphi = \frac{S(S)}{R(S)}$$

Then the transfer function of the closed circuit of the contour of the angle φ takes the following form:

$$Wz\varphi = \frac{Q(S)}{D(S)} = \frac{B(S)S(S)}{B(S)S(S)+A(S)R(S)} \quad (4.11)$$

Let's get the value $P_0(S)$, $Z_0(S)$ and $Z_1(S)$:

$$P_0(S) = 1 \text{ and } Z_0(S) = Z_1(S) = 1. \quad (4.12)$$

Thus, it can be concluded that $A$(S) and $B$(S) are mutually prime. So, it can be assumed that $N_1$+$l$(S),$N_1$(S)$N_0$(S) are the parameters of the possibility to be implemented by the SAR based on modal control. These parameters can be obtained using the formula:

$$N1+l(S)=Ni(S)Pi(S)+Ni-l(S)=\overline{0,l,-1};$$

$$N-1(S)=0,\ N0(S)=1.$$

$$N1(S)=N0(S)=1, \text{ since } \deg B(S)=b=0. \quad (4.13)$$

From the realizability conditions, we obtain the degree restriction of the desired characteristic polynomial D (S) of the closed circuit. The degree of D (S) can be calculated using the following expression:

$$n\geq 2a+\alpha-1 \text{ when } a>b;$$

$$n\geq 2a+\alpha \text{ for } a=b,$$

where $n$ is the degree of D(S) and $\alpha$ is the number of free coefficients.

When $\alpha$=0 $n$=2∗2+0−1=3. (4.14)

The equation will look like this:

$$D(S)=(S+n)(S+n-1)(S+n-2)(S+n-(n-);$$

$$n-i\neq 0; \quad (4.15)$$

$$D(S)=(S+1)(S+2)(S+3).$$

Let's calculate $S$(S) according to equation (4.14):

$$S(S)=-\frac{1}{\beta}N1(S)D(S)-A(S).\gamma(S); \quad (4.16)$$

$$\gamma(S)=\frac{\frac{1}{\beta}N_1(S)D(S)}{A(S)}$$

Then we get:

$$S(S)=11p+6. \quad (4.17)$$

The denominator of the transfer function of the roll angle regulator:

$$R(S)=\frac{D(S)-B(S)S(S)}{A(S)}=\frac{S^3+6S^2}{S^2} \quad (4.18)$$

Thus, the complete form of the transfer function of the roll angle regulator φ has the form:

$$W\text{p}\varphi=\frac{S(S)}{R(S)}=\frac{11S^3+6S^2}{S^3+6S^2} \quad (4.19)$$

Consider the external contour, that is, the contour of the position of the quadcopter along the OX axis. Using the algorithm for finding the transfer function of the roll angle regulator, it is possible to find the transfer function of the X-position regulator. For this, you should determine the values of the parameters a, b, β, n,$N_1$(S),$D$(S),$S$(S) and $R$(S) for the transfer function:

$$WX(S)=\frac{g/I_{xx}}{S^2} \quad (4.20)$$

Values of the parameters based on the geometric parameters of the quadcopter:

$$a=1;$$

$$b=0;$$

$$n=2a-\alpha-1=4-\alpha-1=1-\alpha=3, \text{ when } \alpha=0;\ \beta=b=1;$$

$$N1(S)=1;\ D(S)=(S+1)(S+2)(S+3);$$

$$S(S)=\frac{1}{\beta}N1(S)D(S)-A(S).\gamma(S)=-12p-6;$$

$$R(S)=\frac{D(S)-B(S)S(S)}{A(S)};\quad (4.21)$$

$$R(S)=\frac{(S+1)(S+2)(S+3)-g/Iyy(-12p-6)}{S^2};$$

$$Wpx(S)=\frac{S(S)}{R(S)}=\frac{-12S^2-6S}{S^3+6S^2+599.6p+294.3}$$

where $Wpx(S)-$ is the transfer function of the position along the OX axis.

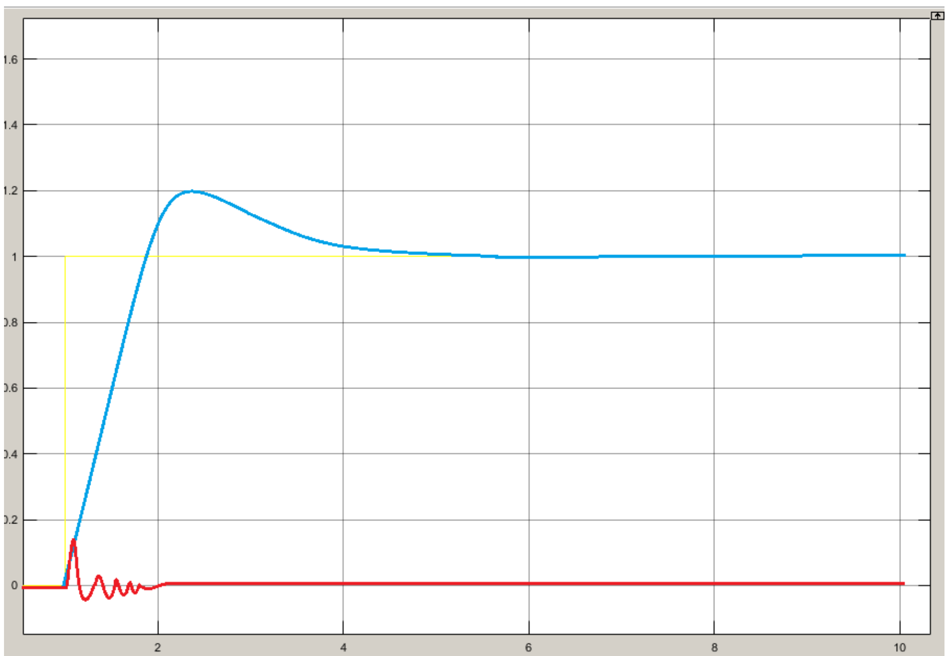



Figure 4.3 - Modeling the X position contour

Since, taking into account the symmetry of the quadcopter, the position contours along the X and Y axes are identical in terms of parameters and structure, since the parameters IYY and IXX have equal values.

$$Wp\theta=\frac{S(S)}{R(S)}=\frac{11S^3+6S^2}{S^3+6S^2}\quad (4.22)$$

$$W\ yeary(S)=\frac{S(S)}{R(S)}=\frac{-12S^2-6S}{S^3+6S^2+599.6p+294.3}\quad (4.23)$$

where $W\rho\theta\ (p)$ is the transfer function of the pitch angle regulator θ;

$WpY(p)$ is the transfer function of the position regulator along the Y axis.

The task of controlling the yaw angle is to ensure a zero value during flight, otherwise the quadcopter rotates around the vertical axis. The adjustment of the angle ψ and other angles θ and φ is based on the same parameters. The only difference is in the moment of inertia parameter IZZ.

IZZ =l2·m (4.24)

where l is the distance from the center of mass to the engine (taking into account the selected frame 0.650/2 = 0.325 m);

m - weight of the quadcopter (3,200 grams)

IZZ = 3.2· (0.325)2=0.338 kg·m2.

Then, the angle regulator ψ has the same transfer function as the regulators θ and φ with the multiplication of its numerator by $\frac{\mathrm{Izz}}{l}$. The transfer function of the angle regulator ψ$Wp$ψ (S) has the following form:

$$Wp\psi(S) = \frac{0.338(11S^3+6S^2)}{S^3+6S^2} \quad (4.25)$$

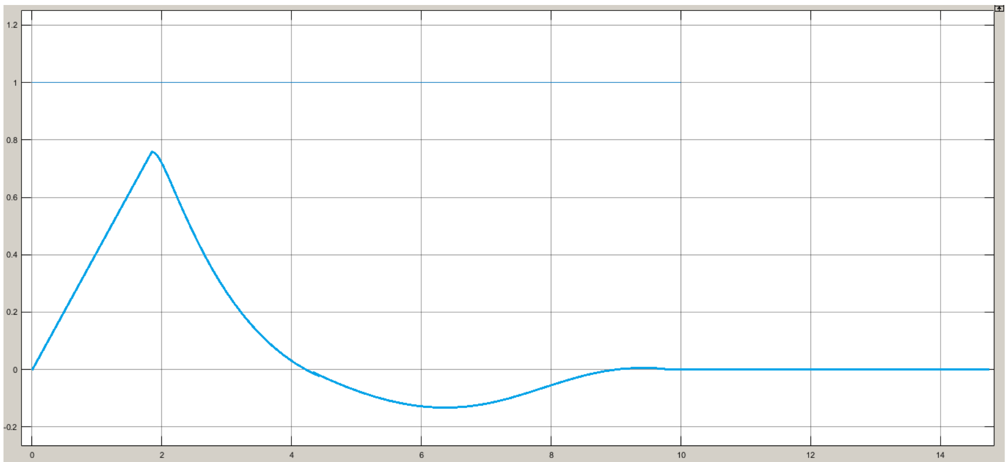



Figure 4.4 - Modeling the corner contourψ. Stabilization of the zero position when disturbed relative to the vertical axis.

The transfer function of the height contour Z of the open circuit Z is represented by two successive integrating links. Therefore, the transfer function of the regulator is also the transfer function of the angle regulators θ or φ multiplied by the output $\frac{g}{m}$.

$$W \text{ yearZ(S)} = \frac{-12S^2-6S}{S^3+6S^2+599.6p+294.3} * \frac{g}{m} = \frac{-12S^2-6S*(3{,}06)}{S^3+6S^2+599.6p+294.3} = \frac{-36{,}72S^2-18{,}36S}{S^3+6S^2+599.6p+294.3} \quad (4.26)$$

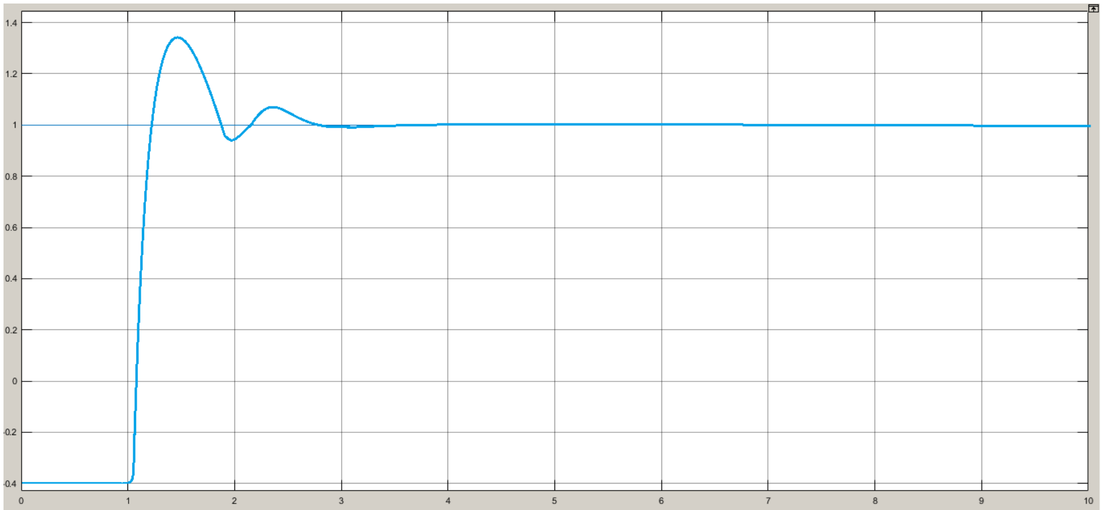



Figure 4.5 - Modeling the contour of the Z position.

In this way, the synthesis of modal regulation was carried out. It can be seen from the graphs that the obtained regulators on three channels of quadrocopter control bring the system to a stable mode. Appendix No. 1 lists the program for setting up the modal regulator in the Matlab software environment.

# 5. EXPERIMENTAL – PRACTICAL PART

## 5.1. Computer simulation environment Matlab/Simulink

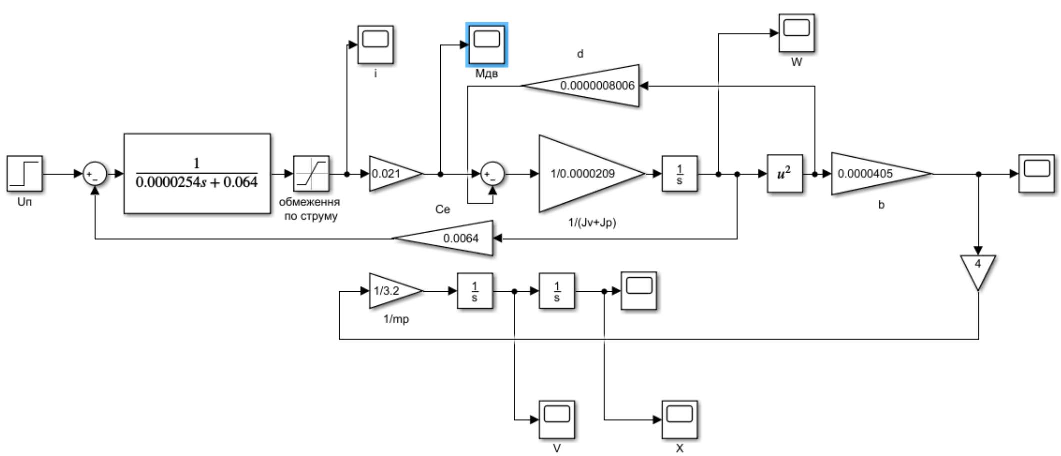
Computer modeling is one of the main methods of analysis of aircraft control systems. Modeling allows you to establish the interaction of all aircraft systems and catch a large part of development errors even before the testing stage. An interactive environment for programming, numerical calculations and visualization of results - MATLAB - is quite popular and simple for the development of control systems. With the help of this program, you can analyze data, develop algorithms, create models and applications. A separate sub-environment is a graphical simulation simulation environment - Simulink, which allows you to build dynamic models, including discrete, continuous and hybrid, nonlinear and discontinuous systems, using block diagrams in the form of directed graphs.

With the help of these simulation programs, the ACS of the quadcopter was reproduced and analyzed.

## 5.2. Computer model of DPS

According to point 2.8 of the diploma thesis, a diagram of a direct current motor was formed, and a specific motor was selectedT-Motor MN3510-15 in point 3.1.2. design part.

Computer model of DPS in the environmentMatlab/Simulink will look like




this:

Figure 5.1 -Computer model of DPS.

where the calculated coefficients were used:

Table 5.1 - DPS coefficients:

| | | |
|---|---|---|
| Up | Supply voltage | 5 V |
| Se | Motor constant for anti-emf | 0.064 |
| b | Aerodynamic coefficient of thrust of one propeller | 0.0000405 N·c2 |
| d | Aerodynamic coefficient of air resistance to propeller rotation | 0.0000008006 N·m·c2 |
| mp | UAV mass | 3.2 kg |

In this way, the main characteristics of the designed engine were obtained:

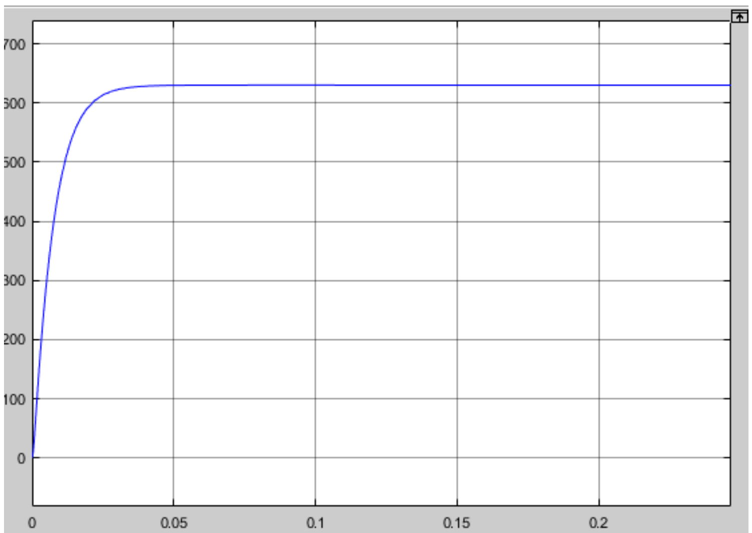



Figure 5.2 - Transient characteristics of engine speed (rad/s)

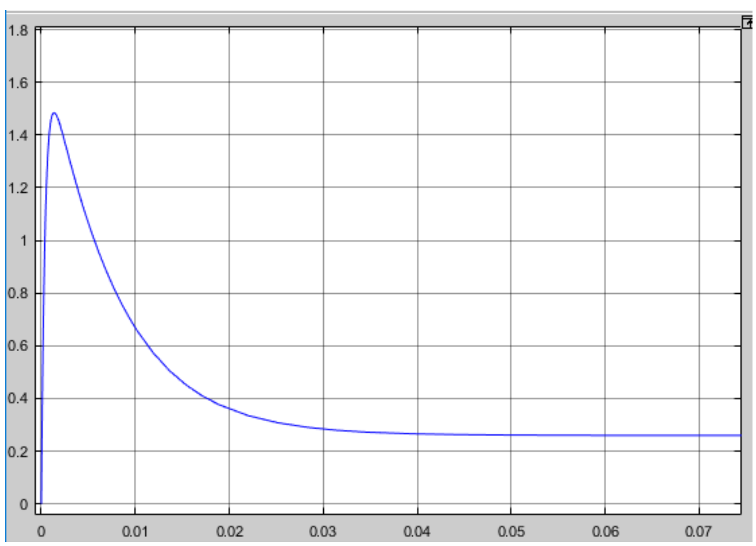



Figure 5.3 - Torque on the motor shaft

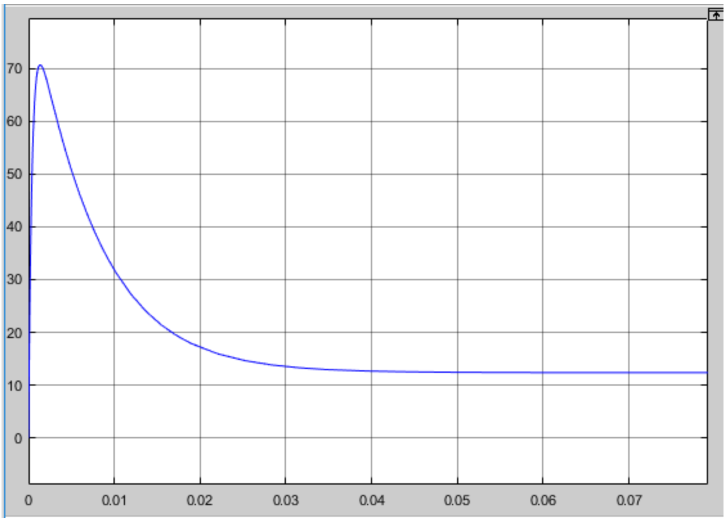



Figure 5.4 - Current characteristics

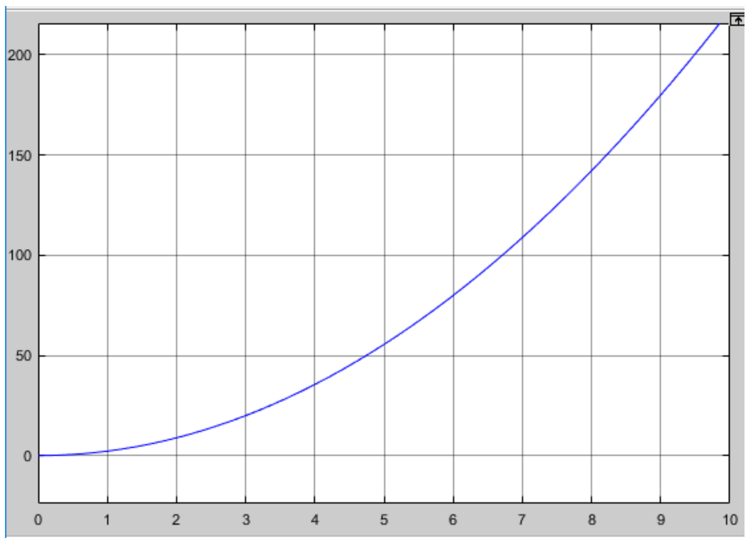



Figure 5.5 - Characteristics of movement or change of the X coordinate.

The transfer function of the selected DPS was found separately

We believe that the electromagnetic time constant of the engine is much smaller than the electromechanical constant, i.e.:$T_e \ll$ Tm =$T_д$

Based on the linearized mechanical characteristics of the electric motor, the idealized transfer function (without taking into account the time delay and winding inductance) from the excitation voltage Uc to the angular speed of rotation of the electric motor rotor ω has the form:

$$W(S)=\frac{\omega}{U_c}=\frac{К_{дв}}{T_д S+1} \quad (5.1)$$

where$К_{дв}=\frac{1}{k\Phi}$– transmission ratio of the electric motor

$T_д$- time constant of the electric motor.

Let's find the coefficient$k\Phi$.

$$k\Phi=\frac{U_н-I_н R_я}{\omega_н} \quad (5.2)$$

Since the quadcopter control system includes a real engine with its own parameters (paragraph 3.2.1.), we will get the followingcoefficient$k\Phi$ (при осьовій нагрузці 85% і 15′пропелерами ):

$$k\Phi=\frac{U_н-I_н R_я}{\omega_н}=\frac{U_н-I_н R_я}{2\pi n/60}$$

Un = 5V, since a current of 5V comes out of the ECS.

$$k\Phi=\frac{5-12{,}3\cdot 0{,}065}{660}= 0.0064\frac{В\cdot с}{рад}$$

Then the proportionality coefficient for EMF resistance is equal to:

$$Кдв = \frac{1}{0{,}0064} =156.25$$

Let's calculate the time constant using the formula:

$$T_д = \frac{R_я\cdot J}{k\Phi^2}=\frac{0{,}065\cdot 0{,}000325}{0{,}000041}=0.52 \quad (5.3)$$

where$J = \frac{1}{2}mR^2$- the moment of inertia of the rotor, which describes the trajectory of the cylinder:

m – the average mass of the propeller [kg]

R - propeller radius [m]

Then$W(S)= \frac{\omega}{U_c} = \frac{Кдв}{T_д S+1} = \frac{156{,}25}{0{,}52\, S+1}$ (5.4)

## 5.3. Computer model of a quadcopter with PD controller

The computer model of the quadcopter with the resulting DPS transfer function will look like this:

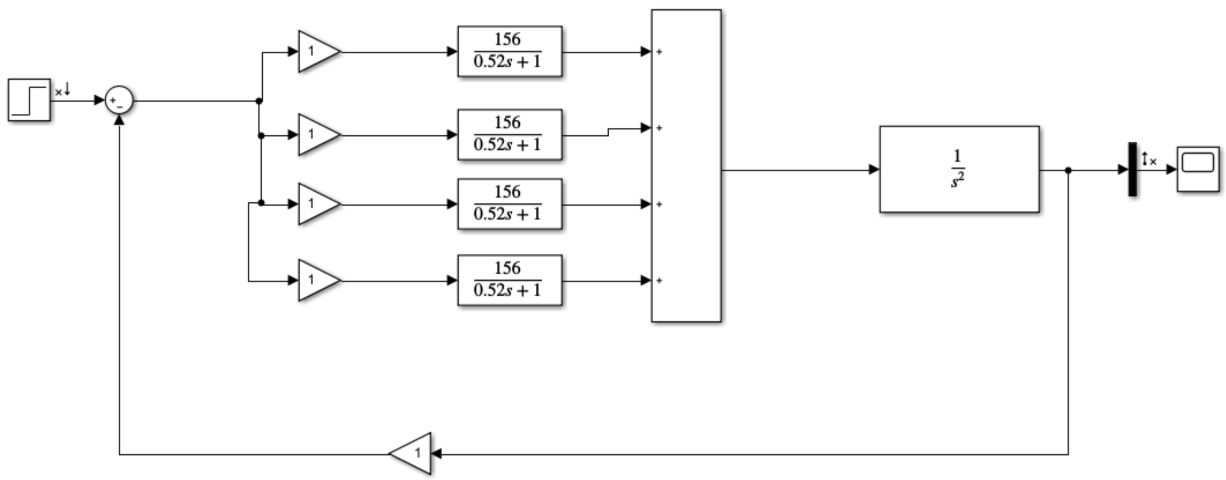



Figure 5.6 -A computer model of a quadcopter with the resulting DPS

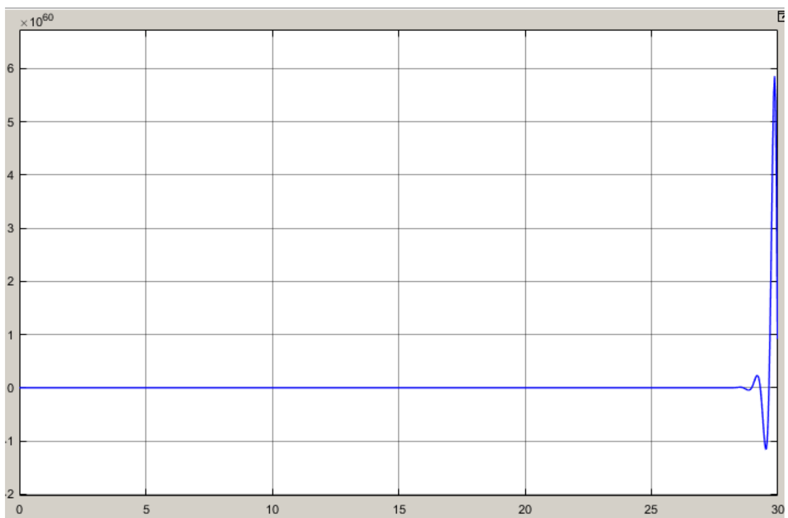



Figure 5. 7 - Transient characteristics of the system

According to the graph of the transition process, we can see that the system is unstable, so it is necessary to use a regulator that is able to debug the system.

Enter the one chosen according to point 2.6. PD regulator and disturbing influence.

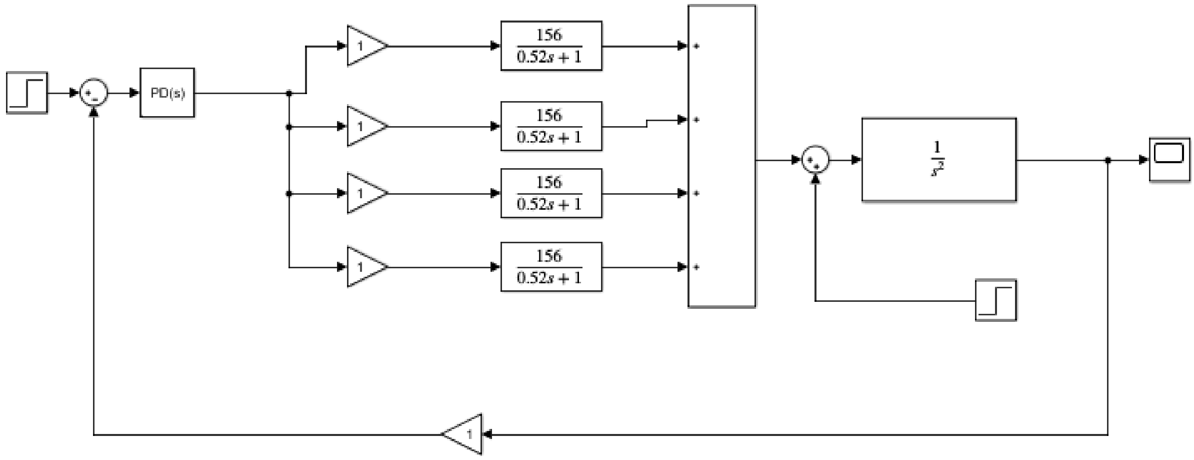



Figure 5.8. Computer model of a quadcopter with PD controller.

Software environmentMatlab/Simulink has a PID Tuner subroutine in its library, which allows you to automatically select the coefficients of the PID controller, depending on the transfer function of the object.

The PID Tuner uses a patented method of adjusting the coefficients of the PID - regulator, based on feedback from the operating characteristics that the user wants to obtain. The initial values of the regulator coefficients are based on an approximate analysis of the system dynamics. The PD regulator was selected in the settings and the "desired" transition process was set in the semi-automatic mode. The table shows stability criteria: settling time, rise time,

Overshoot, peak deviation, gain margin, maximum phase margin, closed-loop stability.

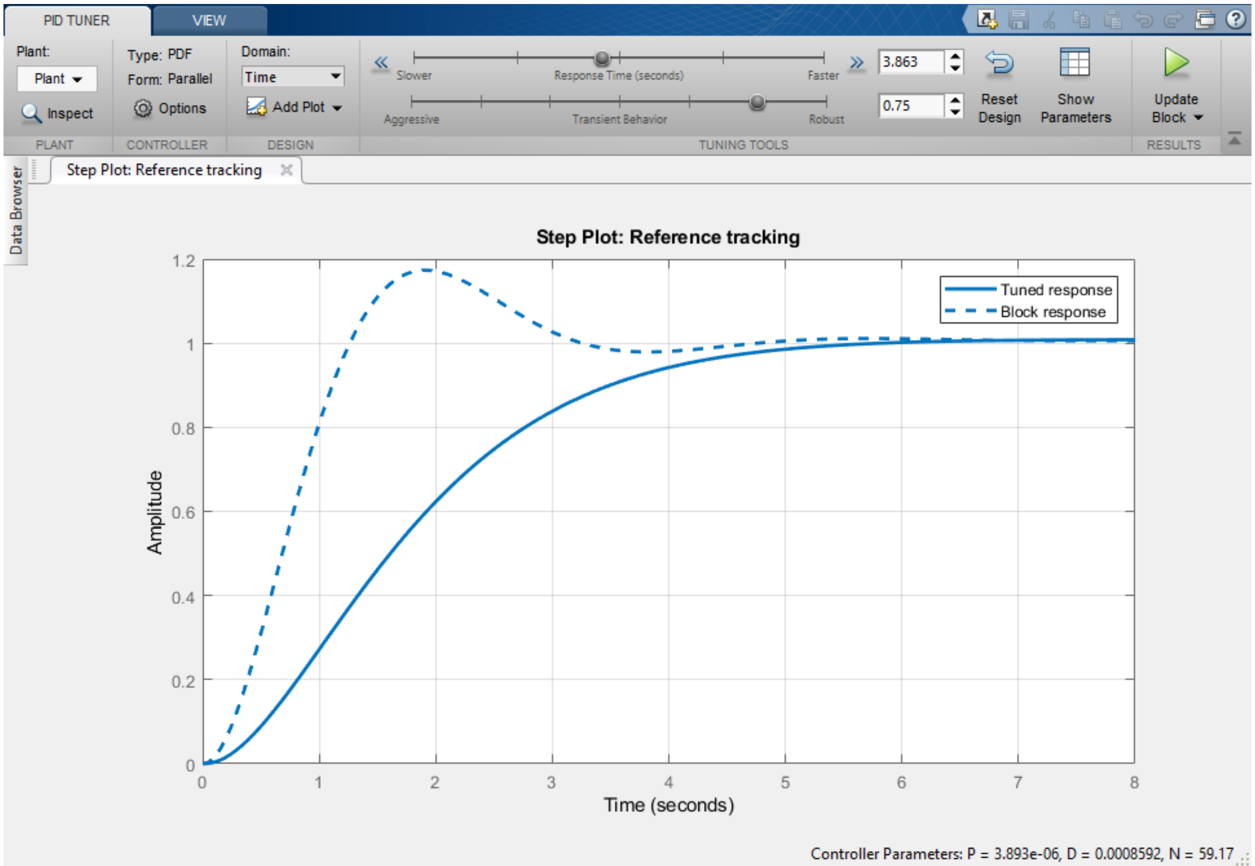



Figure 5.9 - Window for adjusting the PD of the regulator

Controller Parameters

| | Tuned | Block |
|---|---|---|
| P | 3.8929e-06 | 3.9586e-05 |
| I | n/a | n/a |
| D | 0.00085921 | 0.0030294 |
| N | 59.1704 | 170.6494 |

Performance and Robustness

| | Tuned | Block |
|---|---|---|
| Rise time | 2.96 seconds | 0.852 seconds |
| Settling time | 4.8 seconds | 3.96 seconds |
| Overshoot | 0.846 % | 17.3 % |
| Peak | 1.01 | 1.17 |
| Gain margin | 41.1 dB @ 10.7 rad/s | 39.1 dB @ 18.1 rad/s |
| Phase margin | 73.9 deg @ 0.518 rad/s | 51.2 deg @ 1.49 rad/s |
| Closed-loop stability | Stable | Stable |

Figure 5.10 - Obtained PD characteristics of the regulator

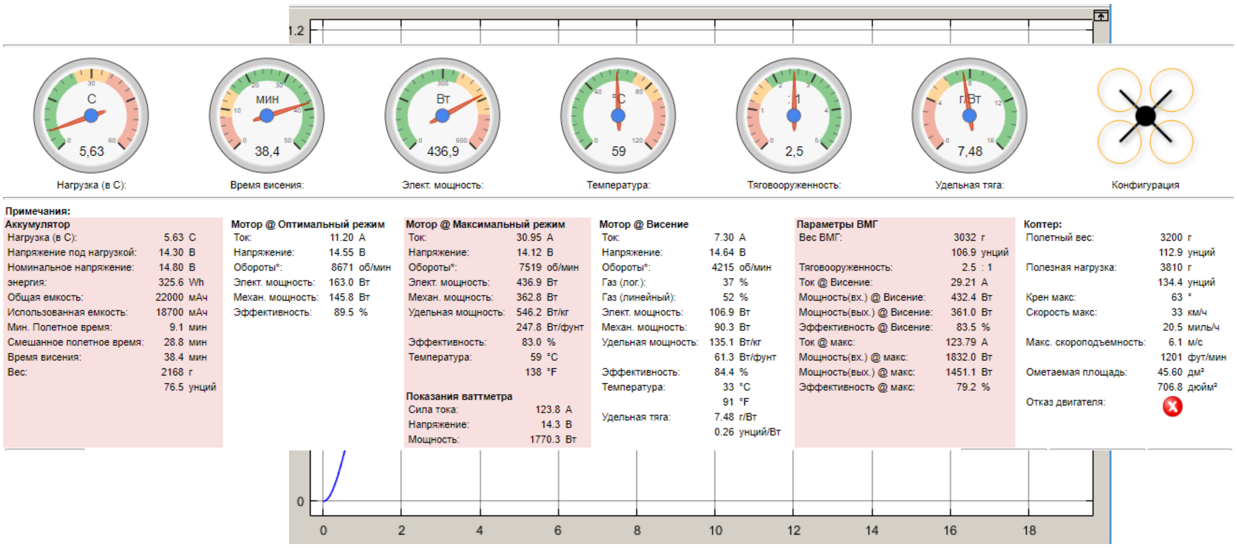


Figure 5.11 - Transient characteristics of the system

## 5.4. Performance analysisquadcopter designs.

The online service www.ecalc.ch was used to evaluate the operational parameters of the quadcopter design, which allows for their calculation and optimization.

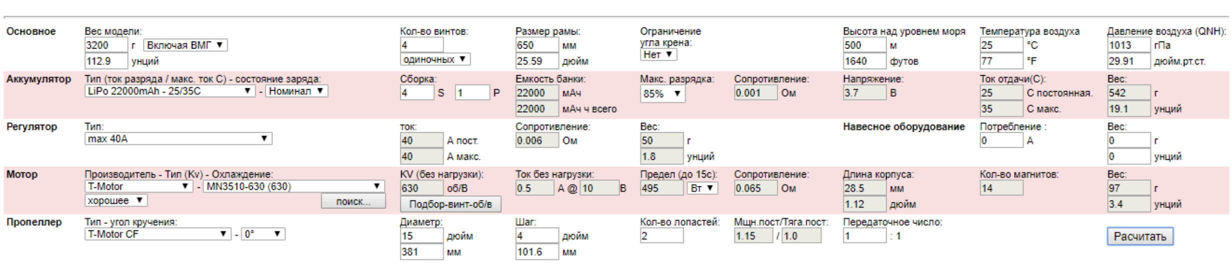
This service has in its database all the necessary parts for the developed design. The necessary elements are entered in the interactive window: battery, speed controller, engine, propellers with additional settings.

In this way, the effectiveness of the developed structure was evaluated. The flight was simulated at an altitude of 500 m above sea level, at 25°C, up to 85% battery discharge.

Figure 5.12 - eCalc input parameters window.

Obtained battery characteristics, optimal flight mode, hover mode, parameters of the rotorcraft group (VMG), and payload:

Figure 5.13 - eCalc output parameters window.



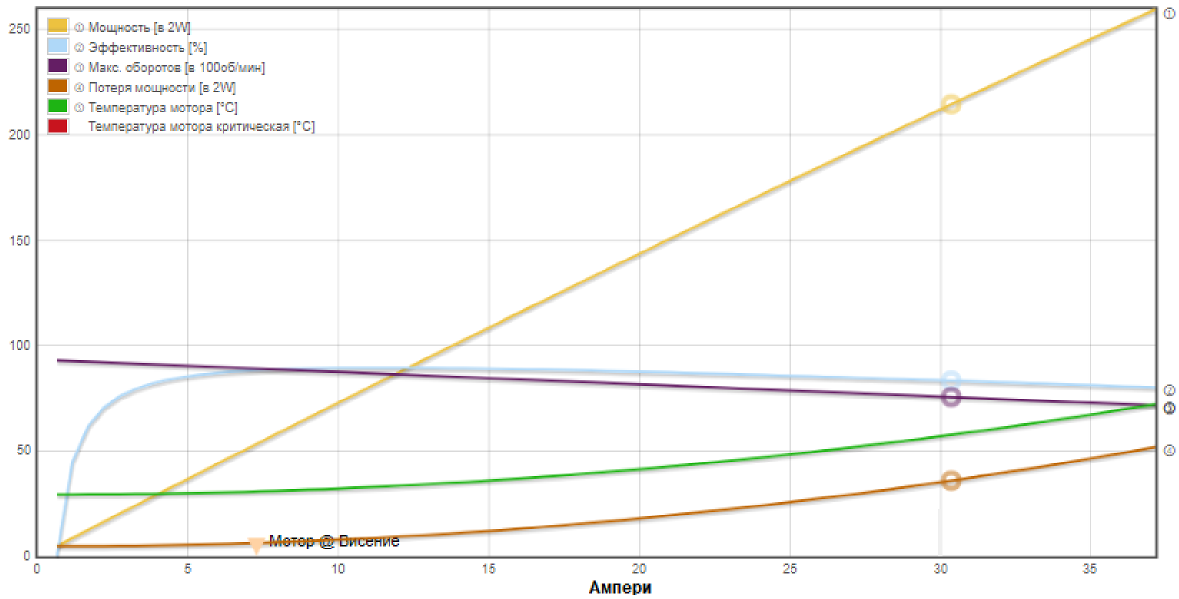



Figure 5.14 - Characteristics of engines

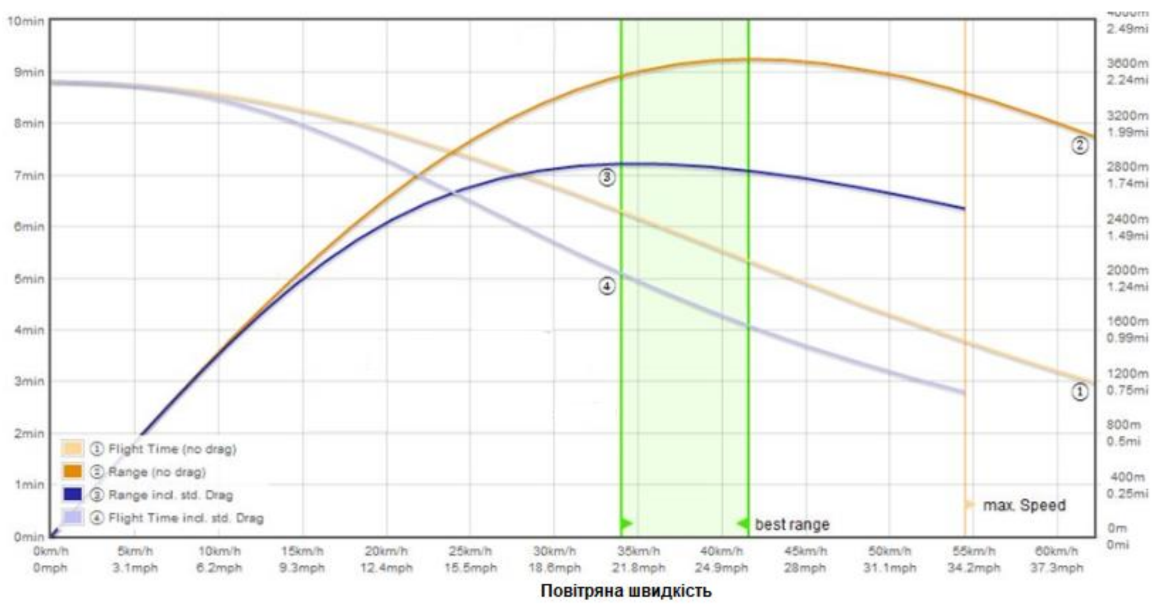



Figure 5.15 - Minimum flight time at maximum load

Graphs of engine efficiency are plotted, and flight time is calculated. It should be noted that the flight time schedules are quite low, which indicates the minimum flight time at maximum load. The payload is 3810 grams, with the total weight of the quadcopter with the selected equipment 3200 grams.

# 6. ECONOMIC PART. CALCULATION OF THE COST AND PRICE OF THE QUADROCOPTER SYSTEM

## 6.1. Purpose of the economic section and description of the product.

In the thesis, a system of automatic flight stabilization of UAVs when entering a given route with modal regulation is developed. This system is intended for multi-rotor UAVs, in particular quadcopters. This adjustment approach can be used in other drones of this type when changing system components. The elements of the quadcopter were selected as individual modules from the many options available on the market.

The automatic stabilization system consists of the following functional units:

- setter of control signals (operator remote control, GPS coordinates);
- flight controller, which includes sensors (gyroscope, accelerometer, barometer, magnetometer);
- electric motors;

As well as accessories and attachments that count as a complete quadcopter system.

The main functions of the stabilization system are the stabilization of the drone in the air relative to the given route, which is achieved by adjusting the number of revolutions of the quadcopter engines, which depend on the parameters of the specified influences (given flight parameters) and disturbances.

The device meets modern requirements for devices of a similar class in terms of design reliability, performance, overall dimensions, and weight.

The purpose of this section is to study the economic feasibility of using the development and its implementation in production, as well as comparing the created quadcopter system with existing analogues. For this, it is necessary to solve the following tasks:

1. segment the device market;
2. determine the competitiveness of this development;
3. calculate the labor intensity of work;
4. prepare estimates of development costs;
5. calculate wages, determine the cost of the object, and calculate the expected profit from the implementation of the system.
6. calculate the break-even point and plot the break-even point.

## 6.2. Market segmentation

In this point, the market segments of the designed system are identified. A segment is a group of consumers who have similar needs, capabilities and desires regarding a product. The segment must be large enough in terms of the number of consumers, as well as in terms of purchasing power, in order to ensure profitable sales.

Market segmentation is the process of dividing consumers into separate segments, taking into account various segmentation principles and factors.

The target consumers of the developed system are aviation factories, enterprises, private individuals who are engaged in the development, assembly and adjustment of multi-rotor devices, as well as manufacturers of various devices, where methods of modal regulation can be used. Since these systems are manufactured to order, it is advisable to segment the market according to end customers.

The main characteristic of the segment is capacity - the number of products that can be sold per year.

Calculations of the market capacity are carried out after determining the composition of the segments and begin with the determination of the total need for the product of this type:

$$S_{повн} = \sum_{i=1}^{L} S_{1повн_i} \quad (6.1)$$

where Spovn is the total need for the product for all segments, pcs. / year;

S1complete - complete need of one segment, pc. / year;

i - segment number;

L - number of segments, pcs.

The full demand of the segment is calculated taking into account the specific features of the product and segments. For many types of goods for individual and industrial purposes, S1 can be calculated according to the following formula:

$$S_{1повн_i} = N_i \cdot Q_i \cdot m_i \text{ , } (6.2)$$

where Ni is the number of enterprises-consumers of the product in the i-th segment;

Qi - the average annual program of products in the i-th segment for which the product will be supplied;

mi - number of components.

Segmentation and calculation of market capacity are given in the table. 6.1:

Table 6.1 - Segmentation and calculation of market capacity

| Organization | Segment code | N, pcs. | Q, pcs. | S1full, units/hour |
|---|---|---|---|---|
| State enterprises | AND | 20 | 10 | 200 |
| Private individuals of Ukraine | B | 2 | 8 | 16 |
| Enterprises of near abroad | IN | 15 | 4 | 60 |
| Enterprises from far abroad | G | 6 | 6 | 36 |
| In total | | | | 312 |

From the table. 6.1. it can be seen that the full capacity of the market reaches 312 copies per year..

## 6.3. Analysis of competitiveness.

Product competitiveness is the level of its economic indicators and consumer properties, which allows it to withstand competition with other similar products on the market. Product competitiveness is a complex property formed by its quality (consumer value), consumption price, effectiveness of marketing and commercial activity and is determined by the consumer's reaction to these external manifestations.

Next, an assessment of the competitiveness of the developed quadcopter system is provided.

The developed system is not unique, but it has a number of advantages compared to competitors. These advantages are due to price and multifunctionality.

On the basis of the available data on the characteristics of competitors' developments and the developed system, an analysis of competitiveness is carried out.

Ready-made quadcopter systems should be considered the strongest competitors on the market:

1. DJI PHANTOM 4 Pro-XI; 42K
2. DJI MAVIC PRO-X2; 34 K
3. GoPro Karma- Khz. 37K

The index - X0 is assigned to the developed system. To assess the positions of competitors, it is necessary to build table 6.2. At the same time, the key factors of success will be the indicators that determine the final characteristics: the quality of the assembly, the accuracy of the stabilization system, and the flight range.

The developed drone system must be compared with similar competing systems. When comparing, it is advisable to apply the method of comprehensive analysis of quality indicators with calculations of generalized indicators and the level of complexity.

Table 6.2 - Analysis of competitor firms

| Key success factors | The results of the ranking of competitors' firms according to the strength/weakness of their positions in the market | | | |
|---|---|---|---|---|
| | Power | | weakness | |
| Development technology | X1 | X2 | X0 | X3 |
| Sales review | X1 | X2 | X0 | X3 |
| Net profit | X0 | X1 | X3 | X2 |
| Cost | X0 | X2 | X3 | X1 |
| Sales area | X1 | X0 | X2 | X3 |

Let's determine the absolute values of the i-th indicators of the j variants of Pij in points. We assign the weighting factor bi as a quality indicator:

$$\sum_{i=1}^{n} b_i = 1 \text{ и } b_i < 0, i = 1; \qquad (6.3)$$

where n is the number of quality indicators.

Quality indicators are divided into minimized and maximized and form a hypothetical (reference option).

For each j-th variant, the relative values of the i-th indicators (kij) by comparing Pij with РиГИП (taking into account the condition kij ≤1).

1. for minimizable indicators;
2. for maximized performance.

We enter the obtained results in table 6.3.

Table 6.3 - Analysis of competitiveness

| The indicator is the weighting factor | | Absolute values of quality indicators | | | | | Relative values of quality indicators | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Variants of the complex | | | | | Variants of the complex | | | | | | | | | |
| | | X0 | X1 | X2 | X3 | Hyp | X0 | | X1 | | X2 | | X3 | | Hy p. | |
| Stabilization accuracy | 0.4 | 4 | 4 | 4 | 3 | 5 | 0.8 | 0.32 | 0.8 | 0.32 | 0.8 | 0.32 | 0.6 | 0.24 | 1 | 0.4 |
| The ability to adapt to changing parameters | 0.2 | 5 | 2 | 2 | 4 | 5 | 1 | 0.2 | 0.4 | 0.08 | 0.4 | 0.08 | 0.8 | 0.16 | 1 | 0.2 |
| Speed action | 0.2 | 5 | 5 | 4 | 4 | 5 | 1 | 0.2 | 1 | 0.2 | 0.8 | 0.16 | 0.8 | 0.16 | 1 | 0.2 |
| Ease of implementation 0.1 | 0.1 | 3 | 5 | 5 | 4 | 5 | 0.6 | 0.06 | 1 | 0.1 | 1 | 0.1 | 0.8 | 0.08 | 1 | 0.1 |
| Working on rejection | 0.1 | 4 | 4 | 3 | 2 | 5 | 0.8 | 0.08 | 0.8 | 0.08 | 0.6 | 0.06 | 0.4 | 0.04 | 1 | 0.1 |
| In total | - | - | - | - | | | - | 0.86 | - | 0.78 | - | 0.72 | - | 0.68 | - | 1 |

The generalized indicator of the quality of the developed system is the largest - 0.86, which can be seen from table 6.3. This shows that the system is competitive.

Having received the generalized, it is necessary to consider the levels Indicators$k_k^0$for all options considered, the competitiveness of the new application compared to competing applications.

$$Y_{j-b} = \frac{K_j^0}{K_k^0} \quad (6.4)$$

where$k_k^0$- generalized indicator of the competitor application.

Quality levels of the new application compared to competing applications:

$$Y_{X0-X1} = \frac{0,86}{0,78} = 1,1;$$

$$Y_{X0-X2} = \frac{0,86}{0,72} = 1.19;$$

$$Y_{X0-X3} = \frac{0,86}{0,68} = 1.26.$$

As a result of the analysis, it can be concluded that the developed quadcopter system has high competitiveness.

## 6.4. Calculation of cost and price of the system

The cost of the product consists of a number of costs. This includes costs for basic materials, large components, direct and additional wages, costs for maintenance and operation of equipment, as well as a number of statewide taxes and deductions.

The following workers are required to design the computer:design engineer, installer-technologist, manager. The length of a working month is considered to be 22 days on average. The list of performers is given in the table. 6.4.

We will calculate the duration of development by types of work. The result of the calculations is contained in the table. 6.4.

Table 6.4 – Composition of work performers

| Position | Salaries, hryvnias | |
|---|---|---|
| | Month | Day |
| Design engineer | 9400 | 427.27 |
| Installer-technologist | 7190 | 326.81 |
| Head | 12500 | 568.18 |

Table 6.5 – Calculation of labor intensity of works

| Type of works | Duration, | | Performer |
|---|---|---|---|

| | days | Labor intensity, person / hour | Design engineer | Installer-technologist | Head |
|---|---|---|---|---|---|
| Preparatory works | | | | | |
| Formulation of the problem | 1 | 2 | + | - | + |
| Analysis of the subject area | 1 | 2 | + | - | + |
| Terms of Reference (TOR) | | | | | |
| Development of system requirements | 1 | 3 | + | + | + |
| Development of TK | 2 | 4 | + | + | - |
| Approval of technical specifications | 1 | 3 | + | + | + |
| Designing a control system with a modal regulator | | | | | |
| Synthesis of the control system | 4 | 4 | + | - | - |
| Assembly works | 3 | 3 | - | + | - |
| Acceptance and delivery works | 1 | 2 | - | + | + |
| Implementation | | | | | |
| System debugging | 2 | 4 | + | + | - |
| Testing and commissioning | 2 | 6 | + | + | + |
| Together | 18 | 33 | 14 | 12 | 7 |

The calculation of the labor intensity of the work is given in table 6.5.

Thus, the total duration of the work will be 18 days, the total labor force will be 33 people. / days The labor intensity of the engineer-designer will be 14 days, the installer-technologist - 12 days, the manager - 7 days.

Let's calculate the basic salary of employees involved in the production of the regulator, taking into account labor costs, the number of performers and the average daily salary. To do this, the number of days worked by individual performers is multiplied by their daily wages:

$$ОЗП = \sum_{i=1}(N_i \cdot ЗП), (6.5)$$

where N_i is the number of days worked by i-th performers;

ZP - daily salaries of i-th performers, hryvnias.

Thus, the basic salary:

$$ОЗП = 427.27 \cdot 14 + 326.81 \cdot 12 + 568.18 \cdot 7 = 13\ 880.76грн.$$

We will calculate the additional salary (DZP), which is 20% of the OZP.

DZP = 0.2· OZP.

As you can see, the additional salary is equal to:

DZP = 0.2 ·13 880.76= UAH 2,776.15

Let's calculate the cost of purchased products necessary for the manufacture of a calculator.

Table 6.6 – List of purchased products

| Name of purchased products | The number of products in the system | Price per product unit, UAH | Amount, UAH |
|---|---|---|---|
| Frame | 1 | 3500 | 3500 |
| Engine | 4 | 2200 | 8800 |
| Propellers | 4 | 248 | 995 |
| ECS | 1 | 1278 | 1278 |
| battery | 2 | 4350 | 8700 |
| Flight controller | 1 | 2270 | 2270 |
| GPS receiver | 1 | 460 | 460 |
| Cell | 1 | 1600 | 1600 |
| FPV equipment | 1 | 1565 | 1565 |
| Wires | 1 | 385 | 385 |
| Suspension | 1 | 3550 | 3550 |
| Timer | 1 | 185 | 185 |
| In total | | | 33,288 |

Table 6.7 – Cost of fixed assets

| Equipment | Number | Price, UAH |
|---|---|---|
| Table | 3 | 800 |
| Chair | 3 | 300 |

| | | |
|---|---|---|
| Lamp | 3 | 400 |
| Collection tools | 1 | 1,000 |
| Computer | 1 | 9,000 |
| In total | | 12,250 |

Deductions to the unified social fund amount to 22% of the basic salary and additional salary:

EUV = 22% · (OZP + DZP) = 0.22 (13 880.76 + 2 776.15 ) = UAH 3,664.52.

The annual rate of depreciation deductions (Am) is calculated as 25% of the cost of fixed assets, for the production of 1 product:

$$\text{Ам} = \frac{25\% \cdot \text{вартість засобів} \cdot \text{Др}}{\text{Д}_{\text{річ}}} = \frac{0.25 \cdot 12\,250 \cdot 18}{22 \cdot 12} = 208{,}8 \text{ грн}$$

whereДр- duration of working days

$\text{Д}_{\text{річ}}$ – кількість робочих днів у році

Non-production costs are calculated according to the formula:

Vpv = 40% · OZP = 0.4· 13 880.76= UAH 5,552.3

Equipment maintenance costs are 10% of the cost of fixed assets:

Internal region = 0.1·12,250 = 1,225 UAH.

The production cost of software product development is equal to the sum of all costs and is calculated according to the formula:

C = OZP + DZP + ESV + Am + Sel + Vtr.obl + Vpv =13 880.76+ 2,776.15 + 3,664.52 +208,8 + 33,288+1,225 + 5,552.3 = 60,595.53 hryvnias.

The development price is calculated according to the formula:

Tsrazr = C + P = 59,370.53+ 11,874.1 = 71,244.64 hryvnias.

where P is the planned profit (20% of the development price).

P = 59,370.53* 0.2 = 11,874.1 UAH.

Full development cost including VAT:

Ts = Tsrazr + VAT.

Value-added tax is 20% of the development price:

VAT = 71,244.64 * 0.2 = 14,248.93 UAH.

Following the previous statements, the total development cost, including VAT, is equal to:

Ts = 71,244.64 + 14,248.93 = 85,493.6 UAH.

Table 6.8 - Calculation of the cost price and price of the product by articles

| No | Articles | Amount, UAH | Formula |
|---|---|---|---|
| 1 | Basic salary (OZU) | 13 880.76 | $ОЗП = \sum_{i=1}^{5}(N_i \cdot ЗП),$ |
| 2 | Additional ZP (DZP) | 2 776.15 | 20% of OZP |
| 3 | Her social contribution | 3,664.52 | 22% ·(OZP+DZP) |
| 4 | Materials and purchased products | 33,288 | from table 6.2 |
| 5 | Amortization | 208.8 | $Ам = \frac{25\% \cdot Вартість\ осн. \cdot 18}{22 \cdot 12}$ |
| 6 | Equipment maintenance costs | 1,225 | 10% of the cost of fixed assets |
| 7 | General plant costs | 5 552.3 | 40% of RAM, |
| 8 | Production cost | 60,595.53 | $п.1 + \cdots. + п.7$ |
| 9 | Administrative expenses | 6 246.3 | 45% of RAM |
| 10 | Selling expenses | 1514.9 | 2.5% of item 8 |
| 11 | Cost of own works | 128,952.3 | $п.1 + \cdots. + п.10$ |
| 12 | Profit (P) | 25,790.46 | $20\%$ від $п.11$ |
| thirteen | Price without VAT | 154742.76 | $П + п.11$ |
| 14 | VAT | 30,948.5 | $20\%$ від ціни без ПДВ |
| 15 | Price with VAT | 185 691.3 | $п.13 + п.14$ |

Thus, the cost of the project's own work on the development of a laboratory workshop is UAH 128,952.3, and the project price (including VAT) is UAH 185,691.3.

The number of ordered copies must not be less than 312 pieces.

The production cost of one copy of the software product (SP) is determined by the formula:

$$VS0 = VS/kpp \qquad (6.6)$$

where VS - production costs;

KPP - the number of copies ordered.

$$BC0 = 60{,}595.53/312 = 194.22$$

The full cost of one copy of the JV software product consists of the sum of the production cost of the VSP, the administrative costs of the AB and the sales costs of the VZ, which are incurred for one copy of the software product:

$$SPd = BC0 + AB0 + Bз0 \qquad (6.7)$$

Administrative costs AB0 incurred per one copy of the software product are determined by the formula:

$$AB0 = AB/CPP \qquad (6.8)$$

$$AB0 = \frac{6246.34}{312} = 20.02$$

B30 sales costs incurred per one copy of the software product are determined by the formula:

$$B30 = VZ/CPP \qquad (6.9)$$

$$B30 = \frac{1514.9}{312} = \text{UAH } 4.86$$

Thus, SP0= 194.22+20.02+4.86=219.1 UAH

Product profitability (product rate) is the ratio of the total amount of profit to the costs of production and sale of products (the relative amount of profit per UAH 1 of current costs):

$$Р_п = \frac{Ц - ВС}{ВС} \cdot 100\% \qquad (6.10)$$

where C is the price of a product unit;

C is the unit cost of production.

$$Р_п = \frac{185691.3 - 128952.3}{128952.3} \cdot 100\% = 44\%$$

Therefore, the profitability is 44%.

Let's calculate the wholesale price of one product PRICES (excluding

$$CPP = SP \cdot (1 + Rp/100) \qquad (6.11)$$

where$Р_п$- profitability ratio.

CPP = 219.1·(1+44/100) = 315.5

Let's calculate the break-even point. Income from the sale of software products is found by multiplying the price of one PP by the number of ordered copies of the PP:

DR=CPP·checkpoint (6.12)

DR=315.5·219.1=69 126.93 hryvnias

The analytical size of the critical program (RCP) is calculated by dividing the fixed costs of the RIIostV by the difference between the price of one software product of the CPP and the variable costs incurred for one copy of the software product (3MV0), i.e.:

RKP=RP0STV/(CPP-3MV0) (6.13)

The annual fixed costs of RP0STV consist of the sum of the following costs:

PPostB= VOU+Am+DV+AB+VZ (6.14)

where VUO - equipment maintenance losses; Am - depreciation;

DV - additional costs;

AB - administrative costs;

VZ - sales costs.

RPostV = 1225+208.8+5552.3+6246.34+1514.9=14646.62 UAH

The annual variable costs of the RZMV consist of the sum of the following costs:

RZMV = VM + FOP + ESVFOP(6.15)

where VM - materials and purchased products;

FOP - wage fund;

EUSFOP is a single social contribution.

RZMV = 33,288+16656.91+3664.52=53,609.43 UAH.

The variable costs incurred per one copy of the software product are determined by dividing the annual variable costs by the annual software product release program:

3MV0 = RZMV/CPP(6.16)

3MV0 = 53 609.43/312= 171.83

$$\text{RKP}=\frac{14646.62}{315.2-171.83} = 101.95 \approx 102 \text{ шт.}$$

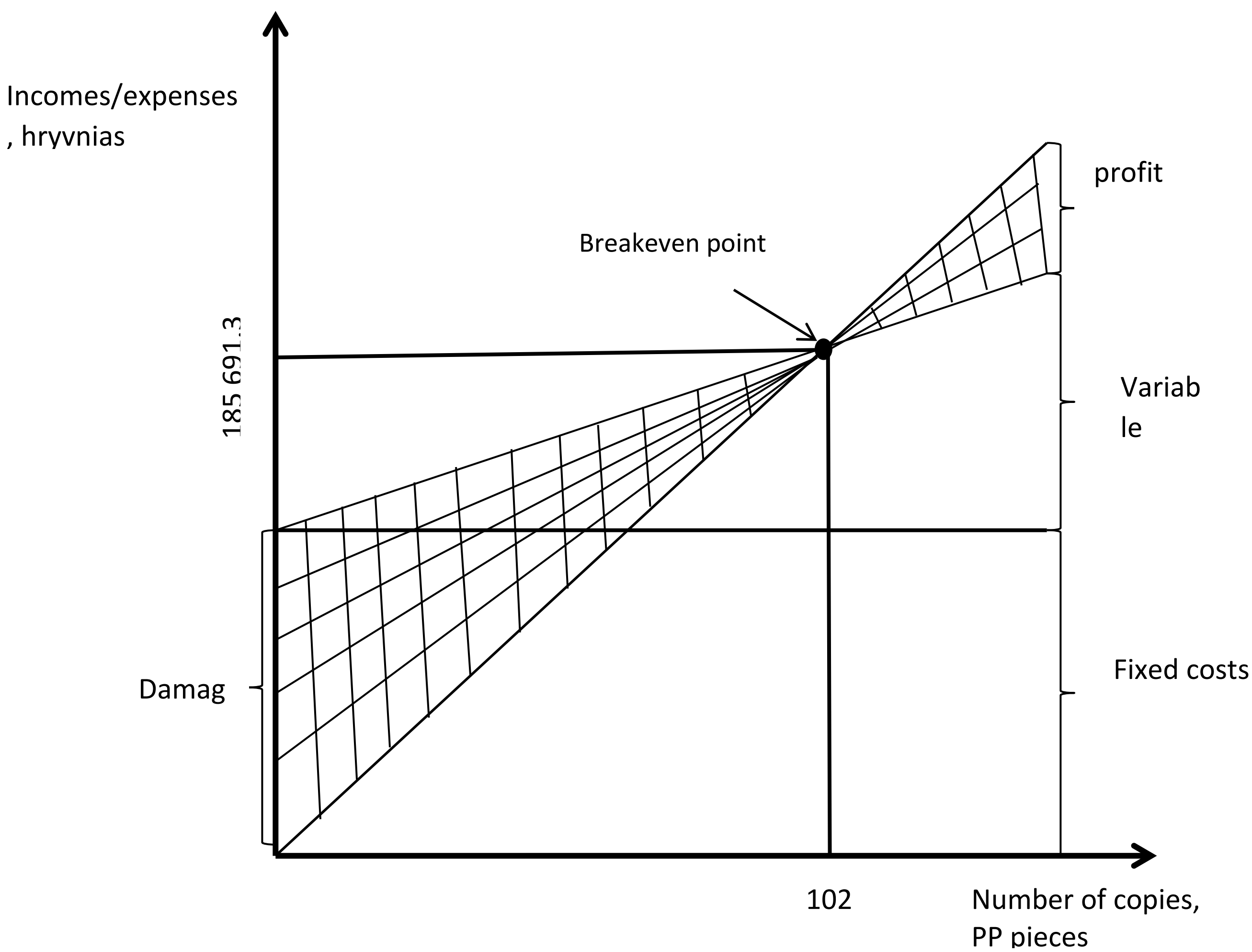
Annual income at the break-even point:

DRBZ =315.5·102 = 32,181 hryvnias

## 6.5. Conclusions to the section

In this section, the price and cost of the quadcopter system was calculated. Thus, the price without VAT was UAH 154,742.76, the price with VAT was UAH 185,691.3. The cost is UAH 128,952.3. The calculation was made taking into account all necessary labor costs, VAT amounted to UAH 14,248.93. The calculation is made taking into account all necessary labor costs. The cost of one copy is UAH 219.1. This device can compete in the market.

The break-even point reaches 102 copies of the product, which is 1/3 of the average annual order of products. It was found that the profitability is 44%, which is a high indicator. The annual income at the




break-even point is UAH 32,181. So the product is profitable.

Figure 6.1 - Definition of a critical product release program.

# CONCLUSION

This thesis is dedicated toUAV control system. The goal was the synthesis of a drone control system when entering a given route.

As a simulated situation, it was proposed to launch a UAV from a carrier aircraft and fly it along a given trajectory with a targetmonitoring emergency zones and terrain reconnaissance.

Taking into account the advantages and disadvantages of existing types of UAVs, a specific type of multi-rotor UAV was chosen - a quadrocopter. This drone has great stability during the monitoring task, and the possibility of long-term barrage over the selected area. Small dimensions and the possibility of installing additional equipment make it easy to transport such a UAV by a carrier aircraft. Among the shortcomings, a relatively short flight time was identified, which is determined by the charge of the battery and, as a result, a small radius of action.

During the research and development of the UAV control system, a mathematical model of the quadcopter was calculated, and the transfer functions for the roll, pitch, and yaw control channels were obtained. These models are non-linear, so the system was linearized using a standard Taylor series expansion. PD was used - regulators that stabilize the control system.

Computer models of the drone were created in the Matlab/Simulink software environment. With the help of a special PIDtuner tool, it was possible to adjust the PD-regulators, and obtain the desired transient characteristics according to the technical task. A separate subdivision of the graduation work was the calculation of the engine parameters, during which its transmission function and transient characteristics that meet the requirements of the technical specifications were obtained.

A patented Kalman filter is used as a filtering device capable of compensating the noise of the microelectromechanical system.

The assembly of UAV parts was carried out in the design part of the graduation work. All elements of the quadcopter are offered as separate modules from the many options available on the market. In this way, the mechanical part of the quadcopter is selected, where the main elements are the frame and motors, the flight controller with a high-performance microprocessor is selected as the control device, the power supply system and the attached monitoring equipment are selected.

The experimental – practical part consisted of computer modeling of the quadrocopter control system. The efficiency of the selected drone assembly was calculated separately using the eCalc online service. The research results showed that the developed UAV has a sufficient payload and is able to fly for more than 30 minutes, which is enough for a flight mission.

A separate section of the thesis was the synthesis of the modal controller of the quadcopter control system. The study of the modal controller was carried out in Matlab/Simulink. As a result, transient characteristics and transmission functions of the control system on three control channels, which have satisfactory indicators, were obtained. As an appendix, the code of the modal controller program in Matlab was developed, where the quadcopter as a rigid body was investigated, and the transmission characteristic and stability reserves of the system in the frequency domain were obtained.

The final part of the graduation work was an analysis of the economic efficiency of the assembled components of the quadcopter, which was carried out in the design part. Market segmentation was carried out and the break-even point of the development was found.

In this way, the UAV control system when entering a given route was developed.The development has practical significance for further study and modernization.

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**Appendices**

## Appendix No. 1
## Listing of the modal regulator synthesis program in Matlab

```
%Setting the transfer function of the OU
A = [1];
B = [1,0,0];
WR = tf(A,B)
WR =
1
---
s^2
%Derivation of the poles of the transfer function; withdistribution of PF in the space of states
field(WR)
[ABCD]=ssdata(WR)
% Eigenvalues of matrix A
eig(A)
% Checking the system's controllability and controllability
V=obsv(A,C)
U=ctrb(A,B)
rank(U)
rank(V)
% Distribution of roots according to Butterworth
[Z, P, K] = buttap(2)
p = [-0.7071 + 0.7071i; -0.7071 - 0.7071i]
% Matrix of feedback coefficients
K=place(A,B,p)
%Checking the eigenvalues of the matrix of a closed system
eig(AB*K)
% We note the desired roots so that the processes in the system run faster
pn = [ -0.7071 + 0.7071i; -0.7071 - 0.7071i]*50
%Supervisor feedback matrix
L= place (A',C',pn)'
L =

1.0e+03 *

2.5000
0.0707

% Dynamic controller matrix
[Ar Br Cr Dr]=reg(A,B,C,D,K,L);
% Transfer function of the dynamic regulator
[num denr]=ss2tf(Ar,Br,Cr,Dr);
Wreg=tf(num,denr)
Wreg =
```

```
3606 s + 2500
--------------------
s^2 + 72.12 s + 2601
% Analysis of a closed system using SISODesignTool.
sisotool (Wreg)

% Analysis of a closed system
Wz=feedback(WR, Wreg)
step(Wz)

Wz =

s^2 + 72.12 s + 2601
-----------------------------------------
s^4 + 72.12 s^3 + 2601 s^2 + 3606 s + 2500
```