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_____________Павлова С.В.
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ДИПЛОМНА РОБОТА

(ПОЯСНЮВАЛЬНА ЗАПИСКА)

ВИПУСКНИКА ОСВІТНЬОГО СТУПЕНЯ
“БАКАЛАВР”

Тема: НАВІГАЦІЯ БПЛА В ПРИМІЩЕННІ НА ОСНОВІ TDOA МЕТОДУ

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DEPARTMENT OF AVIONICS

ADMIT TO DEFENCE
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GRADUATE WORK

(EXPLANATORY NOTES)

GRADUATE OF AN EDUCATIONAL DEGREE

«BACHELOR»

Theme: UAV’S INDOOR NAVIGATION USING TDOA METHOD

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Kyiv 2021

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S.V. Pavlova
“___”___________2021

TASK

for execution graduate work

D.A. Lakhtyr

1. Theme of bachelor work: «UAV’s indoor navigation using TDOA method», approved by the Rector on «23» March 2021.

2. Duration of which: from 10 May 2021 to 10 June 2021.

3. Background to the work: Increasing commercial use of indoor UAVs requires development of robust navigational systems.

4. Content of explanatory notes: List of conditional terms and abbreviations; Introduction; Chapter: Unmanned aerial vehicle use in indoor environment; Chapter 2: Indoor navigation technologies and algorithms; Chapter 3: Mathematical modelling of a 3D positioning system for indoor navigation based on TDOA; Conclusions; References;

5. The list of mandatory graphic material: Graphical presentation of the results of the mathematical modeling of the positioning system.

6. Planned schedule

№	Task	Duration	Evaluation of the performance
1.	Validate the rationale of graduate work theme	10.05-11.05	
2.	Carry out a literature review	12.05-13.05	
3.	Develop the first chapter of diploma	14.05-21.05	
4.	Develop the second chapter of diploma	22.05-29.05	
5.	Develop the third chapter of diploma	29.05-08.06	
6.	Obtaining a review of the diploma	09.06-10.06	

7. Date of assignment: «____»____________2021

8. Supervisor _____________ L.V. Sibruk

The task took to perform _____________ D.A. Lakhtyr

ABSTRACT

Explanatory notes to bachelor work "UAV's indoor navigation using TDOA method": N pages, 20 figures, 28 references.

UAV, INDOOR DRONES, INDOOR NAVIGATION, MULTILATERATION, TDOA, MATHEMATICAL MODELING, POSITIONING ALGORITHM.

Object of the investigation – navigational system for indoor UAVs.

Purpose of the bachelor work – developing of the mathematical model of an indoor navigational system for UAVs, based on TDOA method, suitable for practical applications. Assessing the accuracy of possible indoor navigational system. Estimating performance characteristics of TDOA-based systems.

Method of investigation – mathematical modeling using MATLAB.

The digital mathematical model is similar to the real object of investigation; The accuracy of TDOA-based positioning was investigated using the developed MATLAB model.

Scientific novelty – the investigation of theoretical performance of three-dimensional TDOA-based indoor positioning system was conducted by means of mathematical modeling.

Materials of bachelor work are recommended for study and education processes in the area of UAV navigation, and in practice of UAV development.

Predicted assumptions about the further development of the object of investigation – improving performance of indoor navigational systems; development of autonomous indoor UAVs.

LIST OF CONTENTS

LIST OF ABBREVIATIONS

GPS	Global Positioning System
INS	Inertial Navigation System
LiDAR	Light Detection and Ranging
MATLAB	Matrix Laboratory
PE	Position Estimation
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
TDOA	Time Difference of Arrival
TOA	Time of Arrival
UAV	Unmanned Aerial Vehicle

INTRODUCTION

Actuality. The popularity of UAV’s during last years is greatly increasing. Drones are getting more broad use in various commercial applications. They are used for mapping, monitoring, logistics, media, search and rescue operations and many more possible use cases. One of the recently emerged UAV’s type are indoor drones. Such drones are mostly used for inspections, security monitoring, warehouse operations and public safety. On this basis, a demand for indoor navigation system arises. The specifics of indoor operations of drones, creates unique technical challenges. Development of reliable and precise navigational systems, will allow to implement autonomous UAV system, which will vastly increase efficiency of indoor drone operations.

Studies on this topic are sparse and require further investigations and development. For development of navigation systems, it is possible to rely on existing technologies from different areas, such as indoor positioning for pedestrian navigation, or positioning algorithms, used in aviation.

Estimation of theoretical performance and accuracy of indoor navigational algorithms and technologies can allow further improvements and implementation of new technologies for practical use. The developed mathematical model is used for analysis of TDOA-based positioning algorithm, which can be used in such positioning systems.

Purpose of the work – developing of the mathematical model of an indoor navigational system for UAVs, based on TDOA method and assessing the accuracy of possible indoor navigational system, taking into consideration specifics of practical use of indoor drones.

Object of study – process of UAV positioning and navigation in indoor environments.

Subject of study – indoor positioning algorithm.

Practical meaning of obtained results.

The study provides an overview of modern indoor drones use cases, existing indoor navigational technologies, and possible ways of implementation and improvements on indoor UAV navigational systems. The developed mathematical model provides analysis of precision of TDOA-based positioning algorithm, used indoors. These results can be used to assess practicality and advisability of using such system for specific environments and tasks, performed by a UAV.

According to the tasks of bachelor work, in the relevant chapters, the following studies are:

Chapter 1. Literature revive on existing drone technologies. Examination of modern use cases and technical characteristics of indoor drones, perspectives of their development.

Chapter 2. Literature overview of existing indoor navigational technologies and algorithms, their comparison. Assessing practicality of different navigational methods and algorithms for different use cases.

Chapter 3. Designing the mathematical model of TDOA PE algorithm using MATLAB. Analysis of accuracy of such algorithm using the mathematical model. Comparing obtained accuracy levels with practical requirements for indoor drones.

CHAPTER 1

UNMANNED AERIAL VEHICLE USE IN INDOOR ENVIRONMENT

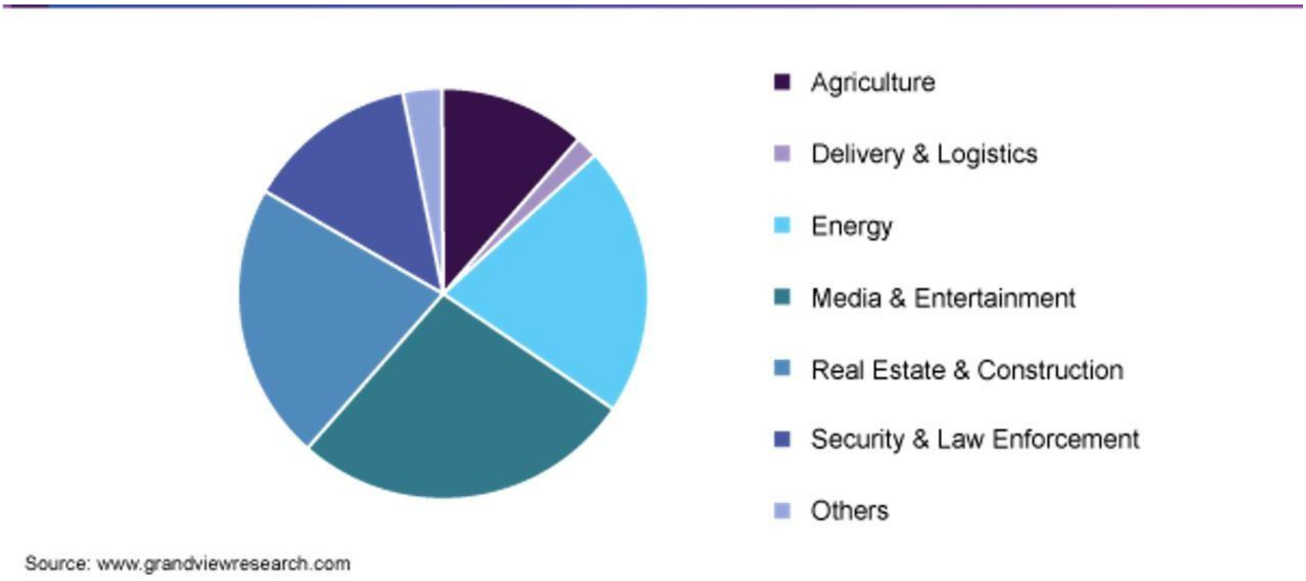
UAVs have shown high potential in various industries. Over last years, implementation of UAVs in various industries is steadily growing. Mostly used in the military applications, now demand for UAVs is emerging in various commercial areas. The commercial drone market is valued at 13.44 billion USD in 2020 and it's speculated to grow with an annual rate of 57.5% from 2021 to 2028 [1]. Use cases in business for drones are considerably growing for past years. Drone manufacturers and software developers are constantly engaged in designing, improving and testing new solution for increasing demands in various market areas.

UAVs come in different types and sizes. They can be classified as fixed-wing, rotary blade and hybrid. The main focus will be on the rotary blade UAVs, as their ability to hover and perform precise maneuvers in confined space makes them suitable for indoor operations. Usually, it's a multi-rotor drone (quadcopters, hexacopters, etc.) which can be equipped with various tools to perform different tasks such as surveillance, material handling, inventory management, mapping and others.

As the indoor usage of UAVs increases, the demand for new technologies that can enable more efficient, safe and reliable operation in indoor environment arrives. One of the main problems to face is the indoor navigation, as it requires more accuracy, than for outdoor operation, with increased complexity and inaccessibility of some common navigational tools, such as GPS.

1.1. General characteristics of indoor UAV applications

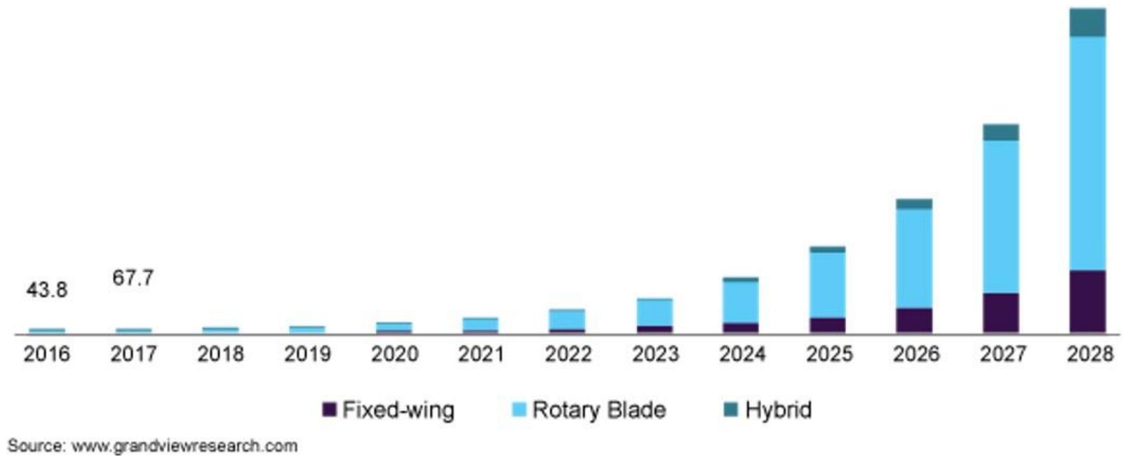
UAVs use cases were mainly associated with outdoor environments. Drones found practical implementations in various applications such as agriculture, logistics, media and entertainment, real estate, construction, security and law enforcement, manufacturing, and others. Drones can be used at dangerous or hardly accessible places for inspections, mapping, and in search and rescue operations [1]. The comparison of the area of application of commercial drones is shown in Fig. 1.



Source: www.grandviewresearch.com

Fig. 1. Global commercial UAV market by end-use

In recent years drones are becoming actively used in various indoor applications. Such implementation of drones can provide grate benefits, but it comes with its own set of technological challenges. The most suitable UAV type for indoor operations is rotary blade drones, as they are able tom precisely maneuver in confined indoor environments, avoid obstacles, hover and move in any direction. Rotary blade UAVs are also the most widespread on the global market. From the report on the global drone market, the highest growth of demand is on rotary blade UAVs [1], which is shown on the Fig. 2. For indoor applications, development and improvement on technologies for this type of drones will be highly demanded.



Source: www.grandviewresearch.com

Fig. 2. North America commercial UAVs demand by type

Indoor applications of drones have several advantages comparing to outdoor applications [2]. Some of such benefits are:

Less hazardous tasks. Implementation of drones can greatly increase safety by excluding human workers from dangerous areas or performing hazardous works. For example, in the warehouse use case, inspections of goods can be performed by drones, which can reach high shelfs, so workers have no need to climb ladders to perform inspections. Also, it can greatly decrease time for such works. It can also be used to replace the need for a human to enter confined or hazardous spaces, or spaces that are difficult to access. For example, sewers, mines, chimneys, pressure vessels. In nuclear power plants drones can be used to replace the need for human operators to be exposed to radiation sources.

Less restrictive regulations. It is much easier to get approvals for indoor UAVs compared to outdoor. In outdoor operations, there are safety concerns, connected with violating restricted airspace, such as in airport area which can lead to accidents. Regulations for UAV operators have been developed. Depending on the category of drones, it can be required to pass strict certifications for the specific UAV, as well as for operation and maintenance staff [3].

Stable weather conditions. There is no wind, rain or fog indoors. It makes operation of drones much easier. It also means that drones in indoor environments, in contrast to outdoor, can be used at any time of day, night, independently of weather conditions.

Operation cost. Implementation of small drones can have comparatively low costs and provide fast return on investment. The benefits of using drones can save additional costs, for example, by detecting faults in equipment early and more efficient during inspections, and also reducing required downtime [4].

On the other hand, there are some technical challenges associated with UAVs in indoor environments. Many problems that appear outdoor – weather, air traffic, collision with birds is not a concern for indoor operation. However, the new set of challenges, which are unique for such environments arrive [2]. Some of them are:

Confined space. Indoor environments can contain many complex obstacles, which increase complexity for drone maneuvering. This means that higher levels of training for UAV operators are required, as well as more advanced software. The presence of obstacles, that can also be dynamic makes development of algorithms for autonomous flying a highly challenging task.

Integration. It can be time consuming to integrate drones into established industry processes. However, this aspect is highly dependent on the specific use case.

Navigation. Most indoor environments have unreliable GPS connection, which makes navigation much more challenging. This means that alternative navigation principles and technologies must be used. On-board navigational systems can be very costly and complex, and in case of small drones, their installation can even be impossible, due to weight limitations. Alternatively, it is possible to install tracking systems, which covers operation area, however it also can be expensive, depending on the specifics of a facility. Moreover, these systems have to provide high accuracy, which is considerably higher than for outdoor navigation. Because of the factors, most modern drone systems are not autonomous [2]. This means a need for an operator, who distantly controls the drone.

Safety. Drone failures can pose higher dangers in indoor environments, compared to outdoor. Battery failures or explosions can lead to ignition in presence of flammable materials inside the facilities. Using drones indoor can lead to incidents, related to collision with humans, which can lead to injuries. The main concern in case of multi-rotor drones is its propellers [5]. Also, collisions with obstacles or other drones can lead to damage of expensive equipment and drone itself.

Noise pollution. Multi-rotor drones create considerable amount of noise [6]. Constant noise pollution can negatively affect health of the workers. It means, that hearing protection should be used. High levels of noise can make drones undesirable for use in public areas, such as stores, malls, airports etc. This problem can be reduced by using more quiet commercial drones, which can be more expensive [6].

1.2. Indoor drone application

As stated above, UAVs found applications in various branches of human activities, and their use is constantly increasing, as the technology develops. Most use cases are related to visual inspections, surveillance, monitoring, etc. Drones are used in several areas of application, such as:

Warehouse management. The use of UAVs in warehouse operations has been constantly increasing over last years. The efficiency of large warehouse operations can be significantly increased by implementing automation and robotics. Use of digital technologies for identification and tracking of goods, such as bar codes, QR codes, radio frequency identification (RFID) and artificial intelligence can enable implementation of UAVs in automation processes [2]. Drones are useful in warehouse environments as they can have ability to fly and hover autonomously, avoid obstacles and perform precise maneuvers. Drones can be adapted for different warehouse types, which can differ by types of stored items, layouts, sizes, purposes and technologies used. Using UAVs in fleets can furthermore increase their efficiency [7]. The three most promising areas of indoor drone use cases in warehouses are inventory management, intra-logistics of items, as well as inspection and surveillance [2].

Task that can be performed by drones in the area of inventory management are: inventory audit, inventory management, cycle counting, item search, buffer stock maintenance, and stock taking. Ordinarily, these tasks are performed by inventory control staff, who move to designated location in the warehouse, scan barcodes of the items, check the units count and move to the next location. It is slow manual task, which is prone to errors, and dangerous due to working in high altitudes. Drones can increase inventory accuracy, reduce labor cost and minimize dangerous tasks for workers.

Also, drones can be used for carrying goods. For example, they can transport parts from warehouse to workshops. Drone can carry small items and follow pre-defined flight path. But there are considerable limitations, such as payload, gripping and placing of the items and navigation.

Inspections. Drones can be used to replace manual inspections in various industries. This includes power generation, oil and gas, infrastructure, chemicals, mining, agriculture and food, shipping, insurance, etc. [8]. They can be used to inspect roofs, walls and ceilings, search for failures in equipment, assessment of technical state of storage containers, tanks, conveyors belts, chimneys, boilers, sewers and other industrial facilities. Indoor drones are good alternative for tasks which require monitoring and inspection in dangerous areas or and at high altitudes.

Drones can be equipped with various tools to collect different types of data. Some of data types, which are currently collected by drone are [8]:

- Visual data. It is the most common use in inspection drones. This data is collected by cameras, installed on the drone. By flying over some area or point of interest, it is possible to get detailed images of objects of study.
- Thermal data. This is also very common data to be collected by drones. For example, in solar arrays it can help to identify potential problem areas.
- LiDAR data. This technology use laser light for measuring distance to objects from the LiDAR sensor. It creates data points, which than can be used to create detailed 3D maps of rooms or objects. It is also commonly used for collecting geospatial data of land area.

- Multispectral data. Special sensors measure reflected energy in specific bands of electromagnetic spectrum. This can be used, for example, in greenhouses for monitoring plant health.
- Hyperspectral data. These sensors measure energy in narrower and more numerous bands comparing to multispectral sensors. This also can be used in agriculture for monitoring plants and crops.

The data which can be collected by drones depends on the availability of compatible sensors, which can be mounted on the drone and it complies weight and size limitations. As technology progresses, we will see even more widespread use of such drones in the area of inspections.

Surveillance. UAVs can be used to provide complete monitoring of warehouses, manufacturing and assembly plants. It can also be used for security in public areas and in homes. There are security drones that are available for private use [9]. Such drones are equipped with cameras and can move to a specific area to provide images of any room without the need of installation of multiple cameras across the building. In commercial use, such drones can patrol buildings by following pre-defined flight paths and provide real-time video feed. If necessary, it is possible to manually control the drone. It can be also equipped with obstacle-avoidance sensors to avoid impacts with people or objects on its path. However, the short battery life of drones can be limiting factor in such operations.

Public safety. Drones are already used by police, fire departments and in search and rescue operations [8]. Both police and firefighters can use drones for gathering field intelligence. For example, using drones to search rooms to locate suspects or victims. Thermal data from drones can help to locate fires and “see” in heavy smoke. It also can be used to locate people in search and rescue operations during emergencies. The gathering of all the information is done from the safe place, so it also decreases risks and allows more effective planning.

Construction. The number of construction management applications can be automated. This includes progress tracking, quality control, and quantity take-offs. These efforts range from image-based 3D reconstruction to the use of laser scanners and RFID [10]. Data from a number of sources must be combined to provide qualitative analysis of a constructions project, because not all of the necessary information can be captured using a single data source. Drones are used in this area as they can hold an array of sensors, providing effective and fast data collection. The ability of drones to maneuver in confined space, allows to investigate hard to reach areas on the construction site. Using pre-defined flight paths can allow autonomous operations.

1.3. Examples of indoor UAVs designs

There are several commercial drones which are designed for indoor operation. Such drones have been used in various industries and for different applications. Commonly, indoor drones are used for inspections. For this purpose, several design features were implemented. To develop the most suitable navigation system for indoor drones it is important to understand their technical characteristics. Some examples of existing drones will be discussed next.

Elios 2 by Flyability. Elios 2 is a quad-rotor drone designed for indoor inspections in confined spaces. The main constructional feature, which distinguish this drone from outdoor drones is the protective frame. The frame has a spherical shape, covering the drone from all sides. It is made from carbon fiber and can allow the drone to sustain collisions in flight. It can recover from hits at up to 4 m/s. The drone is shown in Fig. 3 [8].

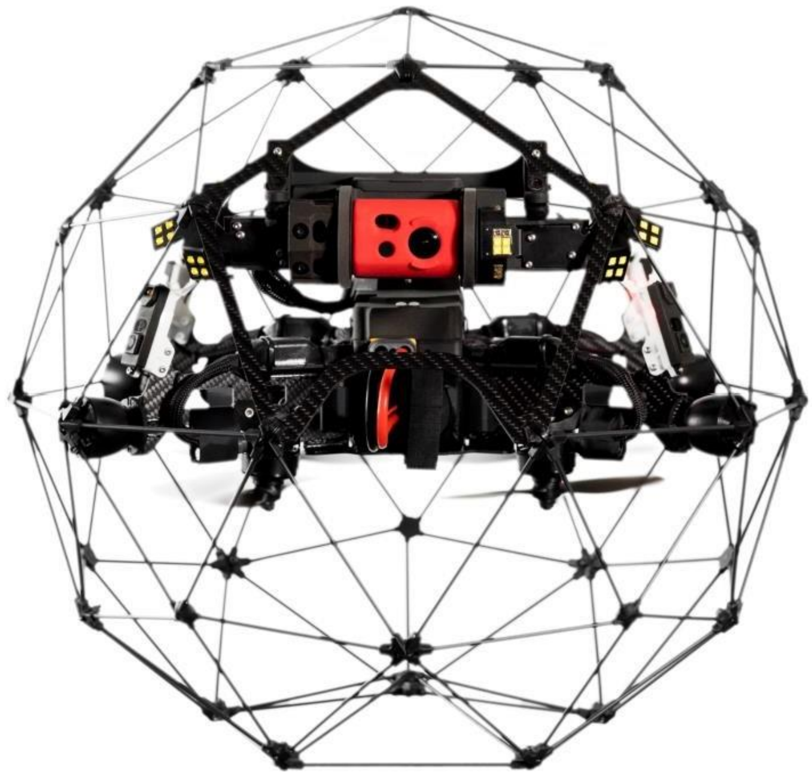


Fig. 3. Elios 2 inspection drone

The diameter of the cage is 40cm, so the drone is able to enter confined spaces. It is equipped with high-quality 4k camera and thermal camera which is placed on a tiltable pod. It is also equipped with powerful lighting system to reveal cracks and roughness on inspectable surfaces. The inspections are performed at close distances and at the angle to the surface, to create visible shadows. The lighting also designed to reduce effects of dust particles on the image quality. The drone is piloted manually by radio control. However, it can provide features such as assisting in maintaining constant distance to objects and stabilization in flight. This drone also comes with software capable of creating 3D maps of the environment. The battery can last up to 10 minutes of flight but, it is possible to quickly change it to a spare one.

Skycopter by Scypersoinc. This is another indoor UAV designed for inspections. It is mainly designed for industrial applications and also can be used in first response in emergency situations [11]. Similarly, it is also a quad rotor drone, protected by an external frame with diameter of 35cm, which is shown in Fig. 4.

Fig. 4. Skycopter inspection drone

As its competitor, it features high-resolution cameras, lightning system as well as tracking and flight stabilization system. Rotors are powered by dust-proof motors, allowing Skycopter to fly in highly dusty environments. The declared flight time is 14 minutes. It is also possible to install different additional sensors, such as gas detectors, thermometer or dosimeter. The drone is also certified for operation in high radiation environments.

Unmanned Recon and Safety Aircraft (URSA). This is a prototype of a quad rotor drone that was tested for autonomous indoor mapping [12]. As the UAV platform Erle Copter by Erle Robotics Company was chosen. It was equipped with LiDAR scanner to create 3D maps of the indoor environments. It also works autonomously by simultaneous localization and mapping. The on-board equipment creates a precise map of the environment builds the map of the unknown environment and uses it for determining the position of the drone and its navigation. It is also can avoid obstacles using 3D mapping. Navigation is restricted to 2D planes. During the testing, this system showed high accuracy of navigation and high quality of resulting maps.

There are several design features which are mainly occur in indoor drones, such as protective frame or lighting system. Commercially available drones for indoor inspections are remotely controlled. However, there are perspectives for implementation of autonomous drones used indoors.

Conclusion to chapter

UAVs use in indoor environment are constantly increasing in the recent years. The area of its application and possible use cases is growing as the improvements in the existing technologies allow more reliable, safe and efficient operations. The most commonly used and suitable type of UAVs for indoors are multi-rotor drones. Due to their high-maneuverability they are perfect solution. Possibility to be equipped with different tools and sensors, makes them a universal tool. The areas of application of indoor drones include construction, manufacturing, warehouse operation, logistics, agriculture, surveillance, insurance, law enforcement and others. The main types of task, which are performed by indoor drones are inventory management, deliveries, inspections using different types of sensors, surveillance and mapping. At present date, indoor operations of UAV are less studied than its outdoor use.

Using UAVs indoors has its own advantages and challenges, compared to outdoors applications. Independence on weather conditions makes operations easier, and available at any time. Indoor UAVs also have less strict regulations, so it is cheaper to maintain. Using drones in hazardous environments and in hard-to-reach places increase work safety for personnel, as it eliminates the need to perform risky tasks manually. Faster and more effective operations compared to manual works, helps to increase profits. However, some technical limitations can restrict UAV use in many cases. The problem of providing reliable navigation and safety issues, associated with collisions with humans and obstacles makes fully autonomous operations challenging. Failures of drones can be more dangerous indoors, as battery damage impose fire hazard. Noise pollution can be concern in public areas. High levels of noise can also negatively affect personnel, increasing health risks if no hearing protection is used.

The area of application of indoor drones is already vast, and have been increasing lately. Most use cases are related to visual inspections, surveillance, monitoring etc. In warehouse operation UAVs can be used for inventory management and intra-logistics. Inspections using drones are performed in various industries including power generation, oil and gas, infrastructure, chemicals, mining, agriculture and food, shipping, insurance and others. For this task, an array of on-board tools is used to provide detailed inspections of objects of study. This includes visual, infrared, LiDAR, spectral and other data. In the area of public safety, UAVs can be used to search rooms for suspects, or victims during police operations or rescues. Thermal imaging can help firefighters investigate place of fire, locate fire source and navigate through smoke, making their work safer and more efficient.

Indoor UAVs are modern technology that can provide grate benefits in various commercial uses as well as private and public areas. The demand on such UAVs continues to grow as new technologies develop. However, there are many technical issues which has to be overcome to enable reliable and safe operation of autonomous drones.

CHAPTER 2

INDOOR NAVIGATION TECHNOLOGIES AND ALGORITHMS

Reliable and precise indoor navigational and positioning systems are critical for autonomous UAV operations. In the case of outdoor use, these technologies have been steadily improving. Navigational technologies are used for flight planning and positioning. For example, it can be used in area mapping. UAV can autonomously fly over specified land area, making aerial photography, or collecting other types of data. The positioning system allows to create databases with georeferencing. The most common technologies used for these tasks are GPS or inertial navigation system (INS). The error of GPS positioning can be from less than a meter to several meter, depending on the environment and the equipment [13]. For outdoor flights, which can cover areas which are measured in square kilometers, errors of such magnitude are acceptable. However, for indoor operations, such accuracy is not sufficient. Also, inside buildings GPS accuracy worthens, or even can be unavailable. Precise INS systems are expensive, and are impossible to use on smaller drones, because of weight and size limitations. Considering these facts, the need for accurate indoor positioning systems arises. The technologies for indoor positioning have been actively studied in the area of pedestrian navigation and wayfinding. Many papers describe use of different indoor navigation and positioning technologies and algorithms for personal use, primarily for smartphones. These technologies can be adopted to use with indoor drones. However, for pedestrian navigation, usually only two spatial dimensions are required to be measured. For drones, altitude is a very important factor, so such systems need to be improved to precisely measure position in all three spatial dimensions.

Existing positioning technologies include infrared, ultrasound, magnetic, optical and vision, radio frequency, visible light, dead reckoning, inertial navigation system and hybrid. Positioning techniques use signal properties and positioning algorithms. Signal properties which are measured in such positioning techniques are Angle of Arrival (AOA), Time of

Arrival (TOA), Time Difference of Arrival (TDOA) and Received Signal Strength Indication (RSSI). The positioning algorithms include triangulation, trilateration, proximity and scene analysis. [14]

2.1. Indoor navigation technologies

The existing technologies, used in the area of indoor navigation use different physical principles for determining position of an object. Most commonly, a ground station is constantly localizing the position of the drone and sends this information to the drone`s navigational controller. This can enable partial or fully autonomous operation of the drone, which can significantly improve efficiency compared to manual drone piloting. The use of fully on-board navigation systems is not common, as it requires complex equipmentinstalled on each drone, reducing their payload and flight time, simultaneously increasing costs. The classification of positioning technologies includes: infrared, ultrasound, magnetic, optical and vision, radio frequency, visible light, dead reckoning, inertial navigation system and hybrid.

Infrared. Active and passive infrared systems were developed. Active systems rely on a special active badge or tag that can be carried by people or attached to tracked object. System tracks objects with a network of sensors connected to central server [15]. Tags have long battery life; they are lightweight and low cost. It’s a considerable advantage for UAVs, as they have limited payload capacity. However, for this system to work, the UAV need to be in direct line of sight of the sensors. This means, that all operating area must be covered by the sensor array. This can be possible in small rooms with few obstacles, but in area of inspections discussed above, drones operate in such environments where installation of infrared sensors is not possible, or the line of sight will be too obstructed requiring additional sensors, which can make system too complex and expensive.

The passive infrared systems do not require special badges or tags. It relies on measuring radiation from heat sources using similar sensor array as in active systems [16]. However, when it might work for locating humans, it is not suitable for drones, as they usually are considerably smaller and their temperature does not exceed ambient by much. Another downside of this system is that it can be inaccurate if other heat sources are present.

Ultrasound. Ultrasound systems relies on use of ultrasonic tags on users and objects. The sound emitted by the tag is picked up by several receivers and the sound source is located using methods of trilateration.

The advantage of such system is high accuracy, high resistance to noise and interference. Systems, using ultrasound technology have been studied in the area of UAV navigation [17]. Such systems can achieve stuffiest accuracy for drone navigation indoors. However, ultrasound systems have similar limitations as infrared systems – the UAV is required to be in line of sight of the sensors. So, this technology is not suitable for all applications.

Magnetic. Magnetic positioning system relies on the use of magnetic signals for position determination within a magnetic field. The system includes fixed transmitters and receivers that are mounted on object of tracking. The receivers receive signals from the transmitters and then sends the position information. The Earth’s magnetic field, and perturbations in it, caused by structure elements can also be used to determine the position of objects [18].

The advantage of magnetic positioning system is high accuracy and that such system doesn’t require direct line of sight, however it can suffer from limited coverage. To improve the coverage, the additional sensors and infrastructure need to be included, which can make system too complex and expensive.

Optical/Vision. Such systems determine position of a person or an object by identifying a marker or image that is within a view of a camera of a mobile device carried by user. The marked is attached to a fixed object, usually it is a bar code or a QR code. The position is determined using the processing power of user’s mobile device. This technology can also be adopted for drones. As most drones have cameras, they can be used to provide visual navigation. Special software can process visual data and identify landmarks. Integrating this system with other sensors such as accelerometers and magnetometers can increase accuracy [19].

The ability of drone to perform autonomous navigation without need to implement complex infrastructure is a great advantage of this technology, as this can significantly reduce the cost. With advanced algorithms, drones can navigate even in unknown locations, avoid obstacles and generate maps of buildings. This possibility can vastly expand the area of application of such drones, compared to other technologies. However, such systems can suffer from low accuracy, interference from bright light and high accumulative errors.

Radio-frequency. RF systems rely on the use of radio signals to locate and track position of a person or an object. The main advantage of using RF signals, is their ability to penetrate walls and obstacles, providing large coverage area with fewer receivers. It also can use already existing infrastructure, which can significantly reduce costs. There are several different categories of RF systems, which include radio-frequency identification (RFID), wireless sensor network (WSN), wireless local area network (WLAN), ultra-wideband (UWB), near field communication (NFC) and Bluetooth [14]. These systems have its own unique limitations and advantages. For drone navigation, Bluetooth and NFC are usually not suitable as they are designed for short rage communication.

UWB-based systems have robust resistance to multipath effects and high bandwidth. These systems can be classified as active and passive. Passive systems use signals, reflected from a tracked object to determine its position. The active systems use special tags, which transmit short UWB pulses. The receivers then receive these signals and locate the trackingobject.

WSN-based positioning systems use a group of collaborative sensors with communication infrastructure for monitoring environmental conditions such as temperature, humidity, light, etc. For navigation purposes, the signals from these sensors can be used to determine the position of the user, knowing the position of each sensor node. This means that, navigational system can be built based on existing infrastructure. However, this system can suffer from low accuracy and reliability.

WLAN systems use high frequency radio waves to connect and communicate between nodes and devices within the coverage area. Positioning systems, based on WLAN can use existing infrastructures to determine the position of tracked object. There are two ways in which WLAN positioning systems can be implemented: by propagation or fingerprinting method.

The most significant advantage of RF systems is that receivers don’t require direct line of sight with tracked object. In some cases, navigation can be done using on-board equipment and existing infrastructure which can reduce cost. However, some obstacles can interfere with signals, increasing errors or increasing attenuation of the signal, limiting coverage area.

Dead Reckoning. Dead reckoning is the process of finding current position by using information about previous position, direction and speed. This method can work autonomously, in environments where radio navigation is not available [14]. This technology uses on-board sensors to determine current position. Using different types of information, such as data from accelerometers, magnetometers and visual data can improve accuracy.

However, this technology is prone to high accumulative errors over time. In case of cheap small drones, the on-board equipment can have low accuracy for using it for dead reckoning. Errors of such system can be compensated in hybrid systems, in which the position, estimated by dead reckoning can be corrected when reliable connection to other navigational systems can be established.

Hybrid. In a hybrid positioning system two or more navigational technologies are used. It provides higher overall performance, as such system takes advantages of one system and compensates for its drawbacks by combining it with another system, which provide better performance in areas, where the first one exhibits its limitations. For example, combination of radio and ultrasound technologies [14].

Hybrid systems can provide significant improvements in accuracy, reliability and usability. However, it requires increased infrastructure usage, which means a higher complexity and costs for implementation of such systems.

2.2. Indoor positioning algorithms.

Positioning algorithms are used for interpretation of received signal. Algorithm obtains the parameters of a signal and then determines direction or distances from tracked object to receivers. Next, the calculation of object position is performed. Positioning algorithms use different signal properties, such as AOA, TOA, TDOA and RSSI. The positioning algorithms are triangulation, trilateration, scene analysis and fingerprinting [14].

Triangulation. Triangulation-based positioning is conducted by measurement of angles. The position of the tracked object can be determined by the intersection of several pairs of angle direction lines. In triangulation, the AOA of the signal is used. The advantages of triangulation are that a position of an object may be found with as few as three measuring units for three-dimensional case, and that no time synchronization between measuring units is required. However, the system loses accuracy when the tracked object is far from the measuring sensor. This means that for large rooms, more accurate hardware or higher number of measuring units to cover the whole area is required [20].

Trilateration. In trilateration or multilateration positioning, object's location is determined by measuring distance from several measurement units to the object. In this algorithm, several signal properties can be used. The distance can be measuring by measuring time for signal to reach the sensors, or by estimating signal attenuation. So, the TOA, TDOA and RSSI can be used in such algorithm. This algorithm can provide high levels of accuracy. However, for measuring an object position in three-dimensional space, at least four measurement units are required, and at least three for two-dimensional measurement [21]. This means, that more complex systems need to be used, increasing overall cost.

Fingerprinting. Fingerprinting or Scene analysis positioning relies on matching of signal features, which are location dependent and compare them with gathered data of the area. Fingerprinting consists of two stages: offline and online. During the offline stage, the survey of the location is performed by taking signal strengths measurements corresponding to coordinates of various location points. During online stage, the signal strength is measured and compared to the previously collected data. The position is then estimated by this comparison [21]. The main challenge of this method of navigation, is time consuming and complex measurements in offline stage. In case of changes in environment, which can affect the signal properties, such measurements need to be repeated to update the signal strength map. In case of drones, this algorithm can be even less valuable, as the dimension of altitude is added, which required to take significantly more measurements during offline stage.

2.3. Signal properties

Positioning algorithms use different signal properties that are geometrical parameters of a signal such as angle, distance or strength. These parameters are used in calculations of the object's coordinates by the positioning algorithms. The most commonly used techniques are AOA, TOA, TDOA and RSSI [14]. Each method has its advantages and drawbacks, when choosing the algorithm for drone navigation, such factors as accuracy and reliability need to be considered.

TOA. This method uses a simple principle of measuring time of signal propagation from transmitter to receiver of the measuring unit. Knowing the time of propagation, and the speed at which the signal travels (in case of radio-frequency systems, it is the speed of light), it is easy to calculate the distance, which the signal traveled. To enable a 2-D positioning, measurements need to be done from at least three different reference points. Knowing the location of these measurement points, and distances from each point to the source of the signal, it is possible to calculate the position, as this shown in Fig. 5.

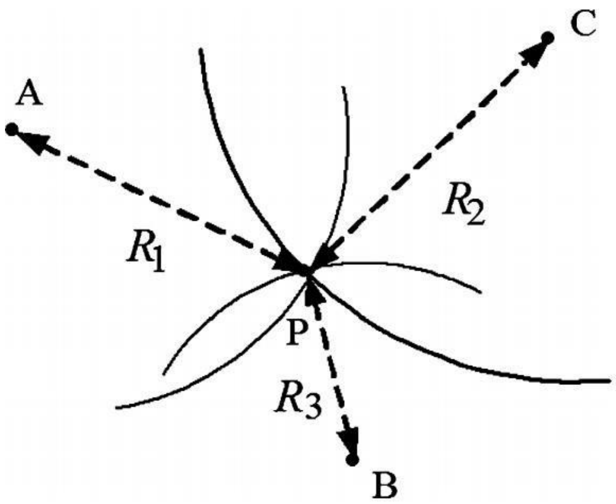


Fig. 5. TOA based positioning

Respectively, at least four measurement units need to be used for positioning in 3-D space. There are several difficulties in implementing TOA method of measurement. First of all, all of the receivers and transmitters are required to be precisely synchronized in time. Second, the transmitted signals need to have a time stamp, so the measuring unit can calculate the distance, which the signal traveled [20]. In case of RF based systems, the accuracy of the synchronization is critical, as the signal travels at the speed of light, which means that slightest error results in significant inaccuracy. For calculation of distance from the transmitter to the receiver a simple equation can be used:

$$R_i = c * (t_i - t), i = 1 \dots 3$$

Where c is the speed of light,

t_i is the time at which signal arrived at receiver i,

t is the time at which signal was sent.

The set of possible locations of the transmitter can be determined. In the two-dimensional case it is a circle. The equitation can be written as [22]:

$$R_i = c * (t_i - t) = \sqrt{(x_i - x)^2 + (y_i - y)^2}, i = 1 \dots 3$$

Where (x_i, y_i) coordinates of the receiver i,

(x, y) unknown coordinates of the target.

In case of three-dimensional navigation, a z-coordinate with respective will be added, and the number of the receivers, and respectively, of the equations, will be equal to four. To find the location of the target, the systems of such equations need to be solved for the unknown coordinates. This can be represented geometrically as finding the point of intersection of three circles (Fig. 5), or in a 3-D case, the point of intersection of four spheres.

TDOA. Time difference of arrival algorithms are also based on determining distance. It finds the relative position of the transmitter by comparing the difference in the propagation time of the signal to several measuring devices. Basically, TDOA measures the difference of TOA at two different receivers, located in different known positions. This method eliminates the need to know when the signal was transmitted [14]. This means, that there is no need for precise synchronization of the receivers with transmitter. However, the measuring units still has to be synchronized. The scheme of TDOA positioning is shown in Fig 6.

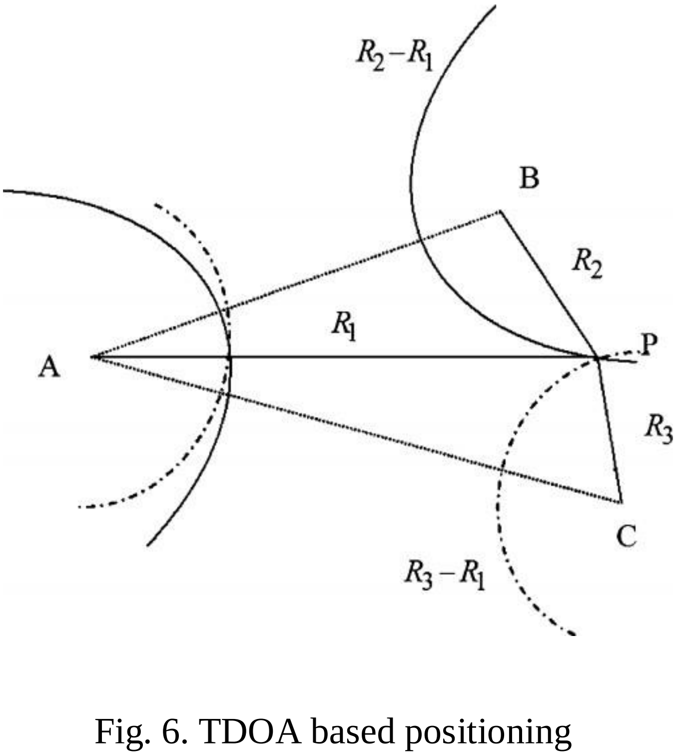


Fig. 6. TDOA based positioning

For a two-dimensional positioning, the intersection of two or more TDOA measurements are used. It can be geometrically represented as intersection of two hyperbolas, which are formed at three fixed reference points to provide an intersection point, which is the position of the target [20]. Similarly, to TOA, at least three measuring units are required for 2-D positioning and at least four for 3-D positioning. The equations from which the coordinates of the target can be calculated have the next form [22]:

$$R_{i,j} = c * (t_i - t_j) = \sqrt{(x_i - x)^2 + (y_i - y)^2} - \sqrt{(x_j - x)^2 + (y_j - y)^2},$$

$$i = 1 \dots 3, \qquad j = 1 \dots 3$$

Where, (x_i, y_i) and (x_j, y_j) are the coordinated of reference points i and j,

t_i and t_j are the signal arrival time in reference points i and j.

For the three-dimensional case, *i* and *j* are from 1 to 4 and variable *z* is added. The respective system of equations is solved to determine the coordinates of the target.

AOA. Angle of Arrival algorithms are based on measuring the angle, at which the signal arrived to different measuring units and using this parameter to estimate distances and obtain the position of the signal source. The advantage of such method, is that it doesn’t require precise time synchronization. Also, fewer reference points are required for position estimation: only two for two-dimensional positioning, and three for three-dimensional positioning. However, the sensors which can use AOA information are more expensive and complex [14]. The other disadvantage is accuracy decrease when the target moves away from the measuring unit. In AOA algorithms, the angles at to the signal source is used to trace the directional lines. By calculating the point of intersection of these lines, it is possible to obtain position of the target (Fig. 7).

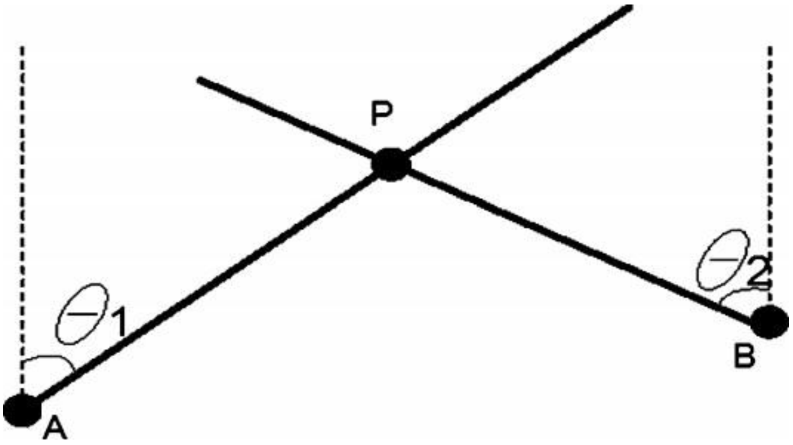


Fig. 7. AOA based positioning

For determining the position of the target by angles of directional lines, the known coordinated of the reference points are used. The coordinates of the target are then calculated using geometric relations of angle and sides of a right triangle. The equation of AOA measurements can be written as:

$$\tan(\theta_i) = \frac{x_i - x}{y_i - y}, \qquad i = 1,2,$$

For two-dimension case it is needed to solve system of two equations. In a three-dimensional space, the horizontal and vertical antenna arrays at each reference points are used. The angle of arrival creates a conical surface of possible positions, and the point of intersection of these surfaces are found to determine the coordinates of a target [23].

RSSI. Received signal strength indicator algorithms are based on measuring the power level of a received signal. The signal power attenuates with distance, so knowing the relation between distance and signal strengths it is possible to calculate the distance between the receiver and the signal source. In indoor environments, where there is a lot of obstacles, RSSI can be significantly affected by multipath, shadowing and signal scattering [14]. The scheme of RSSI positioning is shown in Figure 8.

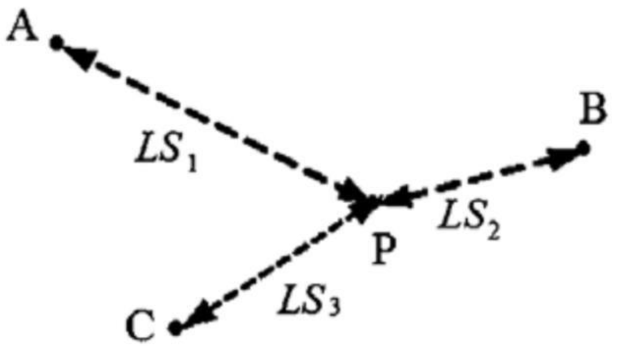


Fig. 8. RSSI based positioning

By obtaining the distances from each measuring unit to the signal source, it is possible to calculate its coordinates, as it is done in TOA algorithms. Similarly, two-dimensional localization requires at least three reference points and three-dimensional localization requires at least four. The relationship between the received signal strengths and the distance of from the source to the receiver can be written as [24]:

$$RSSI = A - 10n \log d,$$

Where A is the signal strengths at distance of 1 meter,

n – signal propagation constant,

d – is the distance to the target

The value A is an empirical parameter that is obtained by measuring the signal strengths value at the distance of 1 meter. To improve RSSI accuracy, various filtration techniques are used.

Using different signal properties have its advantages and disadvantages. For indoor navigation of drones, high accuracy, reliability, easily integrable infrastructure and low weight of drone-mounted equipment are desirable. TOA algorithms can provide high levels of accuracy; however, high precision time synchronization of receivers and transmitter is required. This means, that complex equipment is required to be installed on drones. TDOA algorithms partially eliminate this issue. Only receivers of the measuring units need to be synchronized. Such system can be implemented more easily. TODA also can provide desirable level of accuracy, however the system which can cover large rooms can be expensive, as large number of receivers is required. AOA can provide great accuracy and eliminates the need for time synchronization. It is also working with fewer reference points, making the system much cheaper. But on the other hand, in case of large areas, AOA quickly loses accuracy at long distances, which means that large number of measuring units need to be used in large rooms. Additionally, for three-dimensional positioning, more complex sensors are required for each measuring unit. These two factors make AOA systems expensive at large scales. RSSI systems can be much cheaper, but at the cost of accuracy. These systems also highly affected by the obstacles.

In conclusion, considering the specifics of drone operation indoors, TOA systems are the most complex and expensive, but provide high accuracy at all scales. TDOA and AOA systems can be viable alternatives, with high accuracy and lower complexity. AOA systems can be more suitable for operation in small rooms, where the highest accuracy is achieved and simple system of low number of measuring units can be used. However, at large scales this system becomes too complex and expensive. For application in large rooms, such as warehouses or hangars, TDOA based systems can provide the best solution with high accuracy and acceptable complexity. RSSI systems can be used in applications, where high accuracy is not required.

Conclusion to chapter

Robust and precise indoor positioning technologies and algorithms are a requirement for autonomous UAV navigation indoors. Indoor navigation requires higher accuracy. In most cases, commonly used systems for outdoor navigation are not suitable for indoor use. Existing indoor positioning technologies are mostly focused on pedestrian navigation and wayfinding. However, many of them may be successfully implemented for drones. The positioning technologies include infrared, ultrasound, magnetic, optical and vision, radio frequency, visible light, dead reckoning, inertial navigation system and hybrid. The most commonly used algorithms are triangulation, trilateration, proximity and scene analysis.

The most promising positioning technologies for indoor drone navigation are radio-frequency, ultrasound and vision, as such technologies has been studied for using on indoor drones. They can provide reliable navigation with high accuracy. The use of hybrid systems, which combine several navigational technologies can vastly improve the performance and expand application in different areas. However, hybrid systems require increased complexity and additional infrastructure to support it.

Positioning algorithms obtain received signal and outputs the calculated position of the tracked object. Positioning algorithms can use different signal properties, such as Angle of Arrival (AOA), Time of Arrival (TOA), Time Difference of Arrival (TDOA) and Received Signal Strength Indication (RSSI). Triangulation algorithms use AOA of the received signals. It requires smaller number of measuring units than trilateration, however it suffers from reduced accuracy over distance. Trilateration algorithms may use TOA, TDOA or RSSI. They can have better accuracy, but require higher number of measuring devices to locate position of tracked objects. Fingerprinting algorithms use on-board sensors to measure signal properties, which are dependent on location, and compare it to previous measured parameters in a database. This method requires complex and time-consuming preparations, and may be ineffective for large buildings.

The choice of specific technology and algorithm for drone indoor navigation can depend on various factors. Such factors may include the type of drone, its size and payload; the specifics of the task that need to be performed; the layout of building, rooms or other environments, where navigation is required; the available infrastructure; required accuracy and cost considerations.

CHAPTER 3

MATHEMATICAL MODELLING OF A 3D POSITIONING SYSTEM FOR INDOOR NAVIGATION BASED ON TODA

Multilateration system are used in aviation, in the area of traffic control. These systems provide information to air traffic controllers about the position and the identity of aircrafts in covered area. Multilateration systems use signals from aircraft on-board transponders. Most commonly, the TOA measurements are used in aviation multilateration systems [25]. However, for indoor UAV navigation, TDOA method can be more desirable, as it was discussed above.

Passive positioning and navigation system relies on using the signal of UAV-mounted transmitter, which is received by receiving stations. For determining the position, two steps are required. The first step is to estimate the position dependent signal property, in our case – TDOA. The second step is to use PE algorithm to estimate the UAV position, based on received signal parameter [26]. As the positioning algorithm, multilateration is used. The navigational system estimates TDOA parameter of the emitted signal from the UAV transmitter and uses lateration algorithm to determine the UAV position. The system consists of several receivers, placed around the covered area. The required number of receivers depends on the desirable positioning estimation, either determining only coordinates in two-dimensional plane, or additionally determining height. For three-dimensional navigation, at least four of such receivers are required [14]. Measurements from additional receivers can be used to increase accuracy and reliability.

3.1. Multilateration algorithm for position estimation

In multilateration algorithms, depending on the number of receivers, a system of non-linear hyperbolic equations is solved. If the number of receivers is N, then the number of corresponding equations is N-*1*. Let's denote the coordinates of the target (UAV-mounted emitter) as $x = (x, y, z)$. The coordinates of the i-th receiver is $S_i = (x_i, y_i, z_i)$. The distance, traveled by the signal from the emitter to the i-th receiver is calculated as following:

$$d_i = c * r_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2}, (1)$$

where $c = 3 * 10^8 \frac{m}{s}$,

r_i is the propagation time of the signal from the emitter to the i-th receiver.

The equation for calculating the path difference between the i-th and m-th receivers pair is following:

$$d_{i,m} = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} - \sqrt{(x_m - x)^2 + (y_m - y)^2 + (z_m - z)^2}, \quad (2)$$

Receiver pairs are used as references for multilateration algorithm [26]. Let's denote the i-th and j-th receivers with coordinates (x_i, y_i, z_i) and (x_j, y_j, z_j) as reference pair. The non-reference receivers are denoted as m-th and n-th with coordinates of (x_m, y_m, z_m) and (x_n, y_n, z_n) respectively. For i-th reference receivers, two equations can be written:

$$d_{i,n} = d_i - d_n; \quad (3)$$

$$d_{i,m} = d_i - d_m; \quad (4)$$

Accordingly, the equations for j-th reference receiver are:

$$d_{j,n} = d_j - d_n; \quad (5)$$

$$d_{j,m} = d_j - d_m; \quad (6)$$

Equations (3) and (4), after simplification result into equation of a plane in 3D space. This equation can be written as:

$$A_{i,n,m} = xB_{i,n,m} + yC_{i,n,m} + zD_{i,n,m}, \qquad (7)$$

Where:

$$A_{i,n,m} = 0.5\,\left(d_{i,m} - d_{i,n} + \frac{k_{i,m}}{d_{i,m}} - \frac{k_{i,n}}{d_{i,n}}\right),$$

$$B_{i,n,m} = \frac{X_{n,i}}{d_{i,n}} - \frac{X_{m,i}}{d_{i,m}},$$

$$C_{i,n,m} = \frac{Y_{n,i}}{d_{i,n}} - \frac{Y_{m,i}}{d_{i,m}},$$

$$D_{i,n,m} = \frac{Z_{n,i}}{d_{i,n}} - \frac{Z_{m,i}}{d_{i,m}},$$

$$k_{i,w} = (x_i^2 + y_i^2 + z_i^2) - (x_w^2 + y_w^2 + z_w^2),$$

$$X_{i,w} = x_i - x_w, \qquad Y_{i,w} = y_i - y_w, \qquad Z_{i,w} = z_i - z_w, \qquad w \in [m, n].$$

Similarly, equations (5) and (6), after simplification result into second plane equation, written as:

$$A_{j,n,m} = xB_{j,n,m} + yC_{j,n,m} + zD_{j,n,m}, \qquad (8)$$

Where:

$$A_{j,n,m} = 0.5\,(d_{j,m} - d_{j,n} + \frac{k_{j,m}}{d_{j,m}} - \frac{k_{j,n}}{d_{j,n}}),$$

$$B_{j,n,m} = \frac{X_{n,j}}{d_{j,n}} - \frac{X_{m,j}}{d_{j,m}},$$

$$C_{j,n,m} = \frac{Y_{n,j}}{d_{j,n}} - \frac{Y_{m,j}}{d_{j,m}},$$

$$D_{j,n,m} = \frac{Z_{n,j}}{d_{j,n}} - \frac{Z_{m,j}}{d_{j,m}},$$

$$k_{j,w} = (x_j^2 + y_j^2 + z_j^2) - (x_w^2 + y_w^2 + z_w^2),$$

$$X_{j,w} = x_j - x_w, \qquad Y_{j,w} = y_j - y_w, \qquad Z_{j,w} = z_j - z_w, \qquad w \in [m, n].$$

Equations (7) and (8) can be represented in a matrix form as follows:

$$\begin{bmatrix} B_{i,n,m} & C_{i,n,m} & D_{i,n,m} \\ B_{j,n,m} & C_{j,n,m} & D_{j,n,m} \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} A_{i,n,m} \\ A_{j,n,m} \end{bmatrix}, \qquad (9)$$

$$Q_{ij} \cdot x = a_{ij}. \qquad (10)$$

The equation (9) is the multilateration 3D PE mathematical model for minimum reference stations configuration [26]. Subscripts i and j in equation (10) indicates the numbers receivers which are used as reference pair. The coordinates of the target (x, y, z) are found by calculating the inverse matrix solution of equation (9). TODA measurements and coordinates of the receivers are used as inputs.

In practice, positioning measurements are obtained with errors. The accuracy of multilateration systems depends on the measurement accuracy of the signal parameter, the special distribution of receivers, and the localization algorithm which is used to convert TDOA or TOA measurements to determine the position of the target [27]. The errors of measurement effect the solution of matrix equation (10). The effect of the error on the solution is defined by the condition number of matrix Q_{ij}, which indicates how errors on the input will be amplified. One way to improving accuracy, is to select reference pair of receivers which will give the best possible condition number [26]. It is also possible to use additional receivers.

3.2. Description of a mathematical model of indoor positioning system

The indoor drones can be used in various scenarios and applications, which means different environments and room layouts. For mathematical model we assume application for warehouse or hangars. In other words, the navigation will be performed in a large open room with high ceiling. This means, that positioning in horizontal plane, as well as determining the height of the UAV above the floor level is required. For reliable drone operation, high accuracy of 3D navigation needs to be obtained. The purpose of mathematical modelling is to simulate the positioning algorithm and estimate positioning errors.

In the mathematical model a hangar with dimensions of 60×40×15 meters is considered. The target will be a UAV, equipped with radio transmitter. The specific technology of the radio transmitters and receivers (for example UWB, WLAN or Bluetooth) is not relevant and does not considered during the modeling. It is assumed, that time synchronization of the receivers is done by GPS. In practice, it is possible to have receivers outside of the building, for example on the roof, which will have reliable GPS connection to provide synchronization for the indoor positioning system. GPS receivers and indoor receivers can be connected by wires to the main server, which will perform required calculations for multilateration algorithm.

The total number of indoor receiver stations used are eight. Four assigned for measurement of the position in the horizontal plane and another four are measuring altitude of the UAV. The receivers of the first group, designated as S_1, S_2, S_3, S_4, are placed in the corners of the building on the ground level. The receivers of the second group, designated as $S`_1$, $S`_2$, $S`_3$, $S`_4$, are placed vertically in the middle of the room, two at ground level and 2 at the celling, as shown in Fig. 9. The reference receiver groups have its coordinate systems *x, y, z* for the first group, which is the main reference frame, and *x`*, *y`*, *z`* for the second group. The origin point of the main reference frame is in the center of the hangar at ground level.

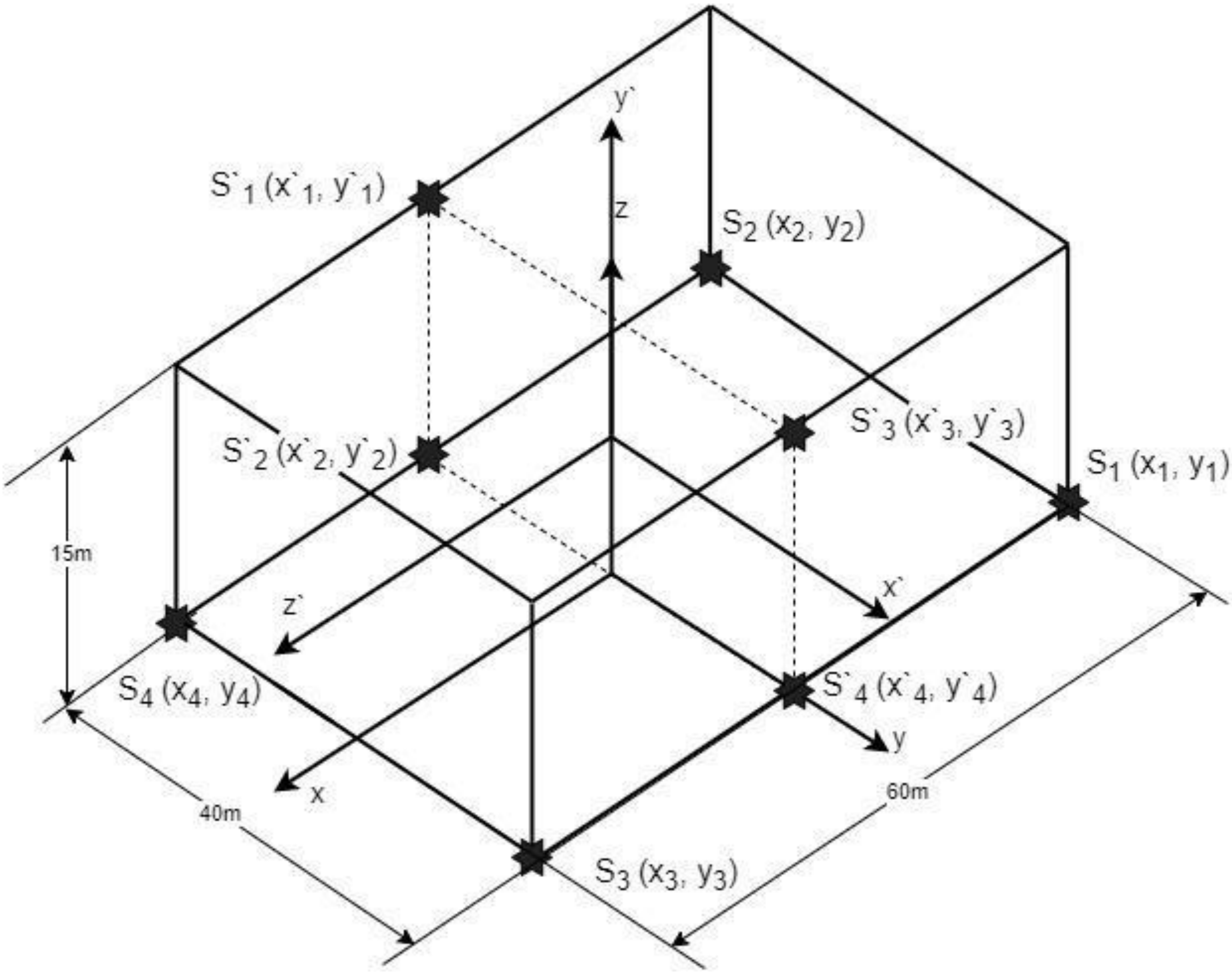


Fig. 9. Scheme of placement of the receivers inside of the hangar

The first group of receivers determines the *x*, *y* coordinates of the target, while the second one finds the position on *z* axis, which is *y`* in its local coordinate system.

The coordinates of the target are set. Using the multilateration algorithm, *x* and *y* coordinates are found by the first group of the receivers and *z* coordinate is found by the second group of the receivers. For each coordinate, a random error of measurement is added. It is generally assumed that the multilateration positioning errors can be modeled by Gaussian distribution with a given variance. This will represent the best-case theoretical accuracy of the algorithm [27]. The variance of the error can be set for different values. The array of values is set for the *x*, *y* coordinates, and a constant value is assigned for the *z* coordinate to estimate errors depending on the position of the target.

Modelling is performed by Monte-Carlo method. For each target position, algorithm is iterated 500 times, adding a random error to each coordinate with Gaussian distribution, provided with constant standard deviation values at each iteration. The algorithm calculates the coordinates of the target. The variance of the resulting measurements and its mean value is estimated and compared to the true value of the coordinates. The influence of multipath and scattering of the signal on the positioning error are not considered. The result of the modeling can be shown in form of three-dimensional surface plot, which can represent values of measured coordinates or its standard deviation, depending on the position of the target. The block-scheme of the algorithm is shown in Fig. 10.

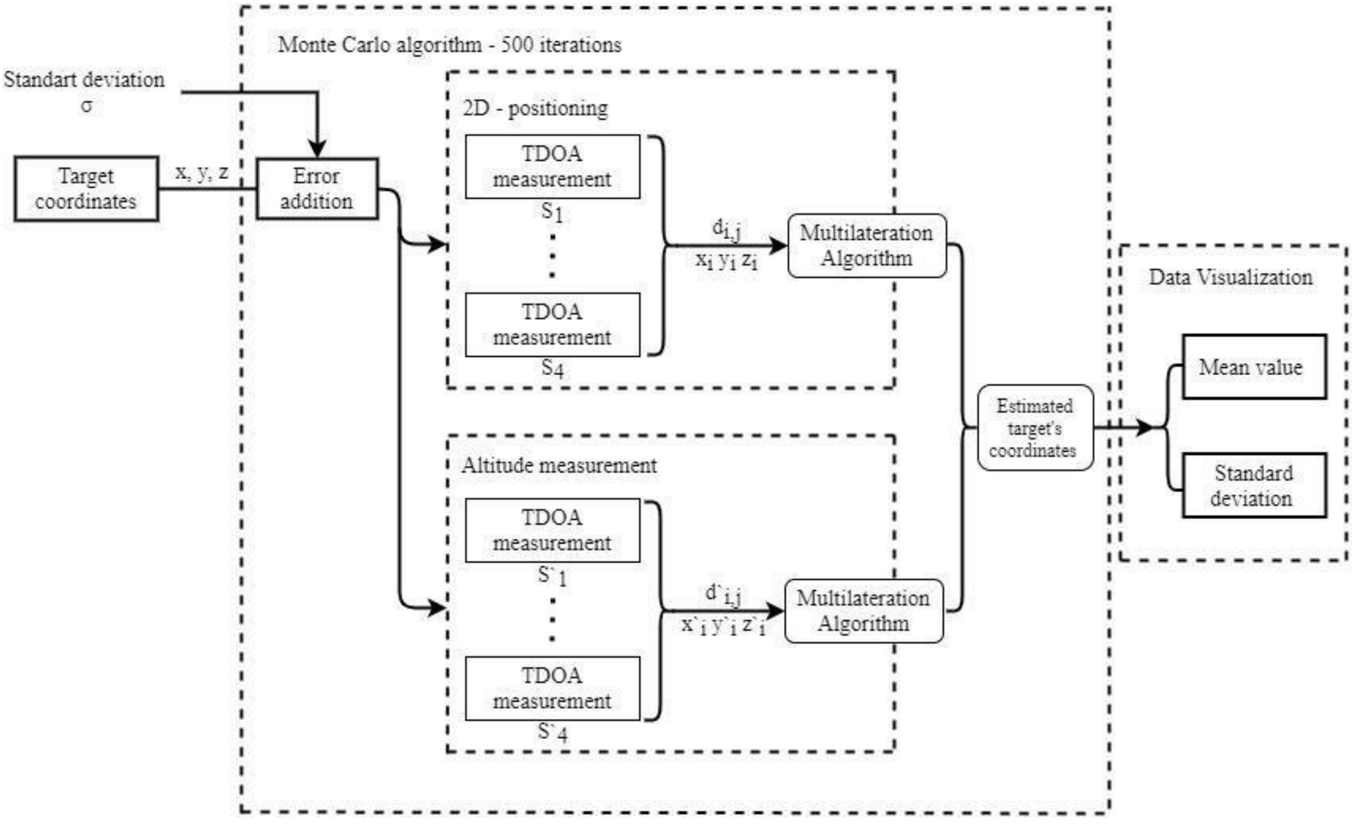
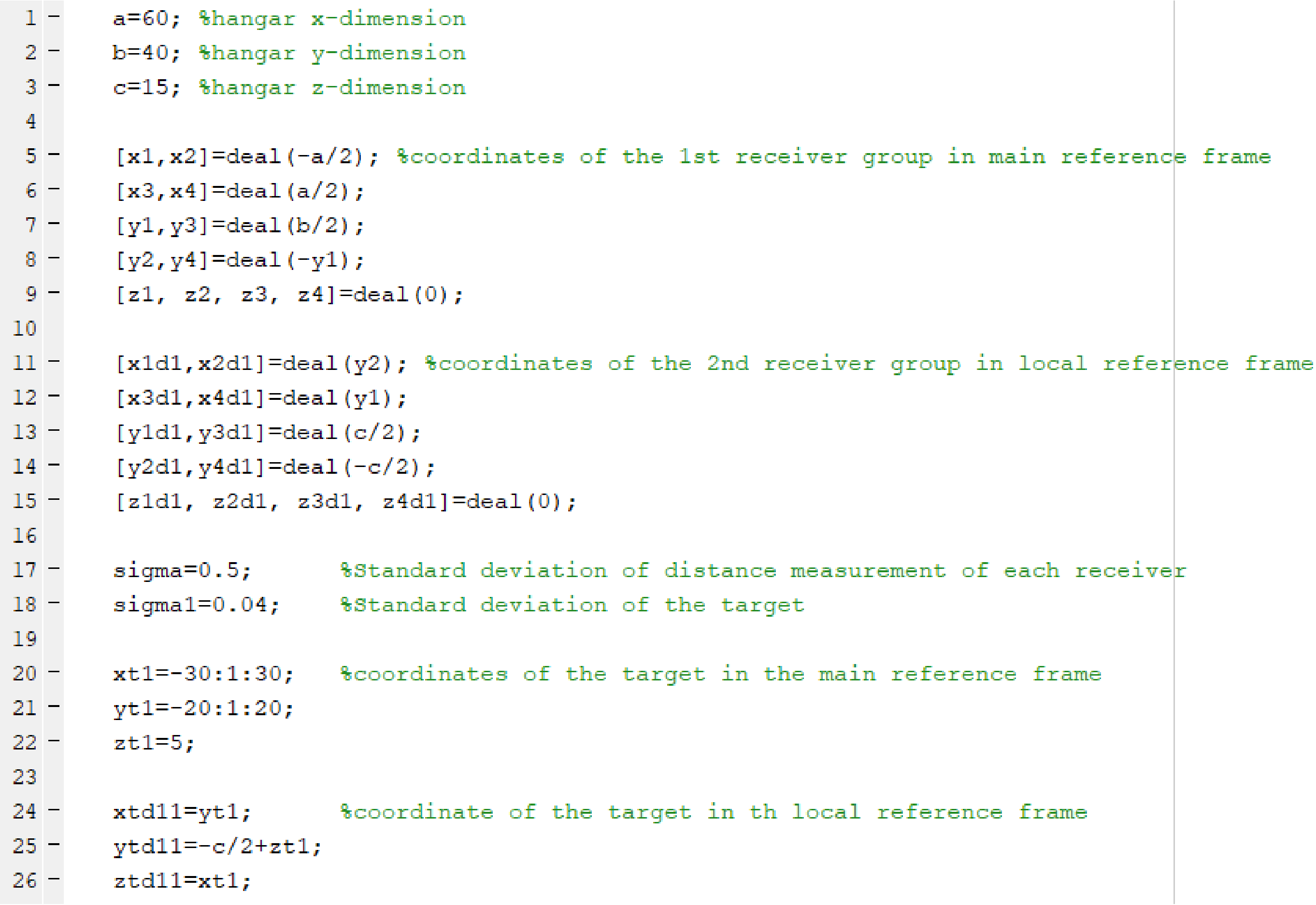


Fig. 10. Block-scheme of the mathematical model

The mathematical model can help to estimate positioning error values and access the performance of the multilateration algorithm.

The modeling is done in the MATLAB software. The cod is written to simulate the work of the multilateration algorithm, with given position of receivers, target coordinates and measurement standard deviation as an input. It is also possible to change the dimensions of the hangar and position of the receivers. On the output we get data array of points which represent the output values of the algorithm and the true target coordinates. These arrays can be plotted in the MATLAB environment. The resulting graph represents a surface, for which *x* and *y* coordinates are the coordinates of the target, and the respective data points are plotted on the *z* axis. The MATLAB code of the mathematical model is described next. Fig. 11 shows the code for setting the hangar dimensions and position of the receivers, by assigning values to their coordinates.

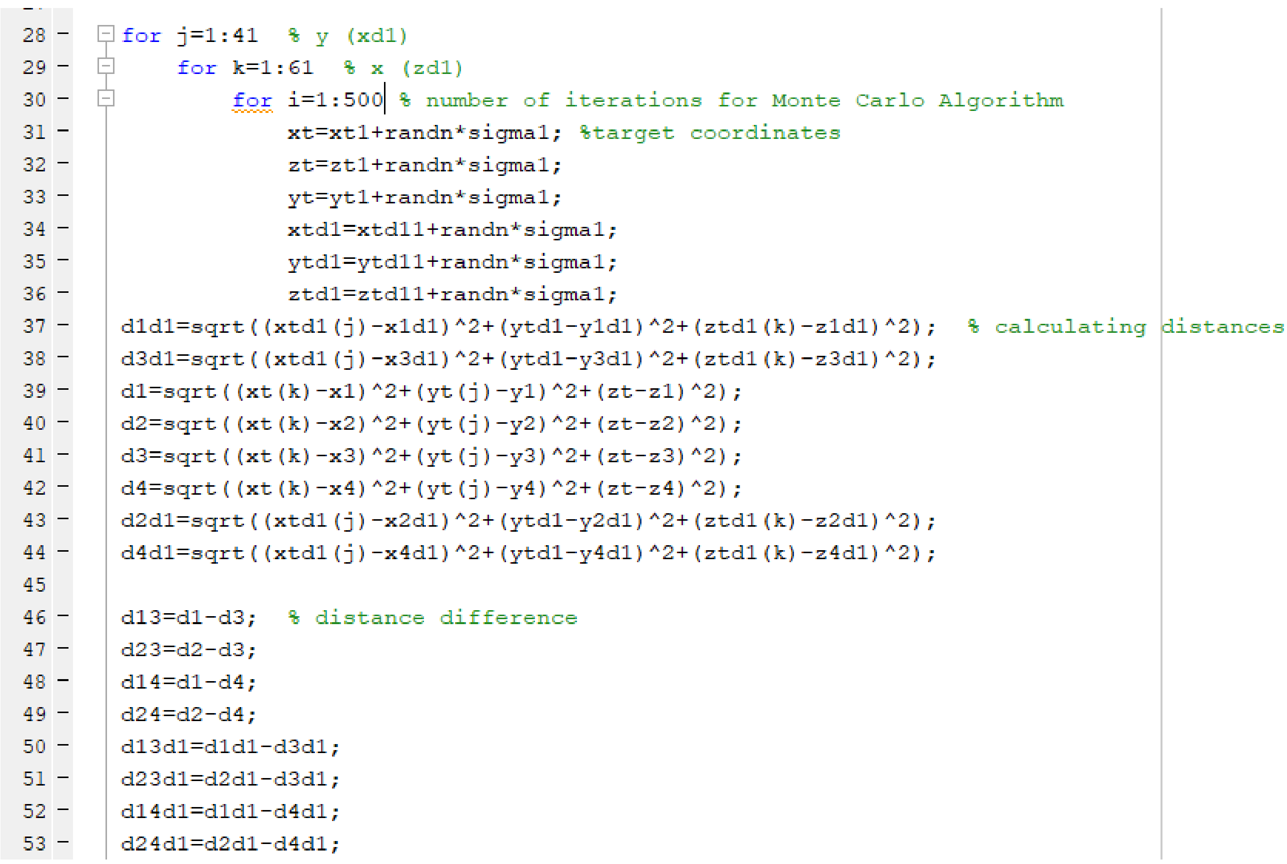


```
 1 -    a=60; %hangar x-dimension
 2 -    b=40; %hangar y-dimension
 3 -    c=15; %hangar z-dimension
 4
 5 -    [x1,x2]=deal(-a/2); %coordinates of the 1st receiver group in main reference frame
 6 -    [x3,x4]=deal(a/2);
 7 -    [y1,y3]=deal(b/2);
 8 -    [y2,y4]=deal(-y1);
 9 -    [z1, z2, z3, z4]=deal(0);
10
11 -    [x1d1,x2d1]=deal(y2); %coordinates of the 2nd receiver group in local reference frame
12 -    [x3d1,x4d1]=deal(y1);
13 -    [y1d1,y3d1]=deal(c/2);
14 -    [y2d1,y4d1]=deal(-c/2);
15 -    [z1d1, z2d1, z3d1, z4d1]=deal(0);
16
17 -    sigma=0.5;      %Standard deviation of distance measurement of each receiver
18 -    sigma1=0.04;    %Standard deviation of the target
19
20 -    xt1=-30:1:30;   %coordinates of the target in the main reference frame
21 -    yt1=-20:1:20;
22 -    zt1=5;
23
24 -    xtd11=yt1;      %coordinate of the target in th local reference frame
25 -    ytd11=-c/2+zt1;
26 -    ztd11=xt1;
```

Fig. 11. Inputs of the mathematical model

On the line (20) the coordinates of the target are assigned. For *x, y* coordinates, a ranged values are assigned, which cover the area of the hangar. For the altitude, *z* coordinate is set to constant value. The target coordinates also calculated for the local reference frame of the second receiver group.

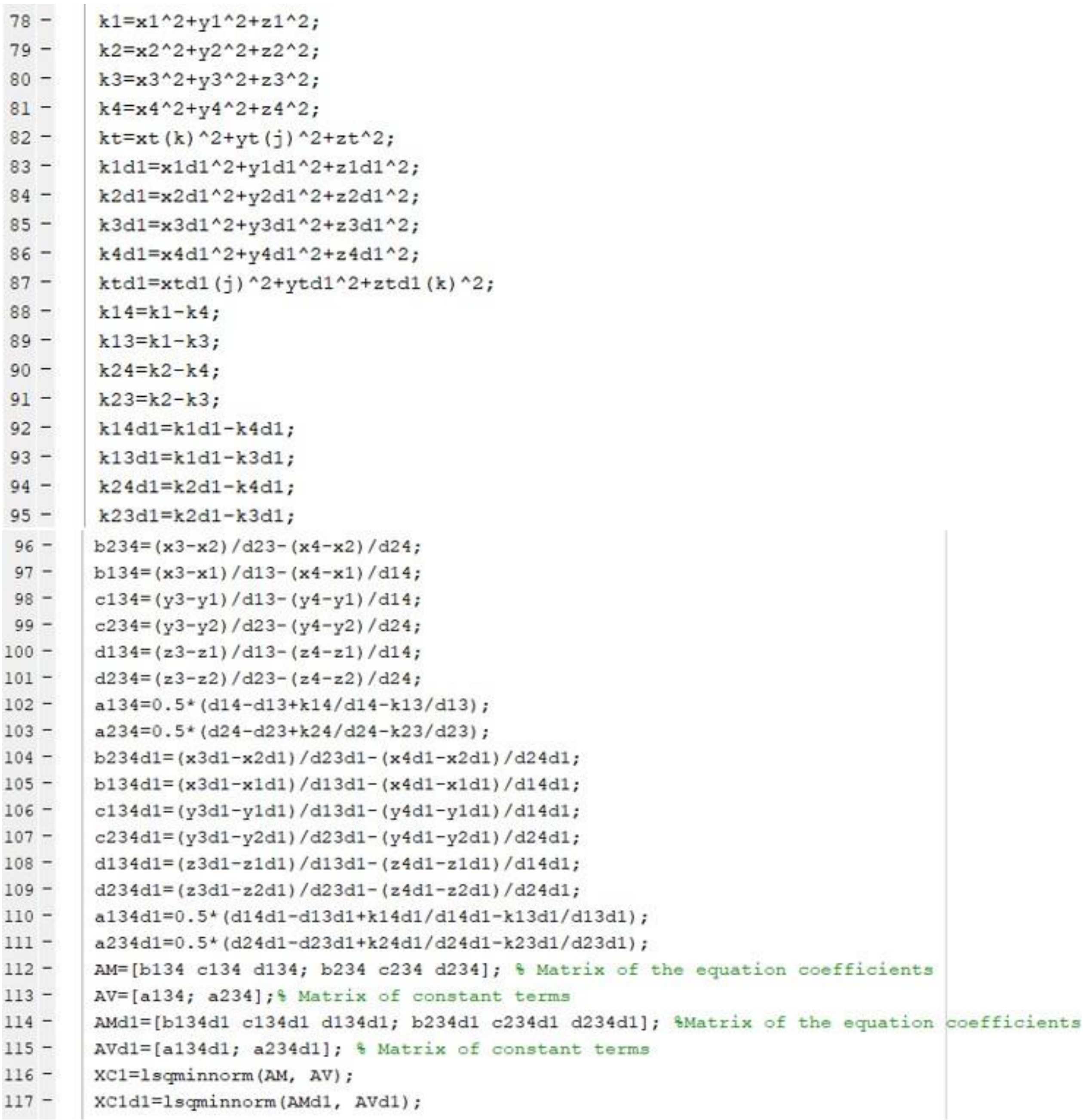
In the next stage, the Monte Carlo algorithm is applied, as it shown in Fig. 12.



```
28 - for j=1:41   % y (xd1)
29 -     for k=1:61   % x (zd1)
30 -         for i=1:500 % number of iterations for Monte Carlo Algorithm
31 -             xt=xt1+randn*sigma1; %target coordinates
32 -             zt=zt1+randn*sigma1;
33 -             yt=yt1+randn*sigma1;
34 -             xtd1=xtd11+randn*sigma1;
35 -             ytd1=ytd11+randn*sigma1;
36 -             ztd1=ztd11+randn*sigma1;
37 - d1d1=sqrt((xtd1(j)-x1d1)^2+(ytd1-y1d1)^2+(ztd1(k)-z1d1)^2);  % calculating distances
38 - d3d1=sqrt((xtd1(j)-x3d1)^2+(ytd1-y3d1)^2+(ztd1(k)-z3d1)^2);
39 - d1=sqrt((xt(k)-x1)^2+(yt(j)-y1)^2+(zt-z1)^2);
40 - d2=sqrt((xt(k)-x2)^2+(yt(j)-y2)^2+(zt-z2)^2);
41 - d3=sqrt((xt(k)-x3)^2+(yt(j)-y3)^2+(zt-z3)^2);
42 - d4=sqrt((xt(k)-x4)^2+(yt(j)-y4)^2+(zt-z4)^2);
43 - d2d1=sqrt((xtd1(j)-x2d1)^2+(ytd1-y2d1)^2+(ztd1(k)-z2d1)^2);
44 - d4d1=sqrt((xtd1(j)-x4d1)^2+(ytd1-y4d1)^2+(ztd1(k)-z4d1)^2);
45
46 - d13=d1-d3;  % distance difference
47 - d23=d2-d3;
48 - d14=d1-d4;
49 - d24=d2-d4;
50 - d13d1=d1d1-d3d1;
51 - d23d1=d2d1-d3d1;
52 - d14d1=d1d1-d4d1;
53 - d24d1=d2d1-d4d1;
```

Fig. 12. Applying Monte Carlo algorithm

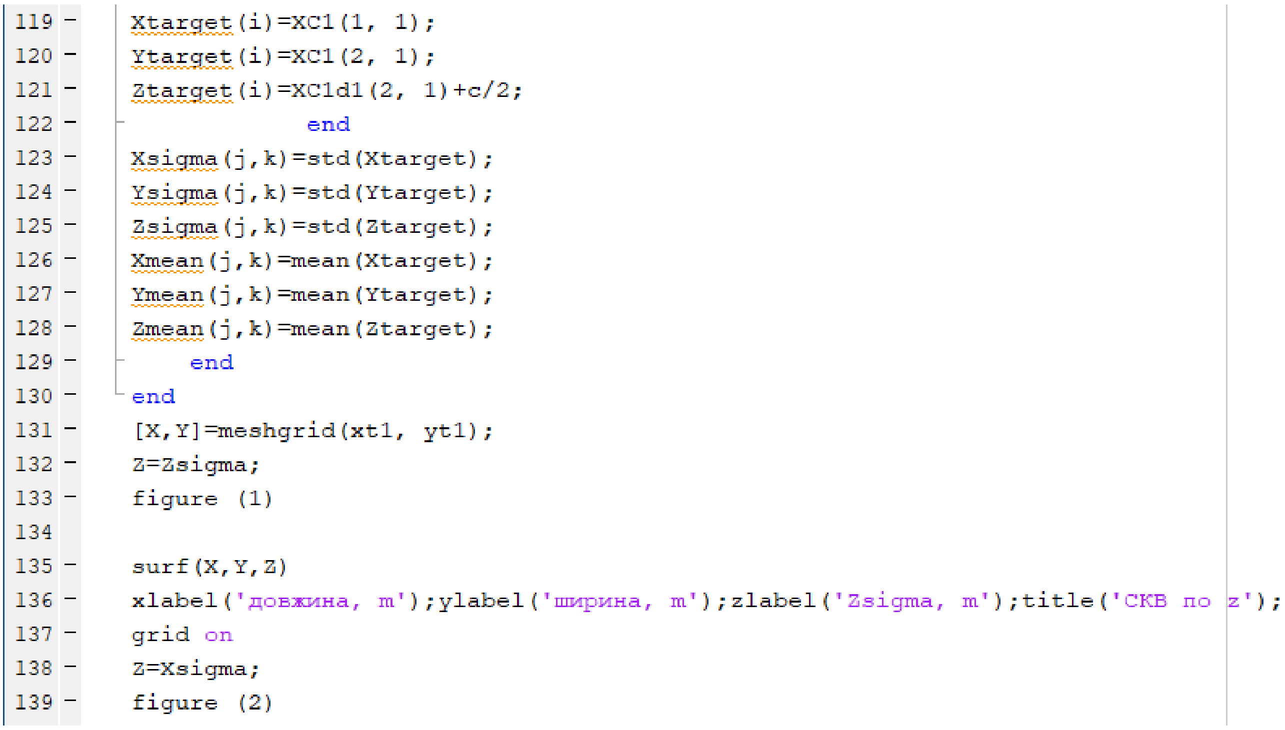
On the line (30), the variable *i* determines the number of iterations for each coordinate value. At each iteration, a random error of Gaussian distribution is applied to the coordinates of the target. The calculation of the TDOA is done next, and repeated for each iteration. Fig. 13 shows the further calculations for multilateration algorithm.



```
k1=x1^2+y1^2+z1^2;
k2=x2^2+y2^2+z2^2;
k3=x3^2+y3^2+z3^2;
k4=x4^2+y4^2+z4^2;
kt=xt(k)^2+yt(j)^2+zt^2;
k1d1=x1d1^2+y1d1^2+z1d1^2;
k2d1=x2d1^2+y2d1^2+z2d1^2;
k3d1=x3d1^2+y3d1^2+z3d1^2;
k4d1=x4d1^2+y4d1^2+z4d1^2;
ktd1=xtd1(j)^2+ytd1^2+ztd1(k)^2;
k14=k1-k4;
k13=k1-k3;
k24=k2-k4;
k23=k2-k3;
k14d1=k1d1-k4d1;
k13d1=k1d1-k3d1;
k24d1=k2d1-k4d1;
k23d1=k2d1-k3d1;
b234=(x3-x2)/d23-(x4-x2)/d24;
b134=(x3-x1)/d13-(x4-x1)/d14;
c134=(y3-y1)/d13-(y4-y1)/d14;
c234=(y3-y2)/d23-(y4-y2)/d24;
d134=(z3-z1)/d13-(z4-z1)/d14;
d234=(z3-z2)/d23-(z4-z2)/d24;
a134=0.5*(d14-d13+k14/d14-k13/d13);
a234=0.5*(d24-d23+k24/d24-k23/d23);
b234d1=(x3d1-x2d1)/d23d1-(x4d1-x2d1)/d24d1;
b134d1=(x3d1-x1d1)/d13d1-(x4d1-x1d1)/d14d1;
c134d1=(y3d1-y1d1)/d13d1-(y4d1-y1d1)/d14d1;
c234d1=(y3d1-y2d1)/d23d1-(y4d1-y2d1)/d24d1;
d134d1=(z3d1-z1d1)/d13d1-(z4d1-z1d1)/d14d1;
d234d1=(z3d1-z2d1)/d23d1-(z4d1-z2d1)/d24d1;
a134d1=0.5*(d14d1-d13d1+k14d1/d14d1-k13d1/d13d1);
a234d1=0.5*(d24d1-d23d1+k24d1/d24d1-k23d1/d23d1);
AM=[b134 c134 d134; b234 c234 d234]; % Matrix of the equation coefficients
AV=[a134; a234];% Matrix of constant terms
AMd1=[b134d1 c134d1 d134d1; b234d1 c234d1 d234d1]; %Matrix of the equation coefficients
AVd1=[a134d1; a234d1]; % Matrix of constant terms
XC1=lsqminnorm(AM, AV);
XC1d1=lsqminnorm(AMd1, AVd1);
```

Fig. 13. Calculations for the multilateration algorithm

In this part of the code, various coefficients for multilateration algorithm are calculated, according to eq. (7-9). In result, the matrices of the equitation coefficients and the constant terms are obtained. These coefficients are used to solve the multilateration eq. (10). The results can now be processed and visualized (Fig. 14).



```
Xtarget(i)=XC1(1, 1);
Ytarget(i)=XC1(2, 1);
Ztarget(i)=XC1d1(2, 1)+c/2;
            end
Xsigma(j,k)=std(Xtarget);
Ysigma(j,k)=std(Ytarget);
Zsigma(j,k)=std(Ztarget);
Xmean(j,k)=mean(Xtarget);
Ymean(j,k)=mean(Ytarget);
Zmean(j,k)=mean(Ztarget);
    end
end
[X,Y]=meshgrid(xt1, yt1);
Z=Zsigma;
figure (1)

surf(X,Y,Z)
xlabel('довжина, m');ylabel('ширина, m');zlabel('Zsigma, m');title('СКВ по z');
grid on
Z=Xsigma;
figure (2)
```

Fig. 14. Data visualization

The mean values of estimated coordinates and their standard deviations are calculated for each target position. This data is given in form of a matrix of data points, which are connected to the target coordinates in the three-dimensional space. The data points are then visualized using surface plots in MATLAB.

3.3. Analysis of the mathematical modeling results.

For the mathematical modeling of the multilateration algorithm, the input variables are set, as it was shown in Fig. 11. The receivers' coordinates represent their position in the hangar, as it is shown in Fig. 9. By running the MATLAB program, the resulting graphs of there-dimensional surfaces are obtained, which represent the values of positioning estimation, depending on the position of the target's emitter. The obtained plots are provided next:

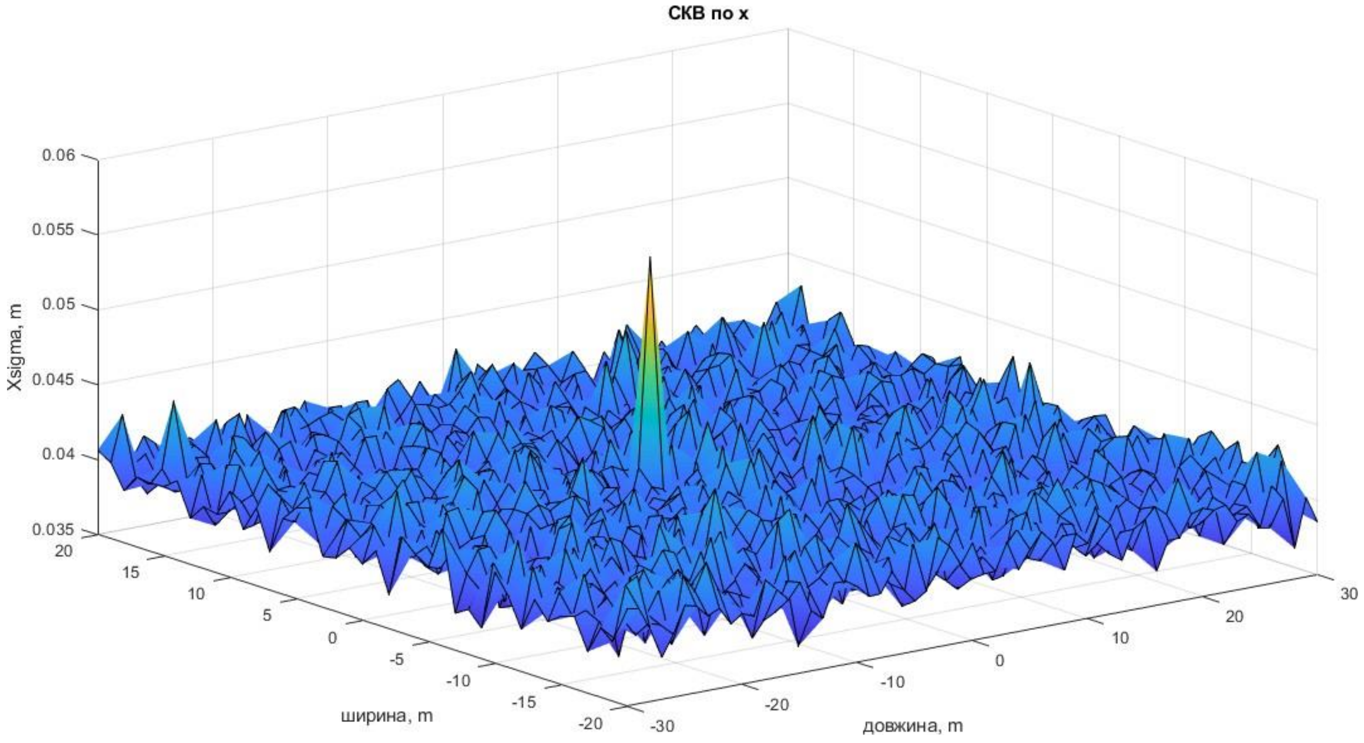


Fig. 15. Standard deviation of x

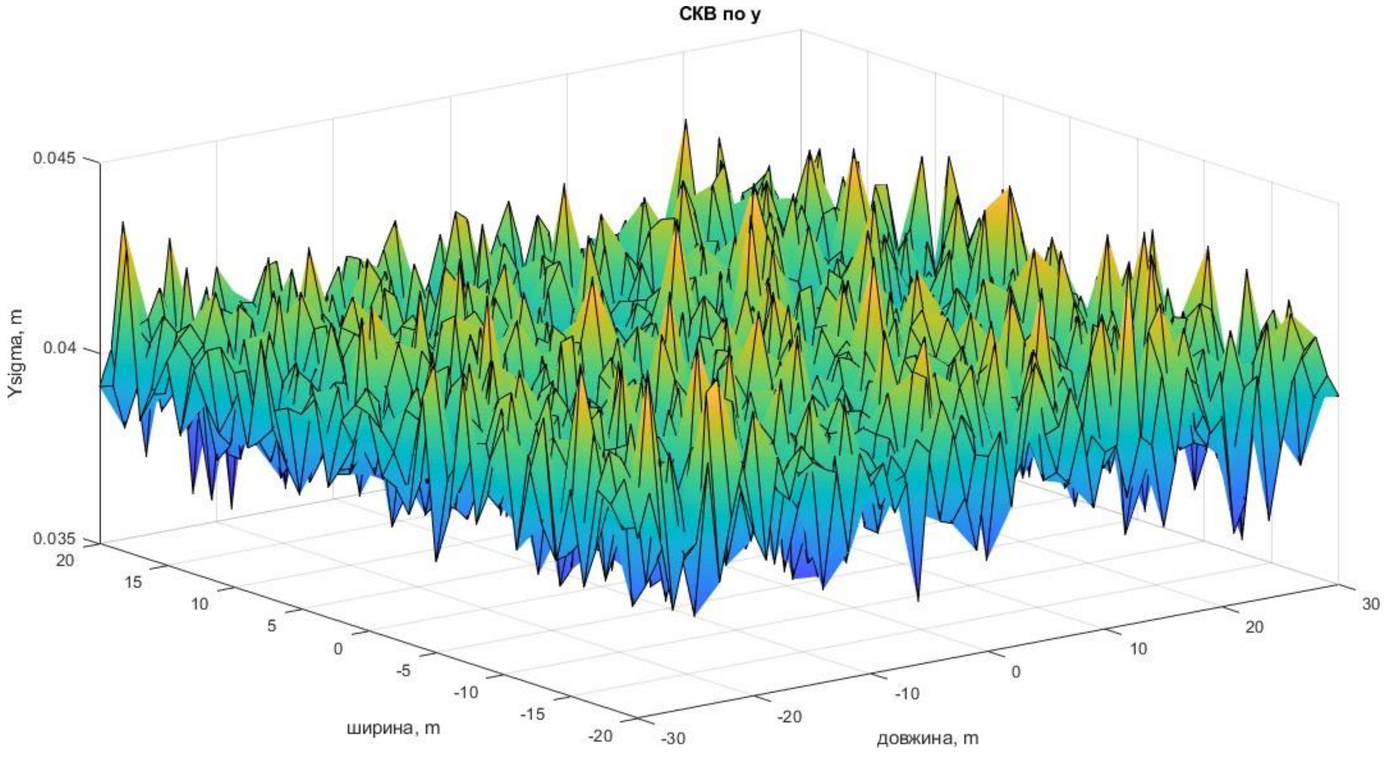


Fig. 16. Standard deviation of y

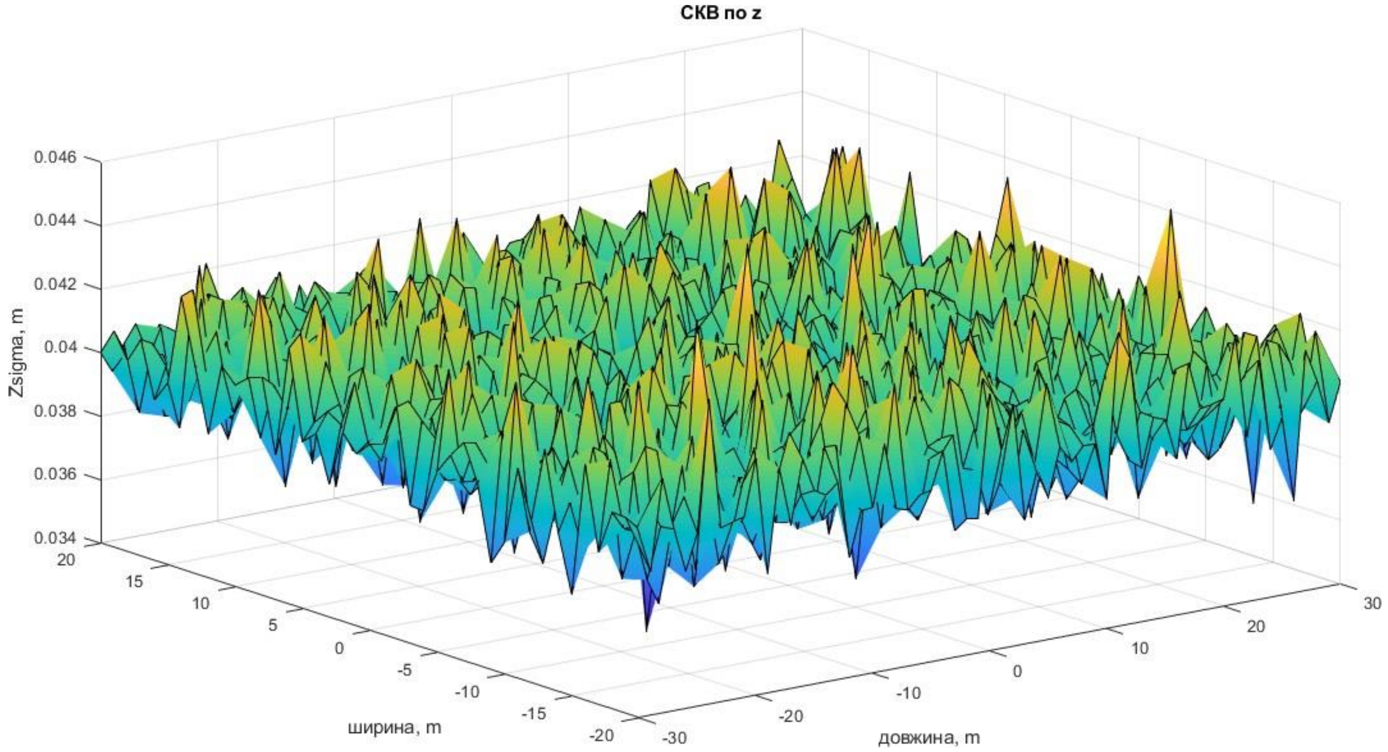


Fig. 17. Standard deviation of z

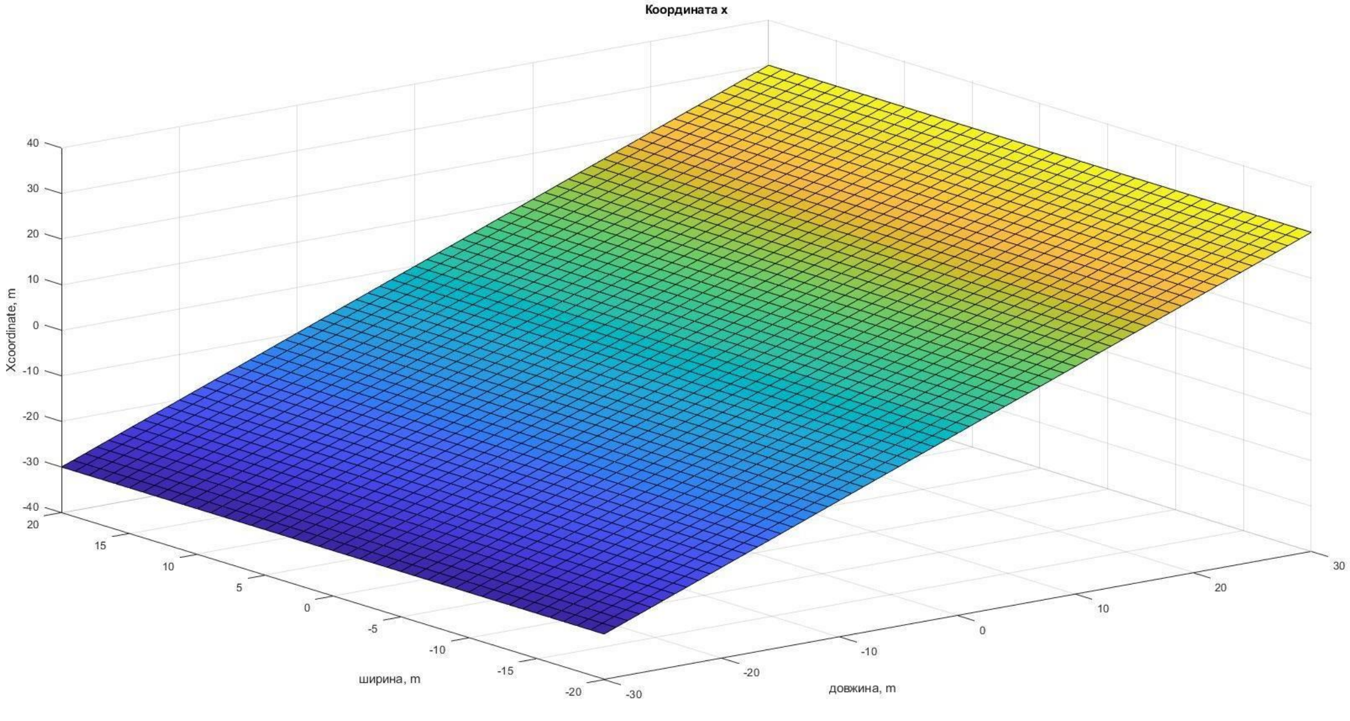


Fig. 18. X coordinate

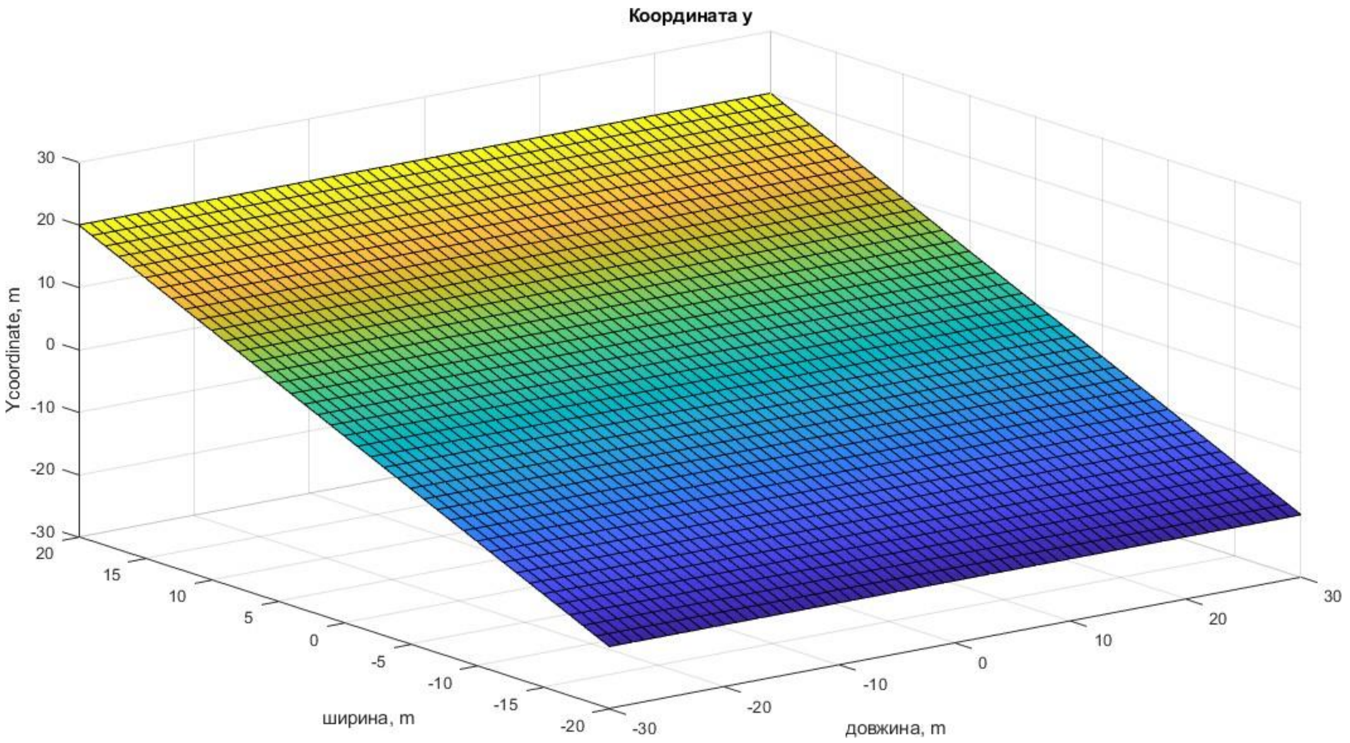


Fig. 19. Y coordinate

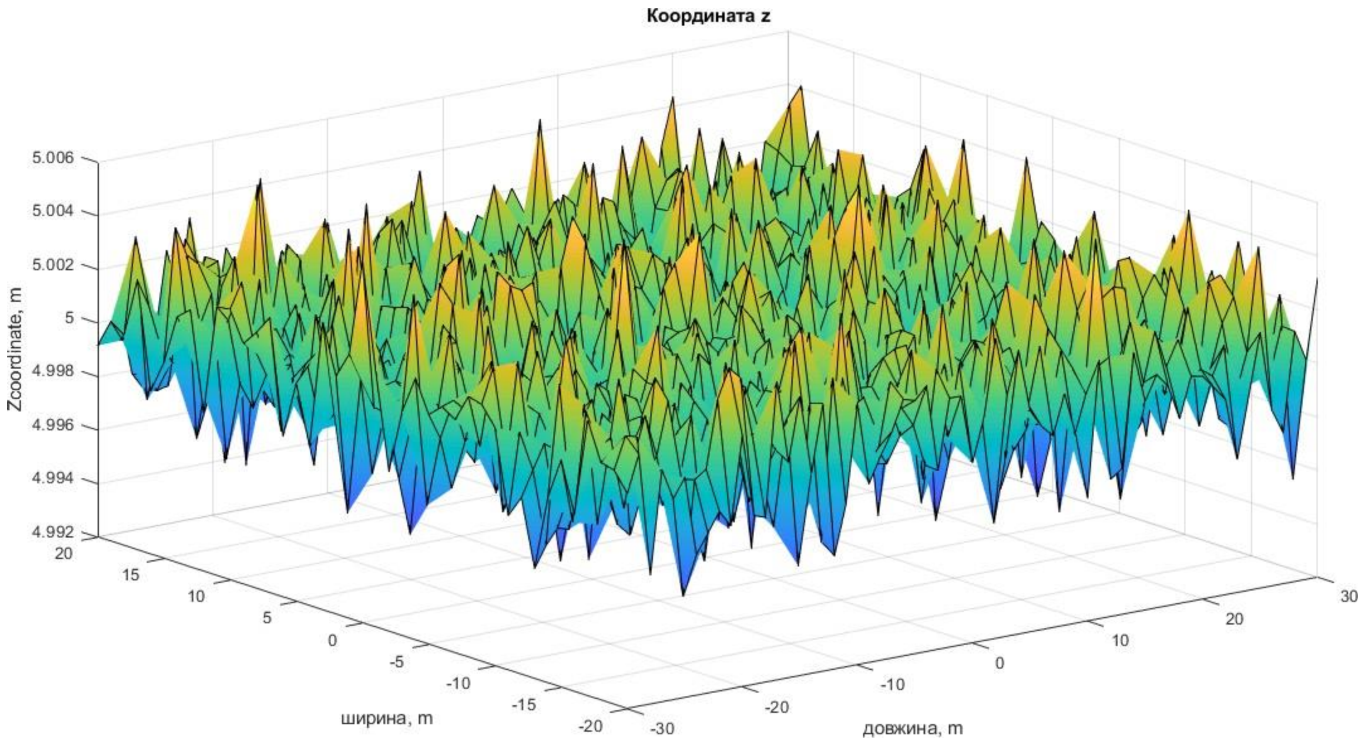


Fig. 20. Z coordinate

Fig. 15-17 show the standard deviation of PE for each coordinate of the target. The graph shows, that the value of the standard deviation is around 0.04 for each coordinate. These values are stay at mostly the same average level across of all possible position inside of the cover area of the positioning system. This means that reliable navigation can be provided by such system. Fig. 18-20 show the estimated coordinates for each position measurement. Measurements are influenced by random errors. From these results, it is possible to estimate the accuracy of such positioning system. The error of the positioning is around 4 cm, which is acceptable for indoor drone navigation. However, such accuracy will be guaranteed only inside the covered room, and if drone will be used outside of it, the accuracy may decrease. This is due to the fact, that in case of positioning outside the geometry of reference stations, the accuracy of TDOA algorithms is significantly reduced [28]. This means that if navigation is required across several rooms, each of it needs to be equipped with receivers. In, practice, the positioning error will be higher, in the presence of obstacles, as errors due to multipath, signal shadowing and scattering will emerge.

Conclusion to the chapter

Multilateration algorithms, which are used for air traffic control can be implemented for indoor navigational systems. In this chapter, a possible multilateration algorithm was studied. Based on this algorithm, the mathematical model of indoor positioning system was developed and tested. The program was written in MATLAB, which is a modern software, suitable for creating and analyzing mathematical models. During the development of the model, a realistic environment for drone navigation was considered. Drones, used for warehouse operations or hangar inspection are navigating in relatively open areas. The system of receivers, which is designed to cover similar areas, is considered. Positioning is done in three dimensions. The required time synchronization is assumed to be done by the means of GPS, for which outdoor receivers are provided. The error estimation is done using Monte Carlo algorithm, that is a large number of iterative measurements were modeled for each UAV position, and the theoretical system accuracy was estimated. The error estimation is done for the positioning algorithm, and does not consider errors caused by obstacles affecting the signal, or its attenuation. The obtained data was visualized using the three-dimensional surface plots.

The mathematical modeling is divided into several steps. In the first step, initial parameters, such as hangar dimensions, true target coordinates and initial standard deviation are set. The coordinates of each receiver are calculated. In the second stage, a Monte Carlo algorithm is applied to the position calculations of the multilateration algorithm. Multilateration is done separately for horizontal coordinates and for vertical positioning. At the third stage, the data gathering and visualization is performed. The block scheme (Fig. 10), and the source code (Fig. 11-14) are provided.

Results of the modeling show high level of accuracy and consistency of the multilateration algorithm inside the covered area. The measured positioning error is 4 cm. This means, that such system and algorithms are possible to implement for indoor navigation. Such system will be mostly suitable for warehouse or hangar operation. The obtained accuracy can be sufficient for intra-logistic, where drones are required to grab specific objects and move them to other location. It can also be used for inspections. However, if we consider inspections in places, where the receivers can’t be installed directly in the inspection areas, the accuracy may not be acceptable. This also means that such system is not suitable for navigation inside unknown environments. Further studies of such system may be connected with modeling of signal dependent errors and addition of filtering to possibly increase overall accuracy of the modeling.

CONCLUSIONS

In the bachelor work various use cases and prevalence of indoor UAVs were considered. Technical characteristics and design features of commercially available indoor drones were analyzed. In the second chapter, indoor navigational technologies, algorithms and methods were considered. They were compared and assess for possible implementation in different areas of indoor drone operation. The TDOA-based positioning system was chosen for further investigation, considering its advantages compared to other alternatives. Finally, the mathematical model of positioning system was developed in MATLAB. The obtained results of mathematical modeling were analyzed and conclusions about system's performance and accuracy were made.

Considering the indoor UAVs, their popularity is rapidly increasing. Indoor drones are mostly used for inspections in confined or hard-to-reach places, inventory management, intra logistics, surveillance and mapping. Most of indoor drones are quadcopters or hexcopters. This design, combined with small size and weight, ability to hover, perform agile maneuvers and avoid obstacles, allows drones to be used in various indoor environments. To increase safety, indoor drones are often equipped with a protective cage, which is able to protect drones and equipment from collisions. Another advantage of drones, is their versatility. They can be equipped with various tools, such as high-resolution cameras, LiDAR, thermal cameras, spectrometers, environmental monitoring equipment etc. However, most such drones have limited battery life and payload. This applies the main limitation for choosing on-board equipment. This means, that during development of navigational system, light-weight equipment should be considered. On the other hand, the accuracy, required for indoor navigation is considerably higher than for more classical use of drones outdoors. Such requirements impose a technical challenge during the development of positioning systems. Most of existing system, such as GPS or INS, are not suitable for indoor drones, as they can't provide sufficient accuracy and reliability, or meet the weight limitations.

Indoor navigation for UAVs is not deeply studied yet. Most of existing indoor navigation technologies are developed for pedestrian navigation or other purposes. However, some of them can be implemented for drones. Positioning systems are classified by the technology (infrared, ultrasound, magnetic, optical, radio frequency, dead reckoning and hybrid), positioning algorithm (triangulation, trilateration, proximity and scene analysis) and used signal properties (AOA, TOA, TDOA, RSSI). The most promising positioning technologies, suitable for indoor navigation of UAVs are RF, ultrasound and vision. Such technologies were already studied or implemented for some drones. The most suitable PE algorithms and signal properties are different for specific environments and use cases. TOA system are highly expensive, but provide high levels of accuracy at all scales. AOA systems are less complex and inexpensive at small scales, requiring less receivers. However, for large areas of operations, to sustain desired levels of accuracy, additional receivers need to be added to the system, so this advantage is diminished, as the cost of the individual receiver is higher compared to other system. Such systems are mostly suitable for 2D navigation in limited area of operation. TDOA can provide high level of accuracy at less complexity than TOA systems. RSSI systems provide the lowest accuracy, compared to other. However, RSSI can be useful in applications where lower accuracy levels are acceptable or in combination with other navigational methods in hybrid systems.

For further study, and developing of the mathematical model, a TDOA-based multilateration algorithm was chosen. In the third chapter, the description of the algorithm is provided. The navigational system was modeled, concerning a possible real-life application of indoor drones. The system consists of total of eight receivers, placed inside of a hangar, providing 3D positioning for drone inside the hangar. The mathematical model was designed in MTLAB. For the analysis of accuracy, a Monte Carlo algorithm was applied. A 500 iteration for each position of a target were simulated for random errors. The position of the target is than calculated by the multulateration algorithm. The resulting measuring error of positioning was than estimated. The obtained error is around 4 cm. This value provides an estimation of theoretical performance of a multilateration algorithm, as it doesn’t take into account errors connected with effects of obstacles on the signal propagation. The results of the analysis can be used to assess the desirability of the TDOA method, comparing to alternatives during the designing of indoor navigational systems for UAVs. Some of the application, where such system can be used are: stock tacking in warehouses, intra logistics, surveillance and inspections in environments, suitable for installation of such navigational system. The additional equipment for the drone is light-weight, so TDOA-based systems are suitable for small UAVs. The results of this bachelor work can be used as basis for further studies in the area.

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