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Research Article

System Engineering-Based Conceptual Design of Indoor Navigation System of Unmanned Aerial Vehicles

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Abstract: Unmanned aerial vehicles (UAVs) have been become important day by day because of advantages in our life use cases; specially, they can play important role in the industry 4.0 concept such as automation in production plants. System engineering approach is planning the design and production phases. Every system, subsystem, component, or mission of the systems are investigated before project starts and each requirement is set. The investigation of compatibility between systems and products minimizes the risks during the production phases. This paper proposes the usage of system engineering approach to the conceptual design of an UAV navigation system which aims to be used in indoor environments. In order to provide autonomous indoor flight, system requirements are set by using system engineering approach. Then step by step, the basic functions that UAV needs to complete operation are specified. The required products are listed as a tree and the relation between products and functions are investigated. Thus, the conceptual design of the UAV indoor navigation system is demonstrated by using of the functional tree, the functions and product relation matrix, the product tree, and the use cases. Moreover, the system operational requirements are investigated, and the requirement operation phases, modes and use cases are also determined. Thanks to system engineering, all these complex systems are put together systematically, and the conceptual design is achieved.

Keywords: *Unmanned Aerial Vehicle, Indoor Navigation, System Engineering, Functional Analysis.*

İnsansız Hava Araçları İçin İç Mekan Seyrüsefer Sisteminin Sistem Mühendisliği Tabanlı Konsept Tasarımı

Öz: İnsansız hava araçları (İHA'lar) hayatımızdaki kullanım durumlarında sağladığı avantajlar nedeniyle gün geçtikçe önem kazanır hale gelmiştir; özellikle üretim tesislerindeki otomasyon gibi endüstri 4.0 konseptinde önemli rol oynayabilirler. Sistem mühendisliği yaklaşımı, tasarım ve üretim aşamalarının planlanmasıdır. Sistemlerin her sistemi, alt sistemi, bileşeni veya görevi proje başlamadan önce incelenir ve her gereksinim belirlenir. Sistemler ve ürünler arasındaki uyumluluğun araştırılması, üretim aşamalarındaki riskleri en aza indirir. Bu makale, kapalı ortamlarda kullanılması amaçlanan bir İHA navigasyon sisteminin kavramsal tasarımında sistem mühendisliği yaklaşımının kullanılmasını önermektedir. Otonom iç mekan uçuşunu sağlamak için sistem mühendisliği yaklaşımı kullanılarak sistem gereksinimleri belirlenir. Daha sonra adım adım İHA'nın operasyonunu tamamlaması için ihtiyaç duyduğu temel fonksiyonlar belirlenir. İhtiyaç duyulan ürünler bir ağaç halinde listelenir ve ürünler ile fonksiyonlar arasındaki ilişki araştırılır. Böylece fonksiyonel ağaç, fonksiyonlar ve ürün ilişki matrisi, ürün ağacı ve kullanım durumları kullanılarak İHA iç mekan navigasyon sisteminin kavramsal tasarımı gösterilmiştir. Ayrıca, sistem işletim gereksinimleri araştırılır ve gereksinim işletim aşamaları, modları

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ve kullanım durumları da belirlenir. Sistem mühendisliği sayesinde tüm bu karmaşık sistemler sistematik bir şekilde bir araya getirilerek kavramsal tasarıma ulaşılır.

Anahtar Kelimeler: İnsansız Hava Aracı, İç Mekan Seyrüsefer, Sistem Mühendisliği, Fonksiyonel Analiz.

1. Introduction

Unmanned aerial vehicles (UAVs) have been become important day by day because of advantages in our life use cases. Specially, they can play important role in the industry 4.0 concept such as automation in production plant.

Today, many studies are carried out to ensure the navigation of unmanned aerial vehicles, which we encounter in every field, by using Image Processing and IMU (Inertial Measurement Unit) sensors. There are problems that come with this need, which is generally encountered in cases where there is no or decreased GNSS (Global Navigation Satellite System) signals. IMU sensors need an integration process to convert the data obtained from the sensor into velocity and position data. However, the fact that the data coming to the sensor is noisy. This noise could be due to a variety of factors, including uncertain effects such as interference, temperature changes, or mechanical vibrations. It causes this noise to integrate over time and causes measurement drifts that increase over time. Image processing-based approaches, by providing an additional source of information about the motion of the system, fused with IMU measurements to prevent these drifts. These systems are based generally on Visual Odometry (VO) or Simultaneous Localization and Mapping (SLAM) techniques, the images obtained from the cameras are used to reduce the error in IMU sensor measurements with the help of different algorithms.

Unmanned aerial vehicles (UAV), which have been developing rapidly from the past to the present, are frequently used for both military and civilian purposes today. In addition to being used in the military for intelligence, surveillance, and attack missions, they are also used for civilian purposes such as image collection, observation of a geographical area, data collection and hobby purposes.

UAVs with such widespread use and expected to form the backbone of the armies of the future can be managed by an operator and might have autonomous flight capability. Unmanned aerial vehicles, which are preferred to fly more autonomously, need to know their position, speed, and rotation to perform the tasks they need to do. This is where navigation systems come into play.

Navigation systems are primarily based on the Inertial Measurement Units (IMUs) they contain onboard. These sensors contain at least 3 accelerometers and 3 gyros to measure the acceleration and angular velocities of the UAV. Position and velocity are measured by integrating the acceleration data obtained from the IMU sensor. However, at this point, a problem called drift error arises due to the noisy sensor measurements. Although our drift error is small since it will increase continuously during the integration process, the margin of error in our measurements will increase over time,

causing us to guess our position incorrectly and might be resulting in accidents. GNSS signals, altimeters, cameras, laser rangefinders are frequently used together with IMUs to reduce the amount of increasing error to make accurate measurements.

The prevalence and low margin of error of the GNSS satellite network will make it the number one choice. However, in cases where GNSS signals are insufficient to reach closed environments, weaken or even disappear due to environmental effects, it will no longer be an option to reduce the errors in IMU sensors. Cameras are generally used to overcome this problem. Different image processing techniques continue to be developed by researchers for camera navigation systems consisting of a combination of one or more cameras.

IMU sensors cause increasing drift over time. However, their high sampling rate makes them stand out as the first choice for navigation. On the other hand, although image-based navigation systems do not cause a problem such as drift, they are not a standalone choice due to the high processing power required for image processing and their low sampling rate.

These two systems used together by sensor fusion algorithms to eliminate the disadvantages of both systems. Researchers mainly focused on two techniques for navigation with IMU and image processing-based navigation systems studies. These two techniques are: 1. Visual Odometry [1,2,3]. 2. Simultaneous Localization and Mapping (SLAM) [4,5,6,7,8,9].

Visual odometry is a process that detects the differences between sequential images obtained by cameras and converts these differences into position and velocity information by image processing algorithms. It is usually [3] performed by following these 6 steps:

1. Image acquisition (by a single camera, stereo cameras, omnidirectional cameras)

2. Correction of image distortions caused by external factors.

3. Extraction of the features of objects in the images.

4. Extraction of optical flow vectors from the extracted features.

5. Estimation of the position and speed of the vehicle used via optical flow vectors.

6. Updating the old estimations and repeating the whole process according to the newly acquired estimations.

With this process, the position of the aircraft can be found, and the velocity of the vehicle can be estimated due to the change in position over time. Therefore, it can correct the errors that occur in the IMU sensors.

Unlike visual odometry, in the SLAM technique, a live map of the current environment is created with the cameras on the vehicles. The position of the vehicle is determined by the changes in the live map. The biggest challenge of the SLAM technique, which was introduced by H. Durrant Whyte [4] in 1996, is that it needs an accurate map for localization, and it needs accurate position estimations for mapping. However, different techniques have been developed to overcome this difficulty.

The SLAM technique is performed by following the steps below[3]:

1. First, the initial position of the vehicle is determined as the starting point, or an estimate is made with high uncertainties on a map with some predetermined features.

2. When the vehicle starts to move, new predictions are made through state estimation algorithms (mostly Kalman Filter algorithms are used) and the position of the vehicle is tried to be found.

3. The map is updated through the newly obtained images. And new features obtained by comparing them with previously known features. These features can include points, lines, corners, or other structures that are distinct and easily recognizable. Comparison can be made by feature matching, feature tracking, determining certain geometric metrics, etc.

4. At the end, the 2nd and 3rd steps are repeated continuously, allowing the vehicle to map its environment.

In the SLAM technique, position estimation can be made with increasing accuracy by increasing the accuracy of the live map over time. The SLAM technique is generally seen as a visual and LIDAR SLAM.

In both mentioned techniques, the Kalman Filter [7] is frequently used as the state estimation algorithm. The Kalman filter is an algorithm that provides to reduce the error rate of noisy and erroneous measurements obtained from different sensors by using the mathematical model of the vehicle and to predict the input and output states of the vehicle which is used in. In the algorithm, the estimation is made first. Then, according to this estimate, the differences between the actual observation and the observation obtained by the predictions are calculated. According to the resulting state error, the predicted state is updated. The Kalman filter can be used in linear systems. However, in more complex, nonlinear systems, the Extended Kalman Filter (EKF) and the Unscented Kalman Filter (UKF) are preferred to avoid linearization-related problems.

Image processing systems, which require high processing power, have become one of the main work areas of researchers for navigation, as high processing power has begun to be obtained with small dimensions. Among these researchers, Omead Amidi [1] made the position estimation of an unmanned helicopter with the visual odometry technique he designed in 1994. This technique was then developed by the fusion of different sensors and cameras among researchers.

Bryce Ready [2] combined the visual odometry method with GPS measurements and tested it on micro aerial vehicles (MAVs). In the study using the iterative closest point method, results with over margin of error were obtained unlike Omead Amidi [1]. The results of the study were verified by comparing the estimations with the data obtained from the flight log of MAV.

Stereo cameras were used in Amidi's [1] and Bryce's [2] work. The requirement to calibrate the stereo cameras before the flight is an extra problem in large-scale applications. To overcome this problem, Chaoeli Wang [8] used the advantages of monocular cameras (accuracy, scalability, low-cost calculations) overusing a stereo camera and suggested obtaining image depth feature through ultrasonic or barometric altitude sensors. He tested and verified the algorithm with a model helicopter.

Evan Anderson et al. [9] has also developed a new generation algorithm using VO with GPS/IMU, which requires less computational power compared to the high computational power required by the method used by Bryce B Ready [2]. In the application using UKF, the measurements obtained from the IMU sensors were fused with the measurements obtained by the VO method, and the results obtained were tested and verified on the simulation.

In their paper, Rafik Mebarki et al. [10] propose two methods for estimating the translational velocity of unmanned aerial vehicles (UAVs) using only onboard sensing. The first method is a nonlinear observer designed using Lyapunov synthesis, while the second is based on the unscented Kalman filtering technique. Both methods use spherical images and inertial measurement unit (IMU) data to estimate the velocity without the need to fully estimate the 3D pose of the vehicle, making them suitable for use in UAV systems where computational resources may be limited. The authors demonstrate the effectiveness of these methods using experimental results, and plan to use the estimated velocity as feedback to control the UAV in both indoor and outdoor environments. In future work, the authors plan to use the Shi-Tomasi algorithm to detect natural corners in images, rather than artificial circular landmarks, and to employ two onboard cameras to improve the accuracy of velocity estimation.

S. Rady [11] presents a vision-based approach for localizing an autonomous unmanned aerial vehicle (UAV) in the event of GPS failure. The approach consists of constructing a hybrid map using reduced features obtained through information-theoretic analysis, which are represented by local descriptors with metric positions. The UAV is then localized using the map on two scales: a fast and coarse topological location is identified based on image features and local descriptor matches, while a precise metric position is estimated based on the topological location and the metric positions of the features. The approach offers a combination of accuracy and computational efficiency for UAV localization in emergency situations.

Daniel Megree [12] has designed a SLAM with IMU based navigation system that can work both simultaneously and independently by combining Visual SLAM and Laser Slam techniques. It was aimed to eliminate the problematic aspects of both methods. Testing and validation of the system were done on a quadcopter system. In the tests performed, both SLAM methods were tested both separately and together.

With EU funding, a micro drone swarm project based on image-based control was created by Markus Achtelik et al. [13]. The project aims to produce 3D maps of unknown environments with a swarm of autonomously flying drones. Then, with the maps obtained, the second purpose is to determine ideal points for surveillance and to locate the surrounding radio stations with the radio transceivers they carry. In the tests performed in 3 steps, in the first step, a 3D map of a disaster area was created with the maps obtained by 3 unmanned aerial vehicles. Then, unmanned aerial vehicles were sent to the points specified on the maps obtained. In the last stage, they warned people who might be affected by the disaster with the radio transmitter they carried. In this project, the position estimation of the UAVs was obtained by the fusion of SLAM and IMU sensors.

In his research, Gianpaolo Conte [14] investigated that the errors in the data obtained with the VO and IMU sensors can be compensated in the absence of GPS with geo-referenced satellites and aerial images. In the research where the Kalman filter is used for sensor fusion, it has been revealed that aerial images or geo-referenced satellites can be used to compensate for errors in the navigation system. The system has been tested and verified on the commercial Yamaha RMAX model helicopter.

In his study using the SLAM technique, William Power [15] provided the data obtained from hundreds of previous flights to be taught to the aircraft by using the structured learning technique and provided a more accurate position estimation in the absence of GPS signal of unmanned aerial vehicle swarms.

In brief, it is presented the different navigation methods by using image processing and IMU sensor measurements. There are generally two approaches in studies. However, it is seen that the visual audiometry method is more preferred since it does not spend extra resources to map the environment. In the future, we will see navigation systems that can make more precise predictions with the developing machine learning technology.

System engineering approach is planning the design and production phases. Every system, subsystem, component, or mission of the systems are investigated before project starts and each requirement is set. The investigation of compatibility between systems and products minimizes the risks during the production phases. Functional analysis is an important solution approach for conceptual design of a complex system [16].

In this paper, the system engineering approach is discussed in two topics: Mission analysis and functional analysis. The mission analysis investigates how the operation will be continued, which functions do the system needs. The functional analysis investigates what the needs execute the functions. Image-based navigation systems have designed to use at places where GNSS is not available. A main problem is choosing the references to measure movement because the positioning needs to a reference point to calculate where the object is in a decided coordinate system. For GNSS applications, these references are satellites, and the movement of object is calculated depending on the satellites. To find a reference, indoor navigation systems use different sensors to detect environment and find visual or perceptible references to calculate previous and instant positions. After customer needs are determined, the system requirements can be set. The requirements can be handled into two parts: “Phase and Modes” and “Operational Specifications”. This paper proposes the usage of system engineering approach to the conceptual design of an UAV navigation system which aims to be used in indoor environments. To provide autonomous indoor flight, system requirements are set by using system engineering approach. Then step by step, the basic functions that UAV needs to complete operation are specified. The

required products are listed as a tree and the relation between products and functions are investigated. Thus, the conceptual design of the UAV indoor navigation system is demonstrated by using of the functional tree, the functions and product relation matrix, the product tree, and the use cases. Moreover, the system operational requirements are investigated, and the requirement operation phases, modes and use cases are also determined. Thanks to system engineering, all these complex systems are put together systematically, and the conceptual design is achieved.

System engineering approach is planning the design and production phases. Every system, subsystem, component, or mission of the systems are investigated before project starts and every requirement are set. The requirements and the investigation of compatibility between systems and products minimizes the risks during the production phase. This paper, the system engineering approach discussed in two topics: Mission Analysis and Function Analysis. The main purpose of the separation to these two topics is the Navigation System project has an operational usage. Mission Analysis investigates how the operation will be continued, which functions do the system needs and the Function Analysis investigates what are the needs to execute the functions. The work path will be followed is given in the Figure 1. In this article the related drawings are obtained by using UML language with PLANTUML [17]. Therefore, all designs are implemented by a standard approach using programming language, that is PLANTUML [17].

The preliminary version of the proposed system engineering-based approach is presented at [18]. The rest of the article is organized as follows. The next section introduces the proposed conceptual design. In the last section, some comments and future directions are given.

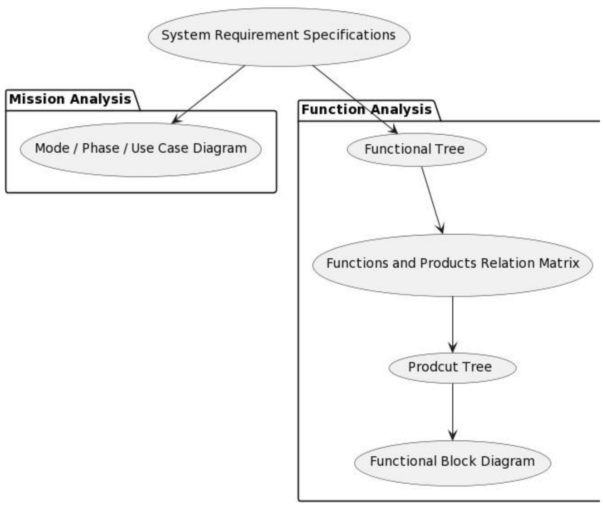

Fig. 1. *The Work Path of System Design.*

2. System Engineering-Based Conceptual Design

A system engineering approach to the conceptual design of a navigation system involves the following steps:

1. Define the problem: Identify the needs and requirements of the system, such as the intended environment, the performance goals, and the constraints on the system.
2. Define the requirements: Specify the detailed requirements for the system, including performance, reliability, and other characteristics that must be satisfied.
3. Development of a conceptual design: Create a high-level design of the system that meets the identified needs and requirements. This design should consider the overall architecture of the system, the sensors and other components that will be used.

Since the problem already defined, the required phases and modes are given as follows:

SRS-RPM-1 The system shall has a “Pre-mission” phase which includes “Device Off” and “Initialization” use cases.

SRS-RPM-2 The system shall has a “mission” phase which provides operational sustainability and includes “Sensor Degradation” use case.

SRS-RPM-3 The system shall has a “post-mission” phase which allows the flight data logging and prepares the vehicle to maintenance.

In the conceptual design, the required 0perational specifications are given as follows:

SRS-ROS-1 System shall not include GPS. The system will be used in indoor operations.

SRS-ROS-2 The system shall work with at least 15cm precision.

SRS-ROS-3 The system shall be able to continue its operation in one sensor loss by using other sensors.

SRS-ROS-4 The system should deactivate itself in the case of multiple sensor loss.

SRS-ROS-5 The system must perceive the obstacles around and must be avoid them.

SRS-ROS-6 The system should map the environment while flying.

SRS-ROS-7 The system shall send live telemetry data to operator or ground control.

SRS-ROS-8 The system shall keep the flight logs into its storage, and they can be accessible after the flight.

Phase / Mode / Use Case Diagram of The System is given in Figure 2. There are totally 3 phases: Pre-mission phase, mission phase and post mission phase. Totally 12 use cases and 8 modes. The detail design of these use cases are not in the scope of this article. In the functional analysis, at first functional tree is designed and it is given in Figure 3. According to the basic functions each representative product or products are selected, and the Function and Product Relation Matrix of The System is constructed. It is given in Figure 4. After that, the Product Tree of The System is obtained using the Function and Product Relation Matrix of The System. It is given in Figure 5. The Connection Matrix between Components and the Functional Block Diagram of The System are constructed by using completed designs.

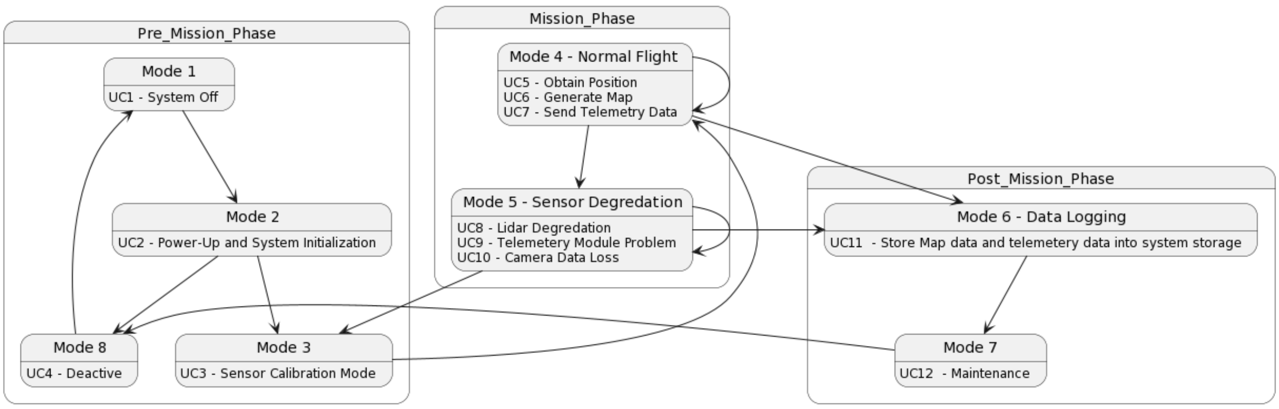

Fig. 2. Phase / Mode / Use Case Diagram of The System.

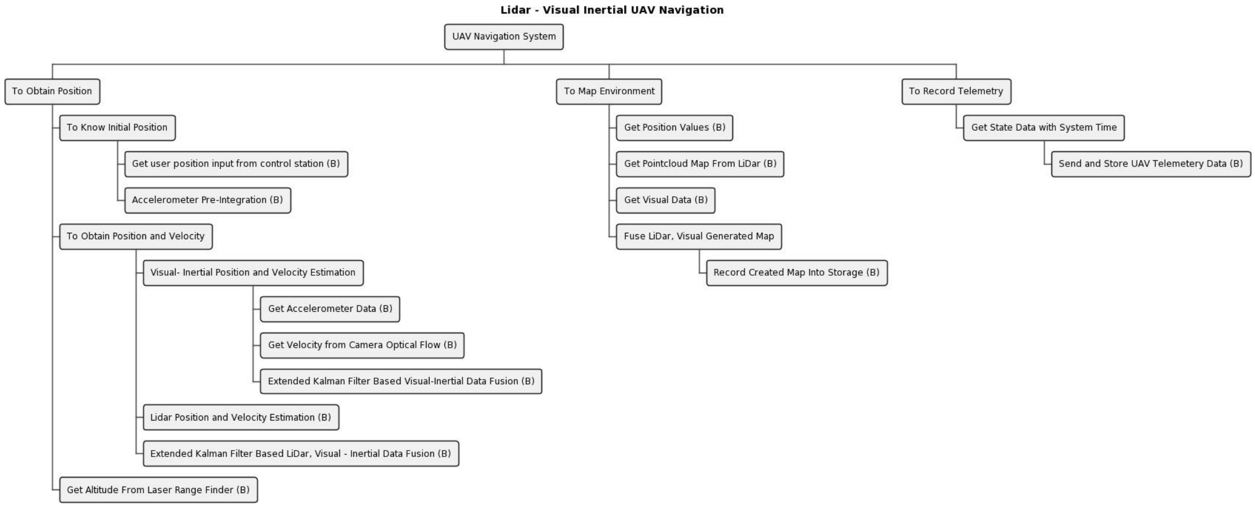

Fig. 3. *Function Tree of The System.*

		Basic Functions											
		Send and Store Telemetry Data	Record Created Map Into Storage	Get Visual Data	Get Pointcloud Map From Lidar	Get Position Values	Get Altitude From ToF Sensor	EKF Based LiDar, Visual, Inertial Data Fusion	LiDar Position Velocity Estimation	EKF VI Data Fusion	Get Velocity from Camera Optical Flow	Get Acceleration Values	Accelerometer Pre-Integration
Basic Components	Accelerometer Component							✖		✖		✖	✖
	Camera Component			✖				✖		✖	✖		
	LiDar Component				✖			✖	✖				
	Microprocessor Fusion Component					✖		✖		✖			
	ToF Sensor Component						✖						
	Telemetery Component	✖											
	Storage Component	✖	✖										

Fig. 4. *Function and Product Relation Matrix of The System*

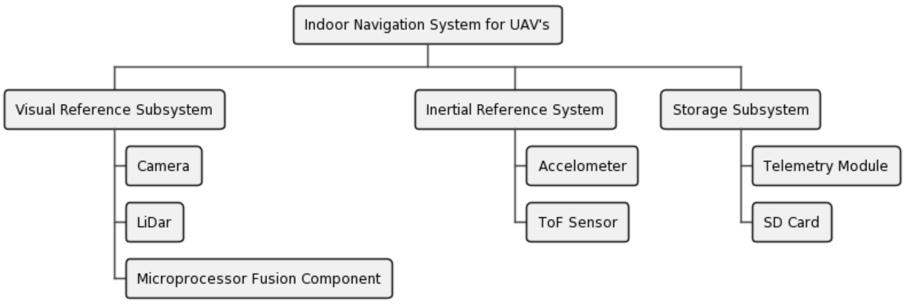

Fig. 5. *Product Tree of The System*

	Accelerometer Component	Camera Component	LiDar Component	Microprocessor Fusion Component	ToF Sensor Component	Telemetery Component	Storage Component
Accelerometer Component		✖	✖	✖			
Camera Component	✖		✖	✖			
LiDar Component	✖	✖		✖			
Microprocessor Fusion Component							
ToF Sensor Component				✖			
Telemetery Component				✖			✖
Storage Component				✖		✖	

Fig. 6. *Connection Matrix between Components*

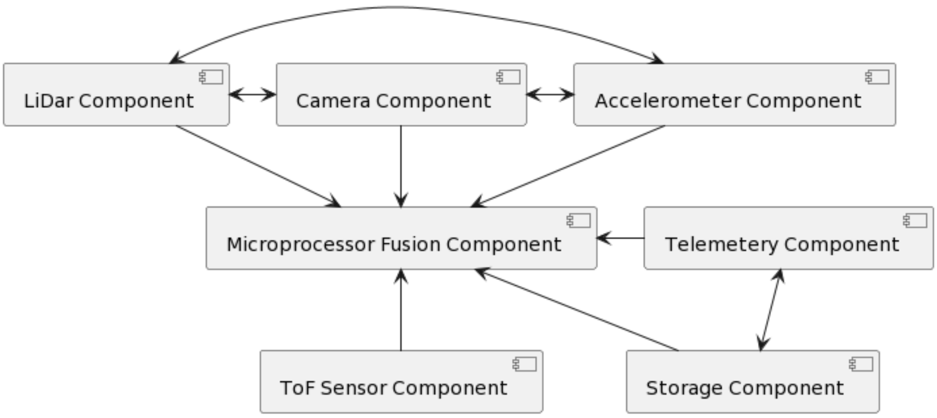

Fig. 7. *Functional Block Diagram of The System*

3. Conclusions and Future Directions

This article proposed the usage of system engineering approach to design an UAV navigation system which aims to be used in indoor environments. To provide autonomous indoor flight, system requirements are set by using system engineering approach. Then step by step, the basic functions that UAV needs to complete operation are specified. Required products are listed as a tree and the relation between products and functions are investigated. On the other hand, the systems operational requirements are investigated, and the requirement operation phases, modes and use cases are determined. Thanks to system engineering, all these complex systems get put in together systematically and the conceptional design done.

In this paper, LiDAR and camera systems are used to meet requirements but for future works, Wi-Fi based localization systems or visual references like QR codes [19] can be used to provide innovative solutions as references to coordinate systems. Also, these features can have some functions as maintaining cooperative working of unmanned systems

Author Contribution

Each author made an equal contribution.

Declaration of Competing Interest

The authors declared no conflicts of interest with respect to the research, authorship, and/or publication of this article.

Kaynaklar

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