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Autonomous Steerable Ram-Air Type Load Parachute System Design and Alternative Trajectory Algorithm

Otonom Yönlenebilen Kanat Tipi Yük Paraşüt Sistemi Tasarımı ve Alternatif Güzergah Algoritması

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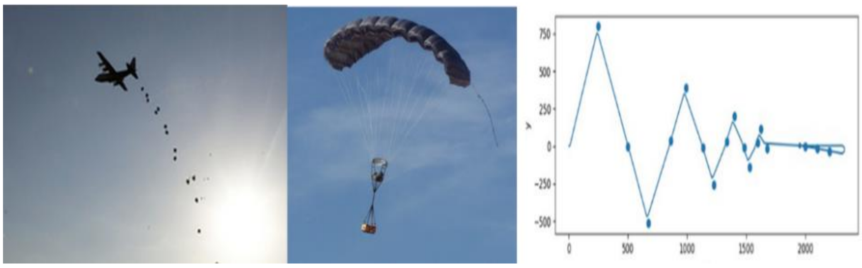
Önemli Noktalar / Highlights

Otonom yönlenebilen kanat tipi paraşüt sistemleri bir çeşit insansız hava aracıdır. Bu çalışmada paraşüt sisteminin istenilen hedef koordinat gidebilmesi için ihtiyaç duyduğu güzergâh algoritmaları ortaya konmuş ve özgün bir tasarım yapılmıştır.

Grafik Özet / Graphical Abstract



Abstract

In areas that cannot be reached by land or sea, the necessary supplies can be delivered by parachute from the air. Airdrop is a commonly used replenishment method in both humanitarian aid operations and military operations. The most important limitations of airdrop replenishment are that the cargo may be affected by the wind and fall into undesirable areas and that the aircraft is vulnerable to enemy air defense systems. GPS-guided, steerable parachutes can be used for high-altitude, long-distance airdrop by protecting the aircraft from enemy air defense weapons and preventing the payload from being blown away by the wind or into the hands of undesirable persons. In this study, the design of the system required by the Turkish Armed Forces is made, the command and control unit is created and the trajectory tracking algorithm is presented.

Özet

Kara ya da deniz yoluyla ulaşılamayan bölgelere ihtiyaç duyulan malzemeler paraşütle havadan ikmal edilerek ulaştırılabilir. Havadan ikmal hem insani yardım operasyonlarında hem de askeri operasyonlarda yaygın olarak kullanılan bir ikmal yöntemidir. Havadan ikmalin en önemli sınırlamaları, faydalı yükün rüzgârdan etkilenerek istenmeyen bölgelere düşebilmesi ve uçağın düşman hava savunma sistemlerine karşı savunmasız olmasıdır. GPS (Global Positioning System) güdümlü yönlendirilebilir paraşütler, hava aracını düşman hava savunma silahlarından koruyabilir ve faydalı yükün rüzgâr sürüklenmesiyle hedeflenen bölge dışına düşmesini veya istenmeyen kişilerin eline geçmesini önleyerek yüksek irtifadan ve yatayda uzak mesafelerden malzeme ikmali yapılabilmesi için kullanılabilir. Bu çalışmada, Türk Silahlı Kuvvetleri'nin ihtiyaç duyduğu hassas güdümlü paraşüt sistemin yönlendirme ünitesinin tasarımı yapılmış, komuta kontrol birimi oluşturulmuş ve güzergâh takip algoritması sunulmuştur.

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1. INTRODUCTION

There are many military applications related to the delivery of the payload to the target area using steerable parachutes. Sherpa, Screamer, Spades, MicroFly are some of them [1]. In general, the system consists of three main parts. These are the parachute, the control unit and the payload [2]. Ram-air parachute wings are used in the steerable load parachute [3]. This dome consists of two layers. Fabric with low air permeability is used in this bottom and top layer. Between the two layers there are cells that control the air flow. The air that enters from the cell side cannot exit from the back and is trapped in these cells. In this way, the wing becomes robust and exhibits a balanced behavior [4]. These wings are guided by two brake lines. The parachute can be rotated in the desired direction by controlling the parachute control lines with motors. In these systems, the parachute guidance system is placed between the main carrier parachute and the load [5]. After the load leaves the aircraft, the main parachute is opened at the desired altitude and the guidance is performed after the dome is completely filled with air. The dome has two steering rope groups. These rope groups merge as they move away from the dome and become a single rope. The guidance ropes are connected to two separate pulleys inside the guidance system. In order to reach the target coordinates entered into the system before the mission, two motors drive the pulleys to which the guidance ropes are connected and progress to the target coordinates is ensured. The air-opened image of the system is shown in Figure 1.

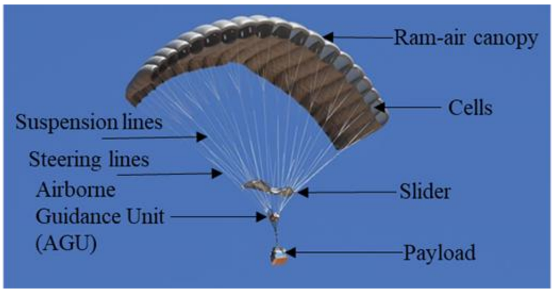

Figure 1: The air-opened image of the system.

In the literature, trajectory planning is generally based on multi-phase algorithms that plan the route by dividing into certain parts [3,6,7]. However, there are also studies that evaluate the trajectory as a single phase.

Guo et al. presented a five-phase trajectory algorithm in their study. These phases are the homing phase, the descent circle phase, the acquisition phase, the EMC (Energy Management Circle) phase, the final phase. Compared to other multi-phase studies, they reduced the turns made in the descent phase and made it suitable for high altitude drops [8].

In the study conduct by Guo et al. et al. a multiphase approach algorithm was designed for use in high altitude launches. The first two phases of the five phases were used for energy management at high altitude and the other two phases were used for energy management at low altitude [9].

Linggong et al. proposed in their study to follow the trajectory in real time without dividing the it into phases and to stay on the route by controlling it with control algorithms [10].

Yi et al. preferred to follow a single-phase route supported by artificial intelligence algorithms in their study. As a result of the simulation, it was shown that the parachute landed at the desired target coordinate with a precision of 12 meters or less, which reacts quickly to changing weather conditions [11].

In their study, Hao et al. determined a single-phase trajectory and reached the target by controlling this route with control algorithms [12].

In the powered parachute trajectory determination study by Qinglin et al. a single phase straight route was determined and it was aimed to stay on this trajectory with the control algorithm. A command and control unit was designed to test the system in a real drop and an electronic card based solely on GPS data was presented [13].

Although a single-phase trajectory was determined in the study on powered parachute systems by Yuhui et al, a reference point tracking strategy was proposed [14].

2. DESIGN OF THE COMMAND AND CONTROL UNIT

In the examination of the existing systems on the internet and on the real product, it was seen that all of them have a rectangular box-shaped outer casing and the guidance rollers are in the front part of the box and side by side [15]. In this study, since it was evaluated that the side-by-side position of the guidance rollers posed a risk of entanglement during the opening of the parachute, they were separated from each other as in the personnel harness and placed on the right and left parts of the system. Since the same parachutes used in personnel jumps will be used, the distance between the guidance rollers was ensured to be the length of the shoulder span of average personnel. Since it is considered that there may be unnecessary space gaps if the design of the outer casing of the device is rectangular, the outer design of the device is designed as a plus shape. In this study, guidelines were made on the reels designed and it was ensured that the routing ropes travelled on these guidelines. On the left and right outside where the reels are located, two different lashing bars were placed connected to each other so that the parachute and the load could be connected at the same time. The lashing bars are not directly attached to the main body, but are attached to a single ground together. In this way, it is aimed to absorb the shock during the opening of the parachute by means of liaison bars without getting on the body of the device.

The design of the command and control device was made with Solidworks [16] drawing program, the outer casing and connection apparatus were made of aluminum metal by molding process, and some internal assembly apparatus were printed with 3D printer. Solidworks drawings of the designed guide unit is shown in Figure 2, the manufactured version of the unit is shown in Figure 3.

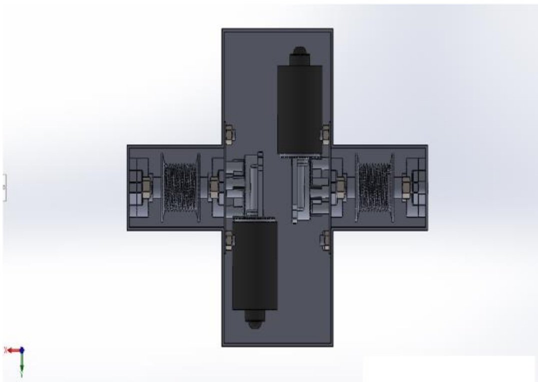

Figure 2: Solidworks drawings of the designed guide unit.

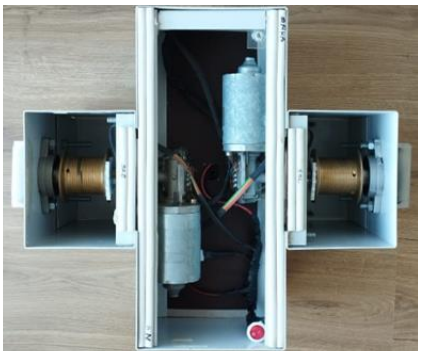

Figure 3: The manufactured version of the unit.

3. HARDWARE AND COMMAND CONTROL BOARD

The reels controlling the ropes are driven by two independent motors. The motors are 24 Volt and 55 RPM (Revolutions Per Minute). Idle operating current is 1 Ampere and forcing current is maximum 7 Ampere. Nominal load torque is 25 kg/cm. In the study, a high torque motor was preferred since the behavior of the motor was not known in advance. As a result of the studies, 12 Volt motors can be evaluated. 12 V 6 A dry batteries were selected as the power source. The system, which works with at least two series-connected dry batteries, has an area where ten batteries can be placed. In the future, the use of lithium-ion batteries, which have a longer life and can be charged faster and are lighter, can be considered.

Each motor is driven separately by IBT-2 BTS7960B motor driver. The ESP 32 module was preferred because it has an embedded Wi-Fi (Wireless Fidelity) module as a processor, has a sufficient number of legs for the system, can perform float point operation (ability to operate with decimal numbers) and has a processing speed of 160 mhz. 9-axis BNO-055 precision accelerometer-gyroscope-magnetic sensor, NEO-7M GPS sensor for position determination, MS5803-01BA altimeter sensor as height sensor, DS3231 real-time clock sensor, micro SD card adapter, current meter and two KY040 rotary encoders were used. A 24C32 eeprom (Electronically Erasable Programmable Read-Only Memory) module was used to prevent the SD card from being damaged by frequently written data such as encoder position. The processor communicated with the GPS sensor via UART protocol, accelerometer, height sensor, clock, SD card and eeprom module via I2C protocol. The front and back side of the command control board is shown in Figure 4.

Figure 4: The Command control board.

Stable reading of sensor data is very important for trajectory tracking [17]. In this study, a Kalman filter is applied to the sensor data [18]. It has been applied to many fields such as in autonomous systems [19] and control system [20]. Using the gyroscope and accelerometer data of the BNO055 sensor used in the command control card, the required Q and R values for the Kalman filter were obtained in the environment created.

While the accelerometer sensor data produces a lot of noise against noise and sudden changes, it behaves stable in long-term measurements. While the instantaneous responses of the gyroscope sensor data are low, in the long term, deviations occur and filtering is needed since the data is processed by taking the integral of the data over time. In the created environment, the instantaneous data value read from the gyroscope was considered to be absolutely accurate and compared with the accelerometer data. A 2D adaptive grid search [21] technique was used to obtain the most appropriate Q and R values based on the standard deviation of the errors. In this way, the Q and R values with the lowest standard deviation were obtained. These optimum values were used for filtering the gyro data to ensure a smooth and long-term data flow.

The 2D adaptive grid search technique is a method used in optimization and mathematical modelling to find optimum solutions in a two-dimensional search space. The main objective of this technique is to perform the search in the regions where the probability of finding a solution with a favorable value is high, rather than exhaustively scanning the entire search space [22]. The mathematical representation of the method is as follows.

Firstly, the parameter space is defined.

$$Q \in [1,0] \tag{1}$$

$$R \in [1,0] \tag{2}$$

$$\Omega = \{(q, r) \mid q \in Q, r \in R\} \tag{3}$$

Then, certain points were selected by Adaptive grid search method. Kalman filter was applied using these points and values. The filtered data was compared with the actual value and estimated errors were obtained. The standard deviation of these errors was calculated as follows.

$$\sigma ij = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(eij, k - éij\ )^2} \tag{4}$$

Where N is the number of measurements, e_{ij}, k is the prediction error at the k measurement for the parameters q_i and r_j , and $é_{ij}$ is the mean error for these parameters.

The values that minimize the standard deviation are then found.

$$(q^*, r^*) = arc\ min_{(q,r)}\ \epsilon\Omega\ \sigma_{ij} \tag{5}$$

These (q^*, r^*) values represent the best-fit parameters with the lowest standard deviation of the estimation errors. As a result, Q value was determined as 0.0019 and R value as 0.6.

4. TRAJECTORY PLANNING ALGORITHM

Various route models have been used in the literature for the autonomous arrival of commanded cargo parachutes. There are two principles that should be taken into account when planning a route. One of these principles is to take the shortest route to the target and the other is to avoid sharp turns. This type of planning was first realised by Dublins in 1957 [23]. This method, known as the Dublins route, basically consists of a 4-stage plan (start, loiter, approach and flare) [24]. Another approach method is the "T Approach" method. It is so named because it proceeds by drawing a "T" shaped landing pattern [25]. In another study, lower cost command and control methods were studied. It is a method that proceeds based on GPS data and reaches the target by speed planning [26,27].

In route planning, a multi-phase algorithm was adopted as in other examples. However, two different approach algorithms and a route algorithm consisting of five phases in total were used. These phases are Start, Approach, Descent, Landing and Emergency phases. Two different routes were designed as straight and zigzag trajectory algorithms. In the straight approach algorithm, ten control points are established between the start point and the target. The closest control point is determined as the target and it is ensured that these control points are passed first. Thus, the principle of travelling the shortest way by making wind correction at lower angles and the principle of avoiding sharp turns are complied with. When the checkpoint is reached, altitude control is performed and if altitude reduction is required, altitude descending maneuvers are performed and the descent procedure is initiated according to the wind direction.

The Arriving Phase Direct Mode is shown in Algorithm 1. The Arriving Phase Zigzag Mode is shown in Algorithm 2. The Descending Phase is shown in Algorithm 3. The Landing Phase is shown in Algorithm 4. Px, Py, Pz corresponds to x, y, z coordinates of P.

Algorithm 1: Arriving Phase Direct Mode

Data: P, T, CP = control points count, τ = Convergence threshold, Ψ = Heading angle of parachute

$$\Delta_x = (T_x - P_x)/CP; \tag{6}$$

$$\Delta_y = (T_y - P_y)/CP; \tag{7}$$

$$(CP_x{}^i, CP_y{}^i) = \left(P_x + \dot{I}\Delta_x, P_y + \dot{I}\Delta_y\right) \ \forall_i \in [0, CP]\ ; \tag{8}$$

for $i \leftarrow 0$ **to** CP **do**

    while dist(CP^i, P) > τ **do**

        if angle (CP^i, P) > Ψ **then**

            Update heading angle

        end

    end

end

Call Alg.(4)

Algorithm 2: Arriving Phase Zigzag Mod

Data: *P, L* = Landing minimum altitude, *D* = Target maximum distance threshold

while dist (P, T) > τ **do**

Do checks;

Calculate target point;

$$\Theta_p = angle(P,T); \tag{9}$$

$$\Delta_p = dist\frac{(P,T)}{4}; \tag{10}$$

$$\Delta_f = (P_z - M_a) * G_r * \frac{1{,}25}{4} \tag{11}$$

$$\Theta_c = cos^{-1}(\tfrac{\Delta_p}{\Delta_f})\ ; \tag{12}$$

$$(T_x^1, T_y^1) = \left(P_x + \frac{\Delta_f}{2\cos(\Theta_c)}\right), \left(P_y + \frac{\Delta_f}{2\sin(\Theta_c)}\right); \tag{13}$$

$$(T_x^2, T_y^2) = \left(P_x + \frac{\Delta_p}{2\cos(\Theta_p)}\right), \left(P_y + \frac{\Delta_p}{2\sin(\Theta_p)}\right); \tag{14}$$

    while dist(P, T^1) > τ **do**

        Update heading angle;

end
while dist(P, T^2) > τ **do**
Update heading angle;

end

end

Algorithm 3: Descending Phase

Data: P, L = Landing minimum altitude, D = Target maximum distance threshold

while $P_z > L$ **do**
if dist(P, T) > D **then**
Call Alg.(1)

end

end

Algorithm 4: Landing Phase

Data: P, E_s = Parafoil estimated speed

$$F_s = E_s + W_s \; ; \tag{15}$$

$$B_s = E_s - W_s \; ; \tag{16}$$

$$R_{mt} = P_z / v_z \; ; \tag{17}$$

$$\Delta_r = (T - P)\cos\Theta_p \tag{18}$$

$$R_{st} = \frac{\Delta_r}{F_s} \tag{19}$$

$$B_d = \frac{(R_{mt} - R_{st})\, F_s B_s}{F_s + B_s} \tag{20}$$

$$U_r = T - C_{yl}(B_d + A_c - W) \tag{21}$$

5. SIMULATION RESULTS

The starting point is defined as 0,0 coordinate and the target is defined as 0,2000 coordinate. It is planned to descend from 3000 feet altitude to the target at 0 feet. It was assumed that the main parachute opened as soon as the system left the aircraft and the drop coordinate was taken as the start coordinate. Figure 5 shows the path followed in a windless environment. As can be seen, the system successfully passed ten control points between the starting point and the target point during the approach phase. When the target point was over the target point, the altitude of 2500 ft was reduced to 500 ft with the descent phase, and when the landing conditions occurred, it followed the control points formed according to the direction of the wind and landed.

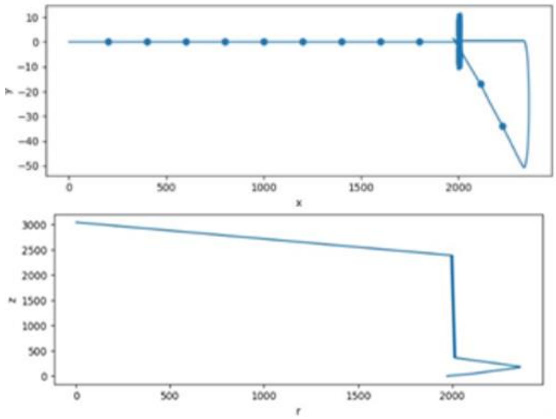

Figure 5: Simulation results of straight trajectory algorithm.

The starting point is defined as 0,0 coordinate and the target is defined as 0,2000 coordinate. It is planned to descend from 3000 feet altitude to the target at 0 feet. It was assumed that the main parachute opened as soon as the system left the aircraft and the drop coordinate was taken as the start coordinate. Figure 6 shows the path followed in a windless environment. As can be seen, the control points were passed with gradually narrowing maneuvers and the altitude of 750 ft was reduced to 500 ft with the descent phase when the target was over the target, as in the straight approach algorithm, and when the landing conditions occurred, it followed the control points formed according to the wind direction and provided landing.

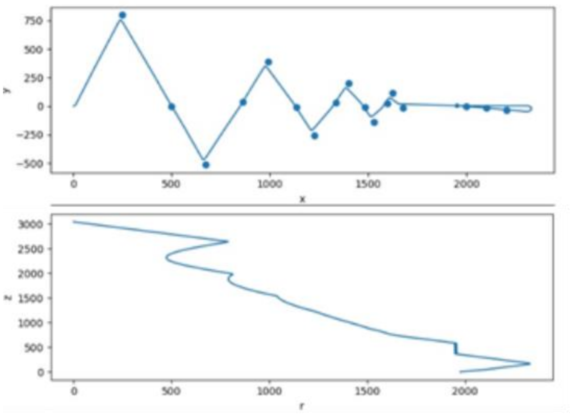

Figure 6: Simulation results of zigzag trajectory algorithm.

6. CONCLUSIONS

With the increasing use of replenishment via airdrop in the battlefield and humanitarian aid activities and the widespread use of steerable parachutes in this field, it is obvious that route planning models will make more precise calculations. The study is considered to be suitable for both the cases of deployment of the main parachute as soon as the system leaves the aircraft or deployment of the main parachute after the free fall with the stabilization parachute up to the desired altitude. After the deployment point of the main parachute, the required approach algorithm is selected with the calculations made and the route created is updated according to the developing situations and the system can change the approach algorithm if necessary. It is evaluated that the presented algorithms are within the limits of the weather conditions required for aerial resupply and are sufficient to land the system at the desired target coordinate by calculating the appropriate load release point by obtaining the altitude winds accurately.

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AUTHORSHIP CONTRIBUTION STATEMENT

Burak CİVELEK: Conceptual design, Data curation, Experimental studies, Writing

Sinan KIVRAK: Methodology, Audit, Approval, Review and Regulation

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

[1] R. Benney, A. Meloni, A. Cronk ve R. Tiaden, "Precısıon Aırdrop Technology Conference", U.S. Army Natick Soldier Research, Development and Engineering Center, Massachusetts, 2007.

[2] M. R. Cacan, E. Scheuermann, M. Ward, M. Costello ve N. Slegers, "Autonomous Airdrop Systems Employing Ground Wind Measurements for Improved Landing Accuracy", EEE/ASME Transactions on Mechatronics, pp. vol. 20, no. 6, pp. 3060-3070, 2015.

[3] I. Kaminer ve O. A. Yakimenko, "On the development of GNC algorithm for a high-glide payload delivery system", IEEE Conference on Decision and Control, 2004.

[4] E. Puskas, "Ram air parachute design considerations and applications", Engineering, Materials Science, 1984.

[5] P. Carrabba, "The Rıght Place At The Rıght Tıme- An Analysis of High Altitude Airdrop and The Joint Precision Airdrop System", Air Force Instıtute Of Technology, 2005.

[6] T. Jin, S. Qinglin, T. Panlong, C. Zengqiang ve H. Yingping, "Active disturbance rejection control (ADRC)-based autonomous homing control of powered parafoils", Nonlinear Dyn., vol. 86, no. 3, pp. 1461-1476, 2016.

[7] T. Jann, "Advanced Features for Autonomous Parafoil Guidance, navigation and Control", 18th AIAA Aerodynamic decelerator Systems Technology Conference and Seminar, 2005.

[8] Y. Guo, J. Yan, Y. Luo, L. Fenghao ve X. Xing, "Optimization in Multiphase Homing Trajectory of Unpowered Parafoil with High-altitude", International Conference on Unmanned Aircraft Systems (ICUAS), Athens, Greece., 2020.

[9] Y. Guo, . Y. Jianguo, W. Cihang, . C. Mengping ve . X. Xiaojun, "Autonomous Homing Design and Following for Parafoil/Rocket System with High-altitude", Journal of Intelligent & Robotic Systems, pp. 2-15, 2021.

[10] Z. Linggong, H. Weiliang, L. Feikai ve X. Wang, "Trajectory Tracking Control for Parafoil Systems Based on the Model-Free Adaptive Control Method", IEEE Access, pp. 152620-152636, 2020.

[11] W. Yi, Y. Chunxin ve Y. Han, "Neural network-based simulation and prediction of precise airdrop trajectory planning", Aerospace Science and Technology Volume 120, p. 107302, 2022.

[12] S. Hao, S. Qinglin, S. Mingwei, T. Jin ve C. Zengqiang, "Accurate Modeling and Homing Control for Parafoil Delivery System Based on Wind Disturbance Rejection", IEEE Transactıons On Aerospace And Electronıc Systems vol. 58, no. 4, pp. 2916-2934, 2022.

[13] S. Qinglin, Y. Li, Z. Yuemin, T. Jin ve C. Zengqiang, "Trajectory tracking control of powered parafoil system based on sliding mode control in a complex environment", Aerospace Science and Technology Volume 122, p. 107406, 2022.

[14] L. Yuhui, M. Zhao, Y. Min, S. Tong ve Z. Zengha, "6-DOF Modeling and 3D Trajectory Tracking Control of a Powered Parafoil System", IEEE Access, vol.8, pp. 151087-151105, 2022.

[15] M. Wuest ve R. Benney, "Precision Airdrop", North Atlantic Treaty Organisation Research and Technology Organisation, Neuilly-sur-Seine Cedex, France, 2005.

[16] D. S. SolidWorks, SolidWorks®, cilt 1, Version Solidworks, 2005.

[17] S. A. Quadri and O. Sidek, "Error and Noise Analysis in an IMU using Kalman Filter", International, vol. 7, pp. 39-48, 2014.

[18] R. Kalman, "A new approach to linear filtering and prediction problems", Journal of Fluids Engineering, Transactions of the ASME, cilt 8, no. 1, pp. 35-45, 1960.

[19] L. Lasmadi, "Attitude Estimation for Quadrotor Based on IMU with Kalman-Filter", Conference SENATIK STT Adisutjipto Yogyakarta, 2018.

[20] A. Ma'arif, I. Cahyadi, O. Wahyunggoro ve Herianto, "Servo state feedback based on Coefficient Diagram Method in magnetic levitation system with feedback linearization", 3rd International Conference on Science and Technology - Computer (ICST), 2017.

[21] Z. Zabinsky, "Stochastic adaptive search for global optimization", vol. 72, Kluwer Academic Publishers, 2003.

[22] P. Eiseman, "Adaptive Grid Generation", Computer Methods in Applied Mechanics and Engineering, cilt 64, pp. 321-376, 1987.

[23] L. Dublins, "On curves of minimal length with a constraint on average curvature and with prescribed initial and terminal positions and tangents", American Journal of Mathematics , pp. 497-516, 1957.

[24] A. Rosich ve E. Gurfil, "Coupling in-flight trajectory planning and flocking for multiple autonomous parafoils", Journal of Aerospace Engineering, pp. 691-720, 2012.

[25] T. Jann, "Advanced features for autonomous parafoil guidance, navigation and control", 18th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, 2005.

[26] M. Cacan, E. Scheuermann, M. Ward, M. Costello ve N. Slegers, "On the development of gnc algorithm for a high-glide payload delivery system", 42nd IEEE International Conference on Decision and Control, 2003.

[27] Z. Erlin ve G. Haitao, "Guidance-based Path Following Control of the Powered Parafoil", CEAI,Vol.22, pp. 42-50, 2020 .