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# ANTENNA TRACKER DESIGN WITH A DISCRETE LYAPUNOV STABILITY BASED CONTROLLER FOR MINI UNMANNED AERIAL VEHICLES

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***Abstract –*** Communication systems have recently been very important in mini unmanned aerial vehicles (UAV), which include many research subjects. Directional antennas are generally used in communication systems, and they should continuously and efficiently follow the UAVs with minimal errors. For this purpose, an "Antenna Tracker" system, which is capable of real-time autonomous orientation based on GPS data from the UAV, was designed. In the beginning, the system's 3-dimensional solid model was obtained in SOLIDWORKS$^{TM}$ and its dynamical model was made in MATLAB / Simulink$^{TM}$ environment. For controlling the system, a discrete-time model-based computed torque proportional controller, which is the state-of-the-art innovation in this study, was designed in two axes, and then its simulation studies were conducted on the STM32 board. The simulation studies showed that controlling the pan and tilt axes is sufficient for effective tracking, and the presented antenna tracker system is suitable for use in mobile ground control stations (GCS). By using a short sampling time for the controller, stable and precise antenna tracking is accomplished for a given reference path. When a 0.5 Hz sinusoidal reference signal input which is the maximum speed for any antenna tracker was used as a sample reference track, ±0.3- and ±0.6-degrees position error of pan and tilt angles were obtained, respectively. The controller can easily satisfy a smooth tracking operation with high accuracy.

***Keywords*** *– Mini UAVs, Antenna trackers, Lyapunov stability, discrete control, UAV tracking*

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## I. INTRODUCTION

Unmanned Aerial Vehicles (UAV) are utilized in a vast of application goals and it continues its developing day by day. As one of these aims, namely observation, is operated for several different purposes in the civilian field, in fact, it is more frequently and importantly in the military [1] [2]. As the main factor of such systems, the directional antennas are generally used for live video streaming and telemetry transmission in Mini UAVs [3][4]. In order to avoid any interruption in the telemetry data or images which are obtained by the UAV, they are providing communication between antennas that must always be located as facing each other at a certain angle. Especially, in such systems where the Ground Control Station (GCS) is mobile, obtaining the right directions of the antennas is a serious problem [5][6]. Actually, the autonomous antenna tracking systems which are called Antenna Trackers, are working for used on military or civil UAVs that communicate with directional antennas. According to the GPS or barometer data were taken by the UAV, Antenna Trackers are positioning the antennas in the communication process to the UAV throughout the flight. It is sufficient to control the pan and tilt axes for tracking; the system rotates 360 degrees on the pan axis and 90 degrees on the tilt axis for optimum tracking [4]. Indeed, for this optimum tracking, one of the most important prerequisites is sensitive positioning with respect to the controller of the system. The most frequently used antenna tracker system in civil UAVs is ARDUPILOT that is an open-source controller [12][13]. One of the biggest advantages of this kind of controller is its compatibility with an open-source Ground Control Station interface and its wide range of documentation. However, it has some drawbacks in terms of practical and academic perspectives.

For practical considerations, it is limited by their cost. Although, its control software is free of charge, the system is designed to be conducted with an expensive controller card such as Pixhawk™ [14]. Besides, the controller of ARDUPILOT's antenna tracker has been developed specifically for servo motors which are costly comparing to common DC motors. The presently designed antenna tracker can be customized through applying open-source systems such as Mission Planner freely, it is an obvious advantage when compared with the other expensive commercial software [15][16].

In academic perspectives, open-source software, and codes do not give a way to accomplish complicated controller design attaining high performance to track the reference UAV signal path due to the complexity of the source codes and lack of capability of the whole functions required for Lyapunov controller [17]. Apart from that the controller which is designed in this open-source libraries, the performance of the controller rules depends directly on the electronic capabilities such as analog/digital readings speed/resolutions and coding techniques such as sampling time and one cycle at processors. The continuous-time control theory does not meet these criteria for the control system in terms of the sampling period and resolution values at measurements in real-life applications [18].

When the current studies are criticized, it could be apparently seen that there is inadequacy on discrete-time modeling and controller design to sensitive position control [7][8][9][10][11].

Astari et al [7] has developed a PID controller in continuous time for such systems. However, these kinds of continuous-time models could not be realized in the real applications adequately. In real systems, the sampling rate is one of the crucial elements which has to be considered due to the process members. Besides, Riyandi et al [8] have designed a PID controller with fuzzy logic for a GPS-based antenna tracker system to increase the system quality compared to the conventional PID controllers. Although this controller achieved high accuracy and a better response than the previous ones, the fuzzy logic usage in such systems has a low implementation quality. Actually, the fuzzy logic algorithm must be developed for each unique case therefore it may not be an optimum solution. Uthman et al [9] has mentioned that a discrete control system using a PID controller is better in terms of achieved a better control on satellite angle deviation while they designed a PID controller in continuous time. Accordingly, the various research studies on the antenna tracker control systems show that general approaches constituted in continuous time, which yields less realizable systems.

Due to the whole reasons given above, the discrete-time modeling and controller design is the best approach to implement the Antenna tracker device. Otherwise, the implementation of any code with the basis of continuous one cannot be easily performed in practice.

In this study, the antenna tracker system with a Lyapunov-based proportional controller in discrete time to track the mini-UAVs has been designed. First, the mathematical model of the mechanical system is obtained. Then, a torque computed controller in discrete time based on the Lyapunov Stability Theorem is applied. Moreover, the model is reformed within the capability of the usage for any antenna tracker system, since can be modified by changing the moment of inertia and damping ratio coefficients. This makes an innovative improvement in academic manners. The system consists of a GPS-based, two-axis antenna tracker with a discrete proportional controller. The controller is embedded on an STM32 board. The deficiencies of the previous research projects were tried to be eliminated by the developed antenna tracker.

## II. METHOD

### A. System in General

The designed antenna tracker system has a structure that can move 360 degrees in the pan axis and 90 degrees in the tilt axis. Tracking will be carried out according to the GPS data received from the UAV. GPS will be used to measure the position of the Antenna tracker and the Inertial Measurement Unit (IMU) to measure its angle. Basically, the coordinate points of the UAV are determined by GPS and transmitted to the GCS, the antenna receives the coordinates of the UAV and transmits them to the GCS antenna position and the position of the plane. After specifying the orientation by using the angle calculation algorithm, the data is sent to the controller which triggers the drive system and the IMU gives feedback to the controller to identify the error.

### B. Figures and Tables

Three major factors were taken into consideration during the design phase; the antenna should be capable to rotate in two axes freely; the cost should be competitive compared to the other trackers in the market, the system should be compact, accessible, and easy to carry by one person. To meet these requirements firstly it was decided to use 3D printed ABS part due to its effective cost, practical design, and fast production ability; it can be printed in complex parts within hours, which is much faster than the molding process or machined parts [19]. In figure 1, the view of the 3D design is given. To be simply accessible, the system will be mounted over a tripod that can be quickly detachable to ensure proper transportability to the fly zone. Also, to distribute the weight of the antenna, two bearings will be used. The system consists basically of a scaffold, two brushed DC motors, an antenna, an inertia measurement unit, a tripod, and several fasteners. SOLIDWORKS™ was used to design the two axes Antenna Tracker. The part over the tripod can rotate in the pan axis, the upper part can rotate on the tilt axis. The antenna and the tripod can be easily detached during transportation. During the realization of the system, a major challenge that had been encountered was wrapped cables around the device.

Fig. 1. 3D Design of Tracker System

### C. System Modelling

As a design restriction, it is assumed that the tilt and pan axis move independently since the model is operated under low angular velocity conditions. Dynamic equations for the biaxial antenna tracker have been obtained by using Lagrangian mechanics [20]. All the related equations have been applied to the system which was based on the earth fixed frame.

In the antenna trackers, the main mechanical concern is calculating the net moment of inertia during tracking to find the central gravity of the system. Then, the net torque which is fitted by the design requirements has been determined that were calculated as $\tau_{tilt}$ , $\tau_{pan}$ on tilt and pan axis, respectively. Basically, $l$ distance from the center of gravity to torque applied point, $J_{eq}^{tilt}$,$J_{eq}^{pan}$ are the equivalent moment of inertia of the antenna tracker system, $C_{eq}^{tilt}$, $C_{eq}^{pan}$ are equivalent damping coefficient of antenna tracker. $\theta$ is the tilt axis and $\gamma$ is the pan axis angle, and $m$ refers to the mass of rotating part of the system. The model of pan and tilt axes are as follows:

$$\tau_{tilt} = J_{eq}^{tilt}\ddot{\theta} + C_{eq}^{tilt}\dot{\theta} + mglcos(\theta) \tag{1}$$

$$\tau_{pan} = J_{eq}^{pan}\ddot{\gamma} + C_{eq}^{pan}\dot{\gamma} \tag{2}$$

The state-space model of the system for tilt axis is as follows:

$$\begin{aligned}\dot{z}_{tilt} = \begin{bmatrix}\dot{\theta}\\ \ddot{\theta}\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & -\dfrac{C_{eq}^{tilt}}{J_{eq}^{tilt}}\end{bmatrix}\begin{bmatrix}\theta\\ \dot{\theta}\end{bmatrix}\\ + \begin{bmatrix}0\\ \dfrac{1}{J_{eq}^{tilt}}\end{bmatrix}(\tau_{tilt} - mgl\cos(\theta))\end{aligned} \tag{3}$$

Besides, the pan axis as follows:

$$\dot{z}_{pan} = \begin{bmatrix}\dot{\gamma}\\ \ddot{\gamma}\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & -\dfrac{C_{eq}^{pan}}{J_{eq}^{pan}}\end{bmatrix}\begin{bmatrix}\gamma\\ \dot{\gamma}\end{bmatrix} + \begin{bmatrix}0\\ \dfrac{1}{J_{eq}^{pan}}\end{bmatrix}(\tau_{pan}) \tag{4}$$

To achieve a precise amount of moment of inertia as a requirement of the operation; all required variables were found by computer-aided simulations, besides the damping ratio which was defined by experimental data. Indeed, all the design parameters were shown in *the Experiment* chapter.

### *D. Controller Design*

The key factor of the system as a decision parameter is the net torque due to the main part of the system is rotatable. Therefore, for the controller design, the computed torque control method centric model is used. Moreover, position control is used with respect to the Lyapunov-based proportional discrete controller. To attain flexibility on the sampling time during the tracking, the discrete controlling approach would be more beneficial than the other. Furthermore, using one controller parameter comes with an advantage for sake of simplicity. Thus, by changing only one parameter, the system can be modified easily [20][21][22]. In theory, there are many different controller design approaches that have a wide range such as PID, PD, PI, Fuzzy Logic, etc. In this study, the main core is the energy-based controller. So, through constituting a Lyapunov stability theorem-based proportional controller, it is obtained. Here, the main purpose is achieving the convergence to zero in the error over energy equations which gives stability condition of the system. The controller diagram is given in figure 2.

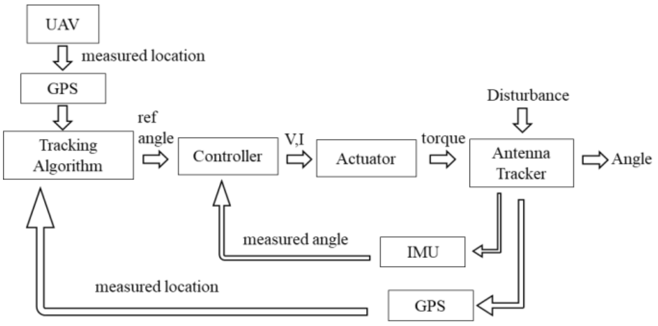

Fig. 2. The controller diagram

Basically, the coordinate of the UAV is determined by its GPS and transmitted to the ground control station. The antenna receives the coordinates of the UAV and transmits its position and the position of the plane to the ground station. After determined the orientation by using the tracking algorithm, the data is sent to the controller which triggers the actuator. The IMU gives feedback to the controller to determine the error. Finally, the system location is attained successfully by the position. This algorithm is repeated for both axes, namely the tilt and pan.

To accomplish the robust control the novel approach has been developed which is based on discrete-time controller design. Firstly, the system has been modeled mathematically, then discretization is done. Finally, an energy-based proportional controller through the Lyapunov Stability Theorem has been designed [17]. Thus, position control of the system was better than the ones whose previous studies.

The results of discretization of (1) and (2) in time are shown in equations (5) and (6), respectively:

$$\begin{aligned}\theta[k+1]\left[\frac{J_{eq}^{tilt}}{d_t^2} + \frac{C_{eq}^{tilt}}{2d_t}\right] + \theta[k]\left[\frac{-2J}{d_t^2}\right]\\ + \theta[k-1]\left[\frac{J_{eq}^{tilt}}{d_t^2} - \frac{C_{eq}^{tilt}}{2d_t}\right]\\ + mg(r+l)\cos(\theta[k-1])\\ = \tau_{tilt}[k-1]\end{aligned} \tag{5}$$

$$\begin{aligned}\gamma[k+1]\left[\frac{J_{eq}^{pan}}{d_t^2} + \frac{C_{eq}^{pan}}{2d_t}\right] + \gamma[t]\left[\frac{-2J}{d_t^2}\right]\\ + \gamma[k-1]\left[\frac{J_{eq}^{pan}}{d_t^2} \quad \frac{C_{eq}^{pan}}{2d_t}\right]\\ = \tau_{pan}[k-1]\end{aligned} \tag{6}$$

In the Lyapunov controller, the selected energy function must always be positive and its change over time must be a negative value to achieve system stability.

Selected the energy function of the system whose e[t] refers to the error of the system as follows:

$$L[e[k]] = e[k]^2 \tag{7}$$

and

$$L[e[k+1]] - L[e[k]] = e[k+1]^2 - e[k]^2 \tag{8}$$

If,

$$e[k+1] = A_e e[k] \tag{9}$$

and substitute for the equation (8):

$$L[e[k+1]] - L[e[k]] = e[k]^2(A_e^2 - 1) \tag{10}$$

It can be expressed as. So, the equality that the system must provide stability which is shown:

$$e[k]^2(A_e^2 - 1) < 0 \; so \; -1 < A_e < 1 \tag{11}$$

The error in the system is as follows:

$$e[k] = \theta_{ref}[k] - \theta[k] \tag{12}$$

and

$$e[k+1] = \theta_{ref}[k+1] - \theta[k+1] \tag{13}$$

To reach the correct results of equation (9), the controller input must be equal to one in equation 14 and equation 15 as for the tilt and pan axis, respectively, by using feedback linearization. Then, according to equation 11, the stabilization of the system can be achieved over controller parameter $Ae$.

$$\tau_{tilt}[k-1] = (\theta_{ref}[k+1] - A_e^{tilt}\left(\theta_{ref}[k] - \theta[k]\right) - (-\frac{\theta[k]\frac{-2J_{eq}^{tilt}}{d_t^2}}{\frac{J_{eq}^{tilt}}{d_t^2}+\frac{C_{eq}^{tilt}}{2d_t}} - \frac{\theta[k-1]\left(\frac{J_{eq}^{tilt}}{d_t^2}-\frac{C_{eq}^{tilt}}{2d_t}\right)}{\frac{J_{eq}^{tilt}}{d_t^2}+\frac{C_{eq}^{tilt}}{2d_t}} - \frac{(mg(r+l)\cos(\theta[k])}{\frac{J_{eq}^{tilt}}{d_t^2}+\frac{C_{eq}^{tilt}}{2d_t}}))/\frac{1}{\frac{J_{eq}^{tilt}}{d_t^2}+\frac{C_{eq}^{tilt}}{2d_t}} \tag{14}$$

and

$$\tau_{pan}[k-1] = (\gamma_{ref}[k+1] - A_e^{pan}\left(\gamma_{ref}[k] - \gamma[k]\right) - (-\frac{\gamma[k]\,\frac{-2J_{eq.pan}}{d_t^2}}{\frac{J_{eq.pan}}{d_t^2}+\frac{C_{eq.pan}}{2d_t}} \ldots$$

$$\ldots - \frac{\gamma[k-1]\left(\frac{J_{eq.pan}}{d_t^2}-\frac{C_{eq.pan}}{2d_t}\right)}{\frac{J_{eq.pan}}{d_t^2}+\frac{C_{eq.pan}}{2d_t}}))/\frac{1}{\frac{J_{eq.pan}}{d_t^2}+\frac{C_{eq.pan}}{2d_t}} \tag{15}$$

If it ranges between

$$-1 < A_e < 1 \tag{16}$$

the stable system can be obtained. As it is shown in the eq. (11), the energy of the error always converges to zero. Therefore, the system could be stable. However, the negative values of $A_e$ can make the system stable but oscillated. Thus, in practice, $A_e$ is taken as between 0 and 1.

### E. Tracking Algorithm

To process the calculations to determine the tilt angle, knowledge of the distance between the UAV and the GCS are required. The distance as seen in figure 3, "d" can be calculated using the Spherical Law of Cosines Equations as follows:

$$\Delta\emptyset = \emptyset_2 - \emptyset_1 \tag{17}$$

$$d = cos^{-1}(sin\emptyset_1 \text{ x } sin\emptyset_2 + cos\emptyset_1 \text{ x } cos\emptyset_2 \text{ x } cos\Delta\varphi) \text{ x } R \tag{18}$$

where $\varphi_1$ is longitude of the GCS, $\varphi_2$ is longitude of the UAV, $\emptyset_1$ is latitude of the GCS, $\emptyset_2$ is altitude of the UAV and R is average radius of earth (6.371×$10^6$ m).

$$\Delta h = h_2 - h_1 \tag{19}$$

$$\theta = tan^{-1}\left(\frac{\Delta h}{d}\right) \tag{20}$$

$h_2$ is altitude of UAV, $h_1$ is altitude of GCS. $\theta$ is the tilt angle for antenna tracker. Thus, the required reference angles are calculated [23].

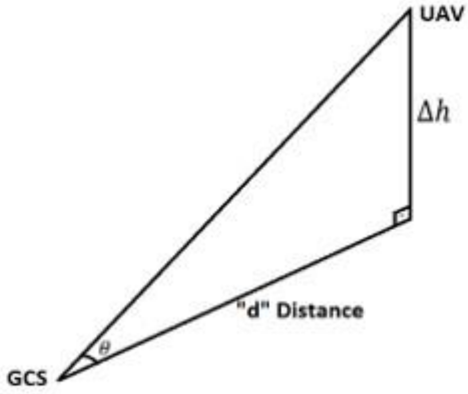

Fig. 3. Tracking angle

Table I. Design Parameters for Simulation

| - | PAN AXIS | TILT AXIS |
|---|---|---|
| **Solver Type** | Centered difference approximation | Centered difference approximation |
| **Refence Signal** | $(\pi/4)\sin(2\pi f t)$ (f = 0.5) | $(\pi/3)\sin(2\pi f t)$ (f=0.5) |
| **Torque Limit** | 2.5 [Nm] | 2.5 [Nm] |
| $\boldsymbol{J_{eq}}$ | $2502.11x10^{-6}[Kgm^2]$ | $3459.55\;x\;10^{-6}\;[Kgm^2]$ |
| $\boldsymbol{C_{eq}}$ | $0.2\;[Nm/(\frac{rad}{s})]$ | $0.2\;[Nm/(\frac{rad}{s})]]$ |
| **m** | 1.17 Kg | |
| **l** | 0.13 m | |

## III.EXPERIMENTS

The design made in SOLIDWORKSTM was transferred to MATLAB / Simulink$^{TM}$ environment and controlled by Lyapunov based proportional discreate controller. Relevant parameter values are given in Table 1.

Various simulations were performed at different sampling times and with different controller coefficients. The simulations conditions under which the test was performed are the coefficients with 0.1, 0.5, 0.9 for pan and tilt axis.

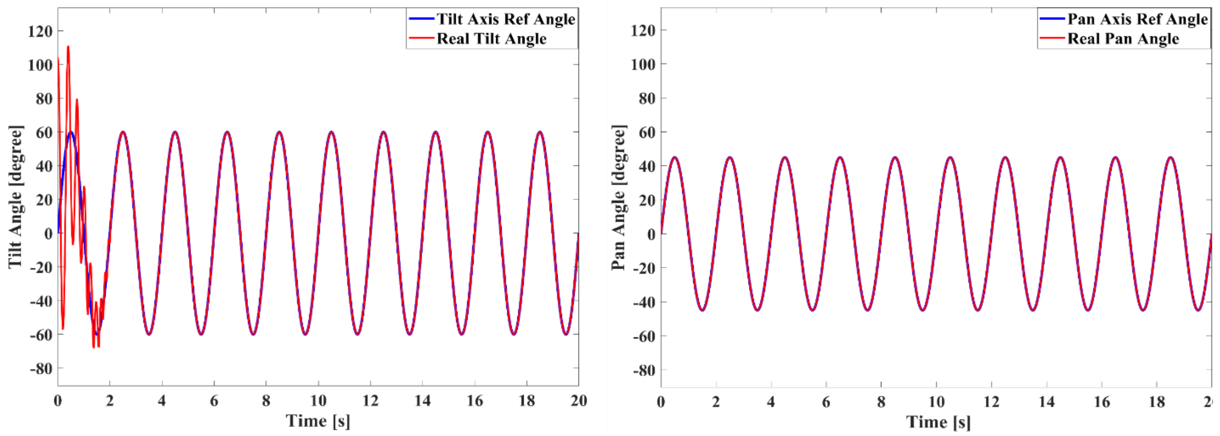

Fig.4. Pan and Tilt Axis References Tracking with 1 ms and 0.1 Controller Coefficient

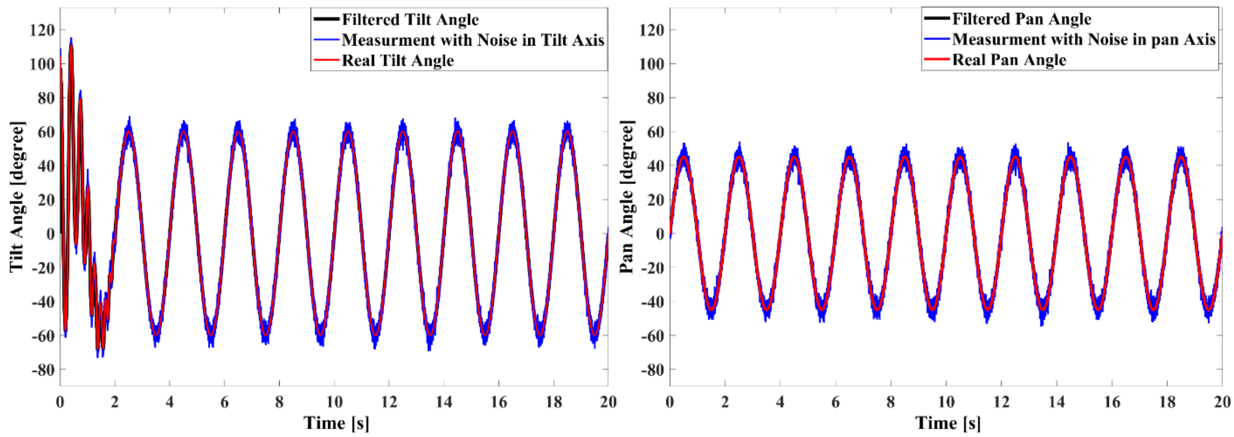

Fig. 5. Pan and Tilt Axis Kalman Filter Results with 1 ms and 0.1 Controller Coefficient

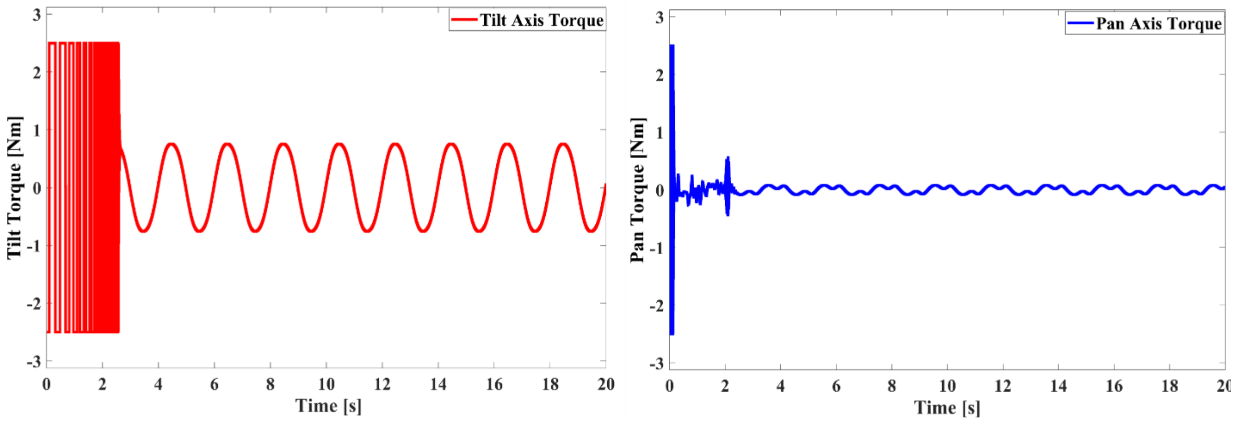

Fig. 6. Pan and Tilt Axis Controller Input with 1 ms and 0.1 Controller Coefficient

As a result of the simulations, the best result for 1 ms sampling time was obtained with a controller coefficient of 0.1 for both pan and tilt axes. Reference tracking controller input and Kalman filter performance are given with these parameters in figures 4, 5 and 6, respectively.

For the tilt axis, a 60-degree 0.5 Hz sine signal can be referenced with an error of 0.02 degrees in 1 [ms] sampling time. For the pan axis, reference tracking can be made with an error of 0.001 degrees for a 0.5 Hz sine signal of 45 degrees. As it can be seen in figure 4, in the tilt axes, the “jitter” is occurred in the beginning of the application due to limiting the torque 2.5 [Nm] as it can be shown table 1. In figure 6 the torque output of the system can be seen clearly. The similar phenomenon is observed for the other simulations of this study. In the same conditions, in a noisy measurement with a standard deviation of 5.7 degrees, the standard deviation of the measurement error for the pan axis was reduced to 0.03 degree for the pan axis and 0.25 degree for the tilt axis. To make the system follow the reference, 0.75 Nm torque is required for the tilt axis and 0.1 Nm torque is required for the pan axis.

## IV. EXPERIMENTAL STUDIES AND RESULTS

The system was set up and tested as in figure 7. The system consists of an STM32F4, two 12V Geared DC motors with encoder, two motor drivers, a power supply, a tripod, an antenna, and connection elements. The feedback for the position of motors for the controller was received by the encoder.

The values in the simulation were used for the system model, except for the damping coefficient. The tests were performed for different sampling times and different controller coefficients. The tests were repeated for different damping coefficients to arrive at the actual damping coefficient of the system.

To make real tests compatible with the simulation, the system was first tested with the same values in the simulation at sampling times of 1 ms. The results are given in figure 8.

For the same test, the error graph in the pan and tilt axes is as shown in figure 8.

Fig. 7. Test System for Antenna Tracker

## V. DISCUSSION

Antenna trackers are the included subsystems that are important for operational appliances. The main requirement of such systems is reaching the tracking with a proper desired path on the tilt and pan axis. However, the generic problem of such systems is possible deviations during communication of directional antennas among the other attendant ones in practice. In this case, the suggested solution in this paper has achieved success to obtain proper tracking of the reference inputs.

As the experimental results showed, the reference path has been tracked with 180 degrees/sec angular velocity within the position error ranges in 0.3 degrees and 0.6 degrees in pan and tilt axes, respectively in 1 ms sampling time. Among the previous research, it can be mostly seen that the error values have been indicated as zero degrees with respect to pan and tilt axes, since they were operated as only simulations and in continuous time cases [9][24][25][26]. However, there is also a narrow range of real-time case studies which have higher error values than this study. Nugroho & Dectaviansyah [23] showed small errors such as 5.62 degrees in the pan axis and 1.51 degrees in the tilt axis in their study. Actually, these error values are even higher than the output of our test in real-time. Also, Hancioglu et al [27] have given their test data results through several test attempts. Their output was higher than our results. Therefore, when comparing to the previous studies the controller of the system shows huge development in terms of positioning.

The performed angular velocity value is above the average for the standard applications and controlled successfully [28][29]. This made huge advantage for tracking especially during take-off and landing phases of flight. Hence the commercial problem for the UAV antenna trackers is reduced.

The controller of the system has been tested for sampling times as 1 ms. As mentioned above under the given sampling time conditions, the system showed good quality tracking with the small error values given in Results section. This benefit came with a flexibility in choosing components of the system. By the way, for the longer sampling time the position error variables are expanded. Therefore, the more sampling time is tested for the controller, the more position error is observed. In any case, the system stays in the stable ranges.

Overall, the design system archives robust control for the tasks whose high angular velocity with high sensitivity. Comparing to commercial antenna tracker systems and academic research, better stability, and less deviation in terms of positioning even if high angular velocities have been

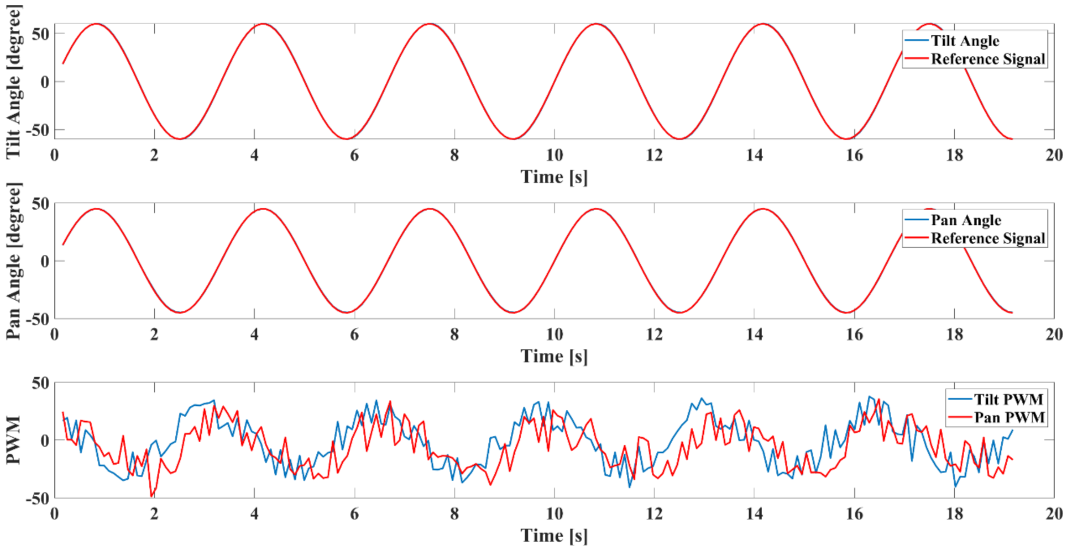

Fig.8 Pan and Tilt Axis Reference Tracking and Controller PWM Input with 1ms, 0.1 Controller Coefficient

obtained as the system superiority. Nevertheless, the vast majority of research in this field has a lack of capability of realizing with continuous-time modality; this study could show higher realizable results in terms of discrete-time controller design. This phenomenon has been proven in Xiong & Zhang's [30] study as well. As an improvement to this study, our work has accomplished the operation task well in practice.

## VI. CONCLUSION

In this study, a discrete-time, the energy-based proportional controller has been presented using the Lyapunov Stability Theorem for antenna tracker systems that is suitable for mini-UAVs. From the results of the study, it can be clearly concluded that the designed controller shows high performance in terms of stability. The UAVs can be tracked within a very low range of error compared to the previous studies in the literature, specifically less than 1 rad range of position error as it mentioned before. By using a 0.5 Hz sinusoidal reference signal input that is actually very high speed for such systems, within the sample reference track; less fluctuated and more stable tracking was obtained in terms of the position of the system in comparison to the other commercial antenna trackers and related previous research. Most importantly, this study involved a brand-new design and achieved a successful discrete-time controller task in this field. By doing so, this approach fills the huge gap in antenna tracker research applications.

## List of Symbols

| | |
|---|---|
| $\tau$ | Torque [Nm] |
| $\theta$ | Tilt Angle [rad] |
| $\gamma$ | Pan Angle [rad] |
| $d$ | Distance [m] |
| $d_t$ | Sampling time [s] |
| $m$ | Mass [Kg] |
| $J$ | Inertia [kgm$^2$] |
| $l$ | Distance [m] |
| $C$ | Damping Coeff. [$\mathrm{Nm}/(\mathrm{rad}/\mathrm{s})$] |
| R | Average Radius of Earth [m] |
| $\emptyset$ | Latitude [rad] |
| $\varphi$ | Longitude [rad] |
| $h$ | Altitude [m] |
| $e$ | Error [rad] |
| $A_e$ | Controller Coeff. [-] |
| $z$ | State Matrix |
| $L$ | Energy function |

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