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Design, manufacture and performance analysis of an automatic antenna tracker for an unmanned aerial vehicle (UAV)

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Abstract

In conducting a disaster monitoring mission, an unmanned aerial vehicle (UAV) has to travel a long distance to cover the region that is hited by a disaster. In the monitoring mission, Air Data and Attitude Heading Reference System (ADAHRS) data are very important to always be displayed on the ground control station (GCS). Unfortunately, the area of monitoring mission is very wide, whereas the usage of an omnidirectional antenna in the disaster monitoring mission is limited to the UAV maximum range. Therefore, a high gain directional antenna is needed. However, the directional antenna has a disadvantage of always being directed to the target. To solve this problem, antenna tracker is made to track the UAV continuously so that the directional antenna can always be directed to the flying UAV. An antenna tracker using a 32-bit microcontroller and GPS with two degrees-of-freedom was developed. It is able to move 360 degrees on azimuth axis (yaw) and 90 degrees on elevation axis (pitch). Meanwhile, the directional antenna is 3 element Yagi type with a radiation capability of 6 dBi. By using the antenna tracker, larger UAV range was obtained and the connection between the UAV and the GCS could always be maintained with a minimum fluctuation of RSSI signal, compared to those without using antenna tracker.

Keywords: UAV-antenna tracker; disaster monitoring; ground control station; UAV.

I. Introduction

Unmanned aerial system (UAS) has several system builders such as an unmanned aerial vehicle (UAV) and ground control station (GCS). The GCS plays an important role in a mission that has been done by the UAV. Air data and attitude heading reference system (ADAHRS) data should always be displayed on the GCS to monitor autonomously the flying UAV.

A specified frequency telemetry module is required in order to monitor the UAV continuously. The operator is able to determine the navigation mission by making a waypoint and monitor the UAV flight data on the GCS during flight. To transmit the signal required by the antenna, two types of antenna are needed, that are omnidirectional and directional antennas which have different characteristic. The most difference of these antennas is a radiation pattern. The omnidirectional antenna has a radiation pattern to all direction, so it has a directivity of 1 dB or 0 dB [1]. Meanwhile directional antenna has a radiation pattern that focuses on a certain degree, so that beamwidth degree of radiation emission would not be emitted to the large area but will be focused on a certain area on a specific angle and has a directivity value higher than 1 dB [2].

Antenna tracker is used for keeping directing high gain directional antenna to always facing the target, in this case an UAV. Considering directional antenna has a radiation pattern that is focused on certain angle and area, whereas the antenna that usually used on UAV is the omnidirectional type, then to keep UAV on the radiation area of the directional antenna, an antenna tracker is needed to track the UAV continuously.

Mechanical design of the antenna tracker has several criteria such as having two degrees of freedom, azimuth angle (yaw) that able to move 360 degrees (continuous rotation) and elevation angle (pitch) that able to move 90 degrees (Perpendicular from planar geometry) [3]. Servo motor or DC motor is needed to

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move the frame on azimuth and elevation axis. In order to obtain high torque and smooth rotation, suitable gear is used.

When a satellite passes over an earth station and point directly at it, the angular velocity of the satellite antenna can increase rapidly due to the gimbal kinematics. Angular velocity minimization method for the satellite antenna tracker was reported [4]. A sting nailing algorithm for fast and correct generation of the shortest path was proposed. The number of control system that implements standard algorithms PID, fuzzy, genetic, neural network, and so forth was developed to control an antenna. Many researchers have developed manual, differential, monopulse, electronic, auto-tracking, left-right, conical, and stepped tracking methods to track the signal source. The performances of the implemented standard algorithms and tracking methods to track signal source were discussed [5].

An attitude heading and reference system (AHRS) for marine satellite tracking antennas (MSTAs) to overcome attitude disturbance due to ship vibration and rotation motion was presented [6]. The performance of the designed AHRS for MSTA is assessed through hardware experiments using a Stewart platform and high precision commercial AHRS. A fault tolerant control (FTC) system is proposed for the satellite tracking antenna that directs the onboard antenna toward a chosen satellite while the high sea waves disturb the antenna [7]. The FTC system maintains the tracking functionality by employing proper control strategy. A robust fault diagnosis system is designed to supervise the FTC system.

A rooftop dish-antenna tracking system was designed, and appropriate motors and corresponding drives were selected. A mathematical model of such a system was presented. The tracking system to control the antenna was realized practically with commercial PLC and display units. A MATLAB-based tracking-system simulator was also developed to test the control system performance [8]. An innovative dual polarization antenna working at Ku band (14 ÷ 14.5 GHz) based on slotted wave guide array (SWGA) technology was presented [9]. The method allows to simultaneously generate two orthogonal circular polarizations that are combined to generate two orthogonal linear polarizations with polarization-tracking capabilities and very low cross-polarization level. The antenna is composed of two interleaved slotted ridge waveguide arrays connected to a polarizer, realized with an array of triangular-base ridged cavities.

Reliability and efficiency of an electromagnetic band gap (EBG) matrix antenna for beam forming and beam steering applications was described and demonstrated through experimental prototype. The proposed antenna is based on the equivalent radiating surface approach and used special EBG antennas called “pixels” to overcome some of the array approach defects. The antenna has demonstrated different electromagnetic behaviors, such as low mutual coupling, high gain preservation for high scanning angles values, etc. [10].

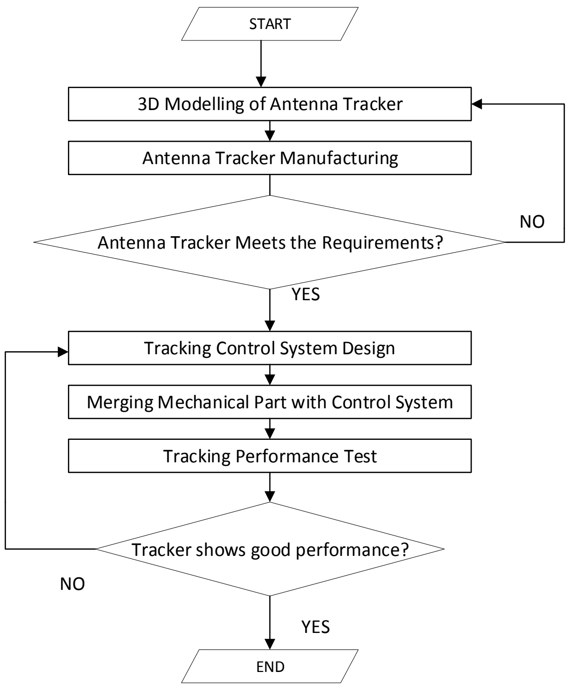


Figure 1. Research methodology

Many previous researches discuss about antenna tracker, however research regarding design, manufacturing process and testing, and application to track an unmanned aerial vehicle is rarely found. This paper shares the design, manufacture, and examination of an antenna tracker with two degrees of freedom in order to track UAV automatically. This allows the UAV to fly and cover wider signal range without losing contact with the GCS.

II. Research method

Research methodology can be shown in Figure 1. The first step is creating a 3D model using Autodesk Inventor Software. Before the design process, the design requirements must be determined. 3D models are based on design results. The second step is machining the mechanical components using CNC Laser Cutting Machine, Lathe Machine, and Drill Machine. The frame material used for antenna tracker is plywood with a thickness of 5 mm. The third step is machining the mechanical components. The gear was made of Polyvinyl Chloride (PVC) material with a flange made of brass. The shaft that needed to move the elevation angle was also made of brass.

The fourth step is designing the control system by using a 32-bit microcontroller and GPS module. Several kinds of setup were done on the Mission Planner Software, such as Firmware Downloading and IMU sensor, barometer, GPS, and electronic compass calibration which exist on 32-bit microcontroller.

The next step is assembling the antenna tracker, and merging the mechanical part with the control system followed by functionality test for the actuator or servo motor that able to rotate 360 degrees (continuous rotation) and elevation of 90 degrees. The last step is

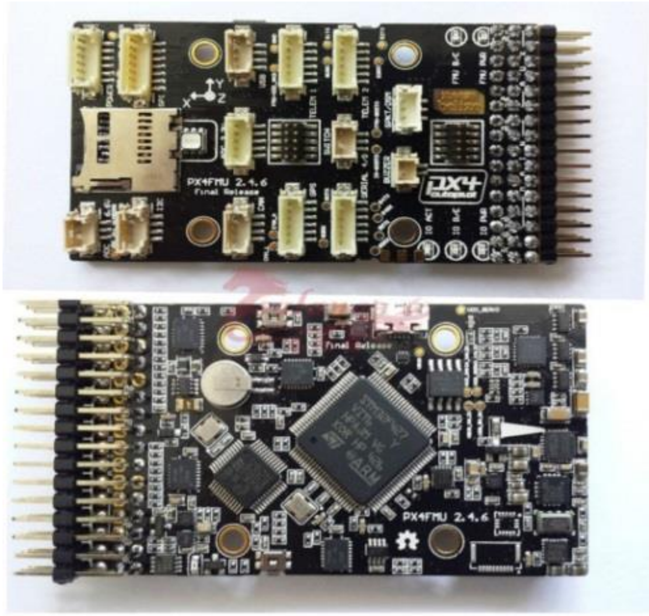


Figure 2. 32-bit controller [6]

implementing the antenna tracker to track an UAV, by setting the control parameter using Mission Planner software, such as PID value and ADAHRS.

The result of tracking ability of the antenna tracker was obtained from the SD card black box data logger controller. These data were processed to be a tendency graphic. Therefore the performance of the antenna tracker can be seen by observing the result of data processing analysis. Besides the tracking performance, the signal connection quality of telemetry modem between UAV and antenna tracker when using an omnidirectional antenna, directional antenna with antenna tracker, and directional antenna without antenna tracker were also compared.

III. Results and discussion

A. Control system of antenna tracker

The antenna tracker was controlled by using a 32-bit microcontroller as shown in Figure 2. It has a specification as follows:

- Microprocessor: 1 chip 32-bit STM32F427 Cortex M4, with specification 168 MHz/256 KB RAM/2 MB Flash, 1 chip 32-bit STM32F103 failsafe co-processor
- Sensor: ST Micro L3GD20 3-axis 16-bitgyroscope, ST Micro LSM303 D3-axis 14-bitaccelerometer/magnetometer, InvenSense MPU 6000 3-axis accelerometer/gyrometer
- MEAS MS5611 barometer
- Voltage input of 3.3 to 10 Volt DC.

GPS module is using uBlox Product with uBlox LEA-6H as the chipset that has an accuracy of approximately 3 meters. Other than that, uBlox LEA-6H GPS already has an electronic compass with the type of HMC5883L. Therefore, there are 2 electronic compasses, the first one is on the 32-bit microcontroller and the other one is on the GPS module. When the antenna tracker works, the electronic compass that used as the primary compass is the electronic compass that located on the GPS module. It is because the electronic compass has a high risk of electromagnetic noise exposure from the cable circuit that located around the 32-bit microcontroller, and there is no electromagnetic noise shielding applied on the microcontroller. GPS module is located at a place away from the cable and telemetry module to avoid electromagnetic noise that causes inaccurate effect of the antenna tracker performance.

B. Antenna tracker actuator

Servo motor was used as an actuator to move the mechanical part of the antenna tracker that are azimuth axis (yaw) by 360 degrees movement and elevation axis (Pitch) by 90 degrees movement along with gear transmission to obtain high torque. The servo motor specification is as follow: angular velocity 62 RPM on 6 VDC; rotation angle 360 degrees (continuous rotation); torque 15 kg.cm @6 VDC; servo dimension $42 \times 20.5 \times 39.5$ mm; and servo motor weight 60 gram.

C. Mechanical design of antenna tracker

Mechanical design of the antenna tracker was adapted to the needs of the assignment that was given to the UAV. In this case, the UAV assignment was to monitor a disaster area which is always identical with the isolated area and difficult to be accessed. Therefore, antenna tracker must be designed to have high portability so that it would be easy to be re-assembled and carried.

The mechanical system of the antenna tracker was designed using Autodesk Inventor Software as shown in Figure 3. On the movement of two degrees of freedom, the azimuth and elevation axis, the antenna tracker was using two pieces of high torque servo motors on each axis. Gear transmission was used to obtain the constant and smooth rotation and higher torque on each axis, as shown in Figure 4(a) and 4(b).

Table 1.
The magnitude of rotation and torque on every axis

Axis	Pinion	Gear	Gear Ratio	Rotation Speed (RPM)	Torque Out (kg.cm)
Azimuth (Yaw)	30	47	0.6	39.5	47
Elevation (Pitch)	31	64	0.4	30.0	61.9

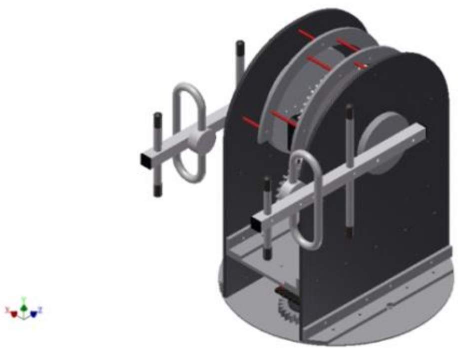


Figure 3. Three-dimensional design of antenna tracker

From Figure 4, it can be seen how each axis of the antenna tracker moved by the servo motor. The movement was smoothened by the gear ratio on every axis and the torque was increased in every axis. To calculate the servo motor torque and rotation on each axis, Equations (1) to (3) were used:

$$\text{Gear Ratio} = \frac{n_{in}}{n_{out}} \quad (1)$$

$$\text{Angular Speed} = \text{Gear Ratio} \times \omega_{in} \quad (2)$$

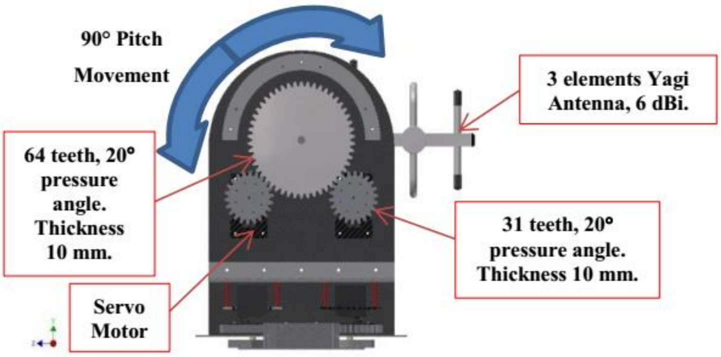
$$Torque\ Out = \frac{\tau_{in}}{Gear\ Ratio} \quad (3)$$

where n_{in} is rotation speed input; n_{out} is rotation speed output; ω_{in} is angular speed input; τ_{in} is torque input.

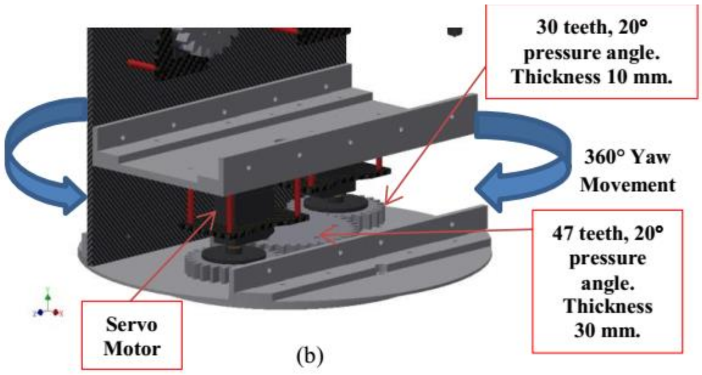
The magnitude of rotation and torque on each axis was obtained, as shown in Table 1. Table 1 was used to select suitable servo motor to rotate the antenna tracker axis.

D. Telemetry configuration

To operate the antenna tracker, radio and telemetry configuration between the GCS, the antenna tracker, and the UAV must be set properly as shown in Figure 5. Telemetry configuration was done in order to avoid telemetry radio signal interference. From Figure 5, it was known that radio configuration telemetry was able to use 2 pairs of telemetry radio with different frequencies. The telemetry radio between the GCS and the antenna tracker was using the frequency of 433 MHz, whereas the telemetry radio between the antenna tracker and the UAV was using a radio frequency of 915 MHz.



(a)



(b)

Figure 4. Movement of every axis: (a) elevation axis (pitch); (b) azimuth axis (yaw)

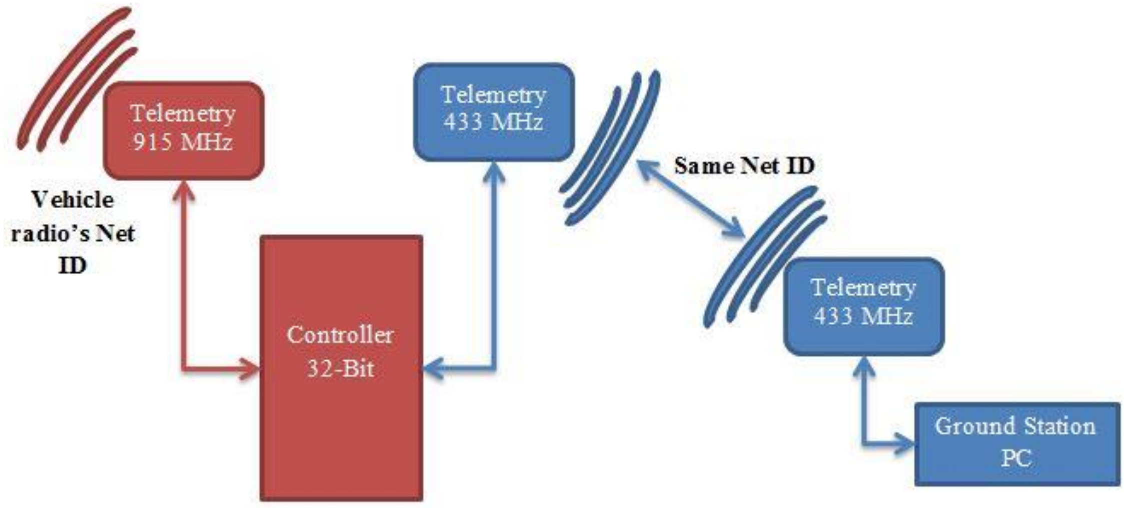


Figure 5. Telemetry configuration [7]

From Figure 5, it can be seen that the 32-bit microprocessor had a function of the antenna tracker controller and ADAHTS UAV data router to be displayed at the GCS at once. With such a telemetry configuration, the antenna tracker was able to be operated wireless without interference between the UAV and the GCS in the routing of ADAHRS UAV data.

E. Antenna

A directional antenna and an omnidirectional antenna were used in the performance test. The directional antenna used was a 6 dBi 3 element Yagi with radiation pattern as shown in Figure 6. The omnidirectional antenna gain was 2.1 dBi. Both antennas were worked at a frequency of 915 to 928 MHz.

F. Tracking algorithm

The antenna was rotated at that azimuth angle relative to the north pole in order to remain the UAV in the radiation pattern of the antenna in the GCS. The azimuth angle was calculated by Equations (4)-(7) [11].

$$\Delta\varphi = \varphi_2 - \varphi_1 \tag{4}$$

$$y = \sin\Delta\varphi * \cos\emptyset_2 \tag{5}$$

$$x = (\cos\emptyset_1 * \sin\emptyset_2) - (\sin\emptyset_1 * \cos\emptyset_2 * \cos\Delta\varphi) \tag{6}$$

$$\psi = \tan^{-1}\left(\frac{y}{x}\right) \tag{7}$$

where φ_1 is *Longitude* of the GCS, φ_2 is *Longitude* of the UAV, $\emptyset_1$ is *Latitude* of the GCS, $\emptyset_2$ is *Latitude* of the UAV. ψ is the *azimuth angle* that is the position of the UAV relative to the north pole.

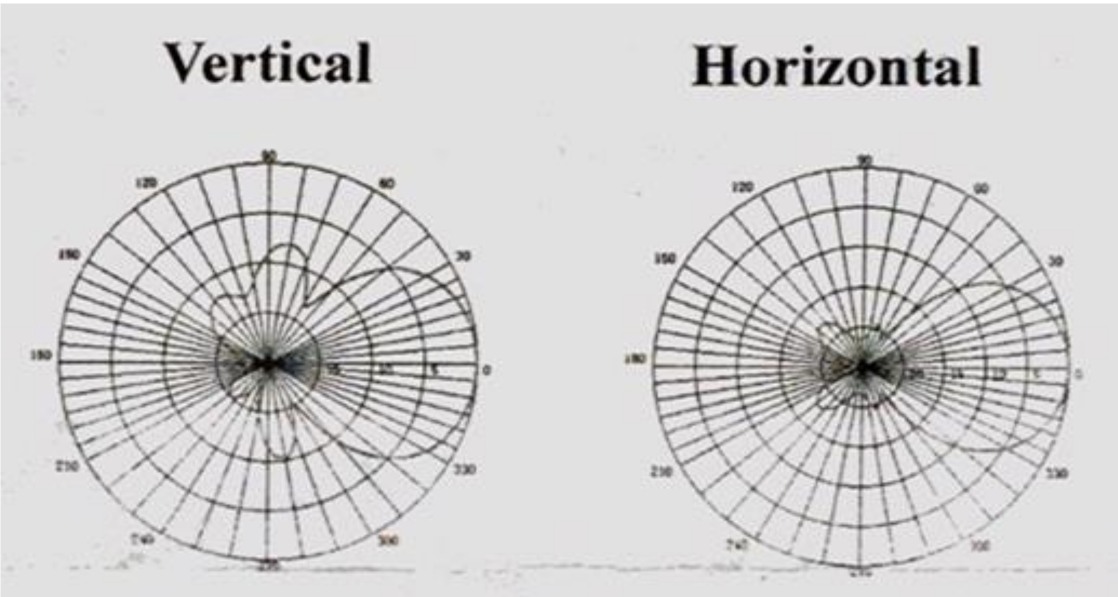


Figure 6. Radiation pattern 6 dBi 3 element Yagi antenna

Figure 7. Antenna tracker performance test

The distance between the UAV and the GCS was also needed. Positions of the UAV and the GCS were known, then the latitudinal angle was linear but the longitudinal degree was depended on latitude. Distance d between the UAV and the GCS can be calculated using the Spherical Law of Cosines Equations as follows:

$$\Delta\varphi = \varphi_2 - \varphi_1 \quad (8)$$

$$\Delta\emptyset = \emptyset_2 - \emptyset_1 \quad (9)$$

$$d = \cos^{-1}(\sin\emptyset_1 * \sin\emptyset_2 + \cos\emptyset_1 * \cos\emptyset_2 * \cos\Delta\varphi) * R \quad (10)$$

where R is average Radius of earth (6.371×10^3 m). By knowing the distance d, altitudes of the UAV and the GCS, and Vertical angle; the controller can calculate pitch angle by using Equations (11) and (12).

$$\Delta h = h_2 - h_1 \quad (11)$$

$$\theta = \tan^{-1}\left(\frac{\Delta h}{d}\right) \quad (12)$$

where θ is rotation angle of the antenna tracker to the horizon, h_1 is *Altitude* of GCS, h_2 is *Altitude* of UAV. While the value of d always positive, θ always on the range of −90° to +90° [12].

G. Antenna tracker performance

When the antenna tracker works, it provided data logs in the memory. The UAV provided data logs that can be downloaded via SD card in the 32-bit controller. The antenna tracker performance was tested with a Quadcopter-type UAV as shown in Figure 7. By simulating an area of the disaster monitoring, performance of the antenna tracker was obtained such as tracking accuracy, signal quality (RSSI), and the error that occurs on every axis.

After the testing was done, the data logs in the SD card of the 32-bit controller were taken and downloaded to a PC for processing. Data processing included tracking the accuracy of the antenna tracker by comparing the desired azimuth angle with the actual azimuth angle of the antenna tracker, and the desired elevation angle with the actual antenna tracker elevation angle are shown in Figure 8. From Figure 8(a) and 8(b), it can be seen that the antenna tracker was able to track the UAV accurately. From Figure 8(a) and 8(b), the blue line showed the desired azimuth and elevation angle while the red line showed the azimuth and elevation angle that were done by the antenna tracker. With a little error, that was an average of 5.62° on the Azimuth axis (Yaw) and 1.51° on elevation axis (Pitch), respectively. Error on each axis can be seen in Figure 9.

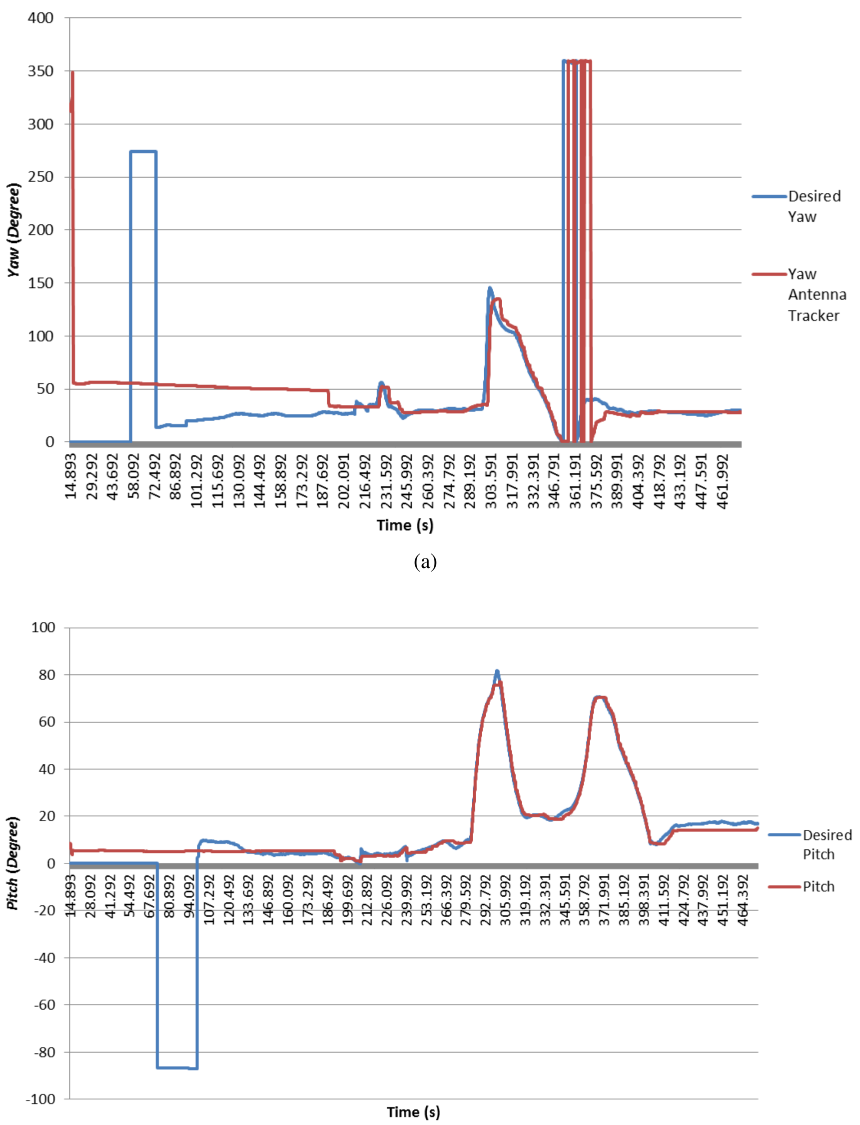
During the test before data recording, uncontrolled movement of the antenna tracker was often occur as shown in Figure 10. This uncontrolled motion due to the controller had not worked properly, so the antenna axis motion had not been controlled. This condition was occurred only for a while when the system was started up.

From the graph in Figure 10, it can be seen that there was a significant error at the beginning of the antenna tracker activation. That was because the GPS module had not received the position of at least 6 satellites, so that GPS status on GCS was still not fixed. However after 202.091 seconds the antenna tracker had worked normally and accurately.

H. Signal quality

To test signal quality, the Received Signal Strength Indicator (RSSI) was measured. The RSSI comparison was carried out between three measurements: when the antenna tracker was in active condition, without antenna tracker, and with the antenna tracker that use omnidirectional antenna type. The results were plotted in Figure 11.

Figure 11 showed that, when the tracker antenna was activated, the signal quality did not fluctuate significantly. When a high gain directional antenna without tracker is used, the signal quality was fluctuated significantly. In the case that telemetry used only an omnidirectional antenna, the signal quality was fluctuated very significant even the lowest signal quality had occurred when using an omnidirectional antenna. From the above results, it was known that the use of antenna tracker can keep the signal quality constantly without experiencing significant fluctuations. This means that telemetry data can be transmitted securely.



(a)

(b)

Figure 8. Antenna tracker performance: (a) azimuth axis (yaw); (b) elevation axis (pitch)

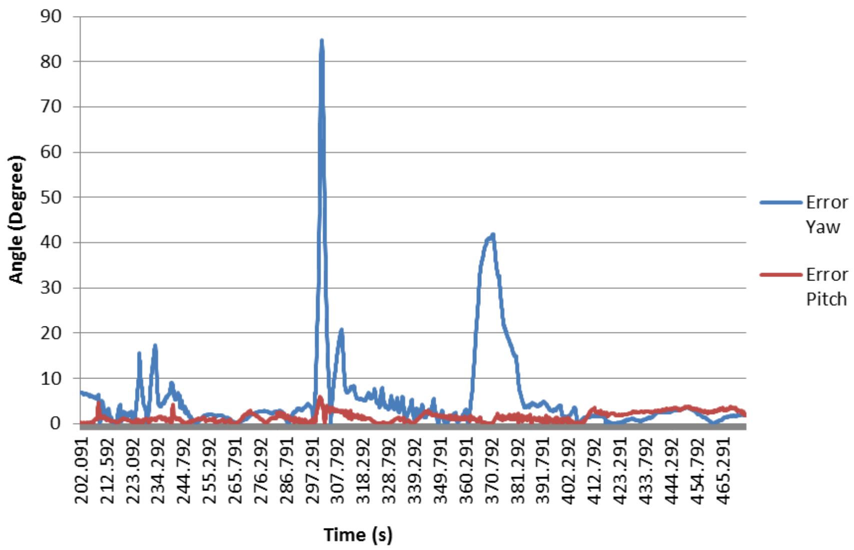


Figure 9. Error on azimuth axis (blue line) and error on elevation axis (Red Line)

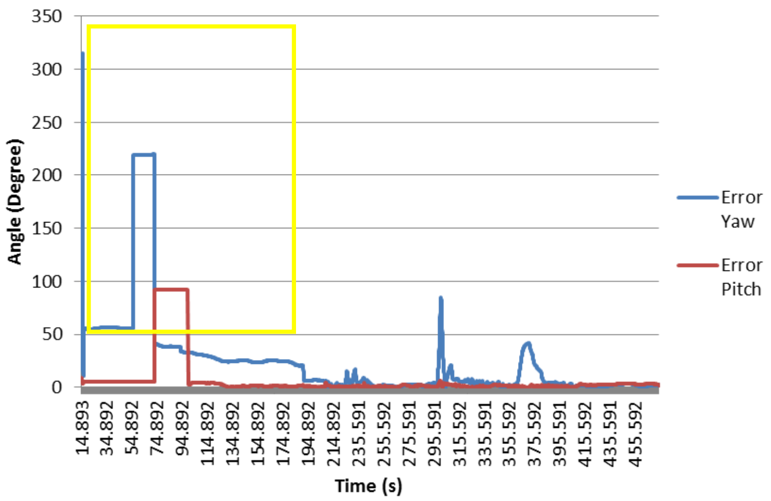


Figure 10. Uncontrolled movement (yellow box)

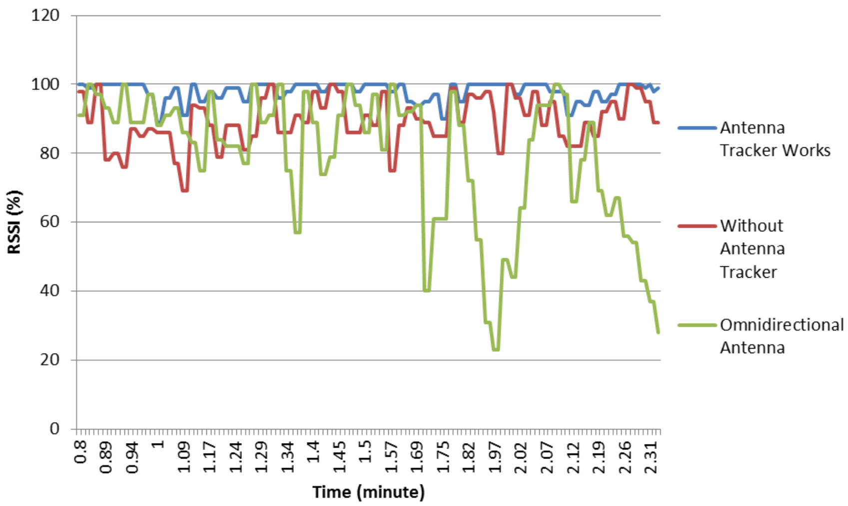


Figure 11. Comparison of signal quality

IV. Conclusion

From the results of this study it can be concluded that the designed antenna tracker could track the UAV accurately with an average error of 5.62° on Azimuth axis (Yaw) and 1.51° on elevation axis (Pitch), respectively. By measuring the Received Signal Strength Indicator (RSSI) it was known that the signal strength was more constantly maintained when it used a directional high gain antenna with tracker compared with a directional high gain antenna and omnidirectional antenna with no tracker. The use of an antenna tracker was necessary when a directional antenna was used, so that the UAV remained in the radiation area of the directional high gain antenna. By doing so, signal quality could be maintained constantly without experiencing any fluctuation. By using this antenna tracker, the data link can be further extended so that an unmanned aircraft will be able to fly further without experiencing signal loss.

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