A Low-cost Antenna Tracking System Integrated with GPS for UAVs

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ABSTRACT

In today's world, unmanned aerial vehicles (UAVs) are increasingly incorporated into different sectors to perform different functions for both military and commercial applications. Depending on the pace of use, the environment affects the signal quality, transmission and reception ability between the UAV and its ground control station (GCS). To mitigate the poor communication and avoid the disruption of communication between the GCS and UAV, an antenna tracking system (ATS) can be used. This work aims to design a good performance ATS using a helical antenna, integrated with GPS. The helical antenna is controlled by proportional-integral-derivative (PID) controller. To improve accuracy and provide redundancy in case of system failure, GPS is integrated to the ATS. The PID controller provides stability of the system in varying system operational stages against internal and external disturbances.

Keywords: Antenna tracking system, Closed loop control, GCS, PID Controller, Unmanned aerial vehicle.

1. INTRODUCTION

Unmanned aerial vehicles (UAVs), commonly called drones, have over the years through research and further development, become versatile tools for use in a variety of sectors for its application [1], [2] . In the most recent time, flying a UAV does not require any prior flight experience due to the advancement in the flight controller technology [3]. Currently, UAVs are part of the defense warfare of most developed and developing countries of the world. The 1940s was the developmental stage in the use of the UAV technology. They were designed and deployed by the United States Air for spying and reconnaissance. At this time, they were functional but not efficient and had some flaws due to their operating systems. Since the 1940s to this present day, UAVs have continuously undergone advancement and technology upgrades, increasing their area of use and versatility [4], [5]. Modern UAVs are used in various industries and sectors for different reasons like news broadcasting, cinematography, agriculture, health, search and rescue, defense, surveillance, and some other recreational activities [6], [7].

 Good signal quality for transmission and reception between the UAV and GCS has always been a key objective in every UAV design [8] . The successful completion of a UAV's mission, prevention of loss or crash, and other critical aspects depend on

reliable remote communication from the GCS. Consequently, the antenna tracking system (ATS) is necessary to minimize distortion and latency in signal transmission and reception between the GCS and the UAV. Several ATS are available for purchase in the market, providing the tracking ability and signal quality improvement but at a much higher cost [9]. The SATPRO is an advanced system, high-performance and precision antenna tracking system that costs about $9,565. It is a professional automatic tracking antenna for radio control, MAVLink telemetry and video systems, for all types of applications with aerial, land or maritime Vehicles. It has the ability to maintain line of sight (LOS) with a UAV from a distance of 250 km. Another system is the MFD crossbow ATS, which costs less than the SARPRO and performs well in tracking UAVs [10] .

In order to obtain the best trade-off for cost and performance, this paper presents a low-cost alternative that integrates GPS to an ATS. The rest of the paper is organized as follows: Section 2 presents the design of the helica antenna. Section 3 discusses the selection of the GPS module and microcontroller. Details on the tracking and control algorithms are presented in Sections 4 and 5. Section 6 presents the simulation results, with discussion and concluding remarks presented in Section 7.

2. DESIGN OF A HELICAL ANTENNA

Firstly, the type of antenna used and its performance characteristics play a crucial role in determining whether the Antenna Tracking System (ATS) can effectively enhance the signal strength transmitted by the Ground Control Station (GCS) and receive the signal sent from the Unmanned Aerial Vehicle (UAV) at its best quality. The helical antenna is chosen because of its good directivity and gain properties. The helical antenna is known to have two types of mode in which it can be operated, depending on the design parameters and reason for use. It operates on two modes known as the: normal mode and the axial-mode. In the normal-mode, the radiation pattern of the helical antenna is in all direction (omnidirectional) in a 3D space. On the other hand, the axial-mode has a more concentrated radiation, usually focused in a specified direction and the wave is circularly polarized. The axial-mode of the helical antenna is the favoured type in UAV application because of its high directivity gain characteristic and increased range [11]. The helical antenna is very much beneficial for use in systems relating and associated with UAVs. Its ease of construction, low-cost-to-performance index and high gain amongst other performance characteristics makes it one of the good choices of antennae for UAV application. In this paper, a circular polarized, directional antenna is chosen with the following design parameters.

2.1 Parameter selection

The achievement of a good and even high-quality communication signal, interference evasion, and obstacle penetration is to a very large extent dependent on the antenna used to generate the signal. Designing an antenna that is capable of providing these requirements is paramount for the ATS to be able to carry out its function successfully. The designed antenna had some pre-selected parameters which are stated in Table 1.

TABLE 1.

Antenna Design Parameters

Parameters	Values
Operating Frequency (f)	2.4G Hz
Number of turns (N)	8
Height	208mm
Polarization	circular
Diameter (D)	40mm
Circumference (C)	125.6637mm
Spacing between turns (S)	26mm

Some other parameters needed for the successful design of the antenna are calculated using their respective formulae as relating to the already known parameters;

Wavelength:

$$\lambda = C/f \tag{1}$$

$$\lambda = \frac{2.998 \times 10^8}{2.4 \times 10^9} \tag{2}$$

$$\lambda = 124.913mm \tag{3}$$

Gain:

$$Gain\ in\ dB = 10.8 + 10Log\left[\frac{C^2 NS}{\lambda^3}\right] \tag{4}$$

$$Gain\ in\ dB = 10.8 + 10Log\left[\frac{125.6637^2 * 10 * 26}{124.913^3}\right] \tag{5}$$

$$Gain\ in\ dB = 14.04 \tag{6}$$

Aspect Ratio (AR):

$$AR = \left[\frac{2N + 1}{2N}\right] \tag{7}$$

$$AR = \left[\frac{2(8) + 1}{2(8)}\right] \tag{8}$$

$$AR = 1.0625 \tag{9}$$

Pitch Angle:

$$\alpha = tan^{-1}\frac{S}{C} \tag{10}$$

$$\alpha = tan^{-1}\left[\frac{26}{125.6637}\right] = 11.7^0 \tag{11}$$

2.2 Designing the antenna in MATLAB

After obtaining, the fundamental parameters required to fully model the antenna, from pre-defined selection and calculations, the helical antenna can be designed using the "MATLAB Antenna Tool Box". The antenna design required writing a MATLAB code to generate the antenna based on the known parameters. Figure 1. shows the proposed antenna in 3D, during its design phase in MATLAB.
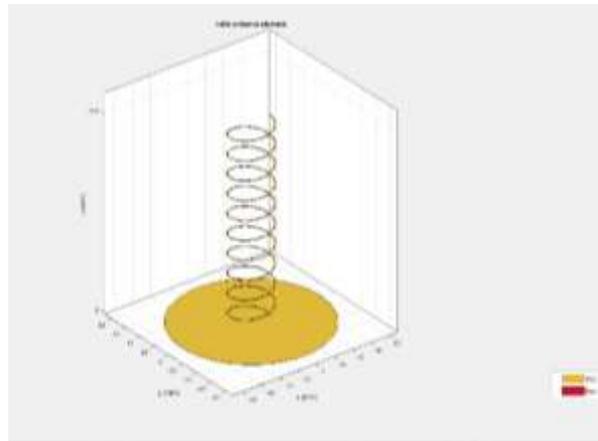

FIGURE 1. 3D projection of the proposed Antenna

3. GPS MODULE SELECTION AND MICROCONTROLLER SUITED FOR ITS INTEGRATION

The global positioning system is a collective network of about 24 orbiting satellites (in space) which communicate together to give the position and navigation information of a particular object with respect to the Earth's surface relative to their own position. GPS is used in the day-to-day activities for location a position, determine a heading or track and monitor a selected target. Most of the automobiles use the GPS for navigation and positioning.

3.1 GPS Module Selection

The selected GPS module is the Adafruit PA1616S (this is depicted in Figure 2). It is a high-performance module, compact and easily integrated with other systems. It is built around the MTK3339 chipset, a high-quality GPS module that can track up to 22 satellites on 66 channels, has an excellent high-sensitivity receiver (-165 dBm tracking), and a built-in antenna. It can do up to 10 location updates a second for high speed, high sensitivity logging, or tracking.

FIGURE 2. Snippet of the AdaFruit PA1616S

The GPS module cannot be a stand-alone system, so it works with other components to make a complete functioning system. It provides the system with certain variables (location, position and even time) needed for the total functioning and increased performance efficiency and reliability.

3.2 Microcontroller Selection

The microcontroller suggested is the Arduino Mega 2560. The Arduino Mega 2560 (Figure 3) is a microcontroller board based on the ATmega2560. It has 54 digital input/output pins (of which 15 can be used as PWM outputs), 16 analogue inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, and a reset button. This selected microcontroller is suitable as there is no delay when it receives, computes and gives out the information from the GPS. The delays caused by difference in transmission pattern (i.e., some module transmit using PWM, SPI (serial peripheral interface), 12C etc.) is minimal in this microcontroller.

FIGURE 3. Arduino Mega 2560 Board

All other subsystems like the DC motor, battery, and so on, are also connected to the microcontroller to be able to achieve the goal of the system.

The suggested components to make up the entire architecture of the ATS is listed as follows

    i.   Two/three Pololu DC motor with Hall effect encoder
    ii.   Telemetry module (ATK-LORA-01)

iii. Plastic Gears
iv. Battery(12Volts,5Ampers)

4. TRACKING ALGORITHM

This is the computational procedure and rules designed to follow the movement or changes in the position of the target UAV over time. This computational procedure is the mathematical and logic rules usually done using a microprocessor which is present in the system using various input data (i.e., Latitude, Longitude, Azimuth position etc.).

This system makes use of two basic algorithms, one for the Azimuth and Elevation tracking (signal strength gradient) and the other for the GPS tracking of the UAV with respect to the GCS.

4.1 Signal Strength Gradient Tracking Algorithm

This method of tracking utilizes the Azimuth and Elevation variations in the radiation of the signal of the UAV and GCS antennae. Marching the Azimuth (horizontal axis, covering 360 degrees from North to South) and Elevation (vertical axis, covering 90 degrees from down to up) radiation gives a position for of the UAV that can be tracked.

Given:

S_i: Signal strength at antenna i.

Azimuth$_i$: Initial azimuth angle of antenna i in degrees.

Elevation$_i$: Initial elevation angle of antenna i in degrees.

Δ Azimuth: Angular spacing between antennae in azimuth

Δ Elevation: Angular spacing between antennae in elevation

i. Computation of Signal strength gradients:

$$\frac{\partial S}{\partial Azimuth}|_i \approx \frac{S_{i+1} - S_i}{\Delta Azimuth} \tag{12}$$

$$\frac{\partial S}{\partial Elevation}|_i \approx \frac{S_{i+1} - S_i}{\Delta Elevation} \tag{13}$$

These partial derivatives estimate rate of change of signal strength with respect to azimuth and elevation angles.

ii. Updating Antenna Orientation:

Adjust the azimuth and elevation angles of the receiving system based on the calculated gradients:

$$\text{New Azimuth}i = \text{Current Azimuth}i + \text{ Learning Rate} \times \frac{\partial S}{\partial Azimuth}|i \tag{14}$$

$$\text{New Elevation}i = \text{Current Elevation}i + \text{ Learning Rate} \times \frac{\partial S}{\partial Elevation}\big|_i \qquad (15)$$

4.2 GPS Tracking Algorithm

The input data from the GPS can also be used to track the UAV using a certain tracking algorithm which seems to be much simpler than that of the signal gradient tracking.

$$\Delta\varphi = \varphi_2 - \varphi c_1 \qquad (16)$$

$$y = sin\Delta\varphi * cos\phi_2 \qquad (17)$$

$$x = (cos\phi_1 * sin\phi_2) - (sin\phi_1 * cos\phi_2 * cos\Delta\varphi) \qquad (18)$$

$$\psi = tan^{-1}\left(\frac{y}{x}\right) \qquad (19)$$

Where φ_1 is Longitude of the GCS, φ_2 is the Longitude of the UAV, ϕ_1 is the Latitude of the GCS, ϕ_2 is the Latitude of the UAV, ψ is the angle formed in the azimuth plane that is the UAV's position relative to the North pole.

The distance (d) between the UAV and the GCS also needs to be calculated. Since the GCS and UAV positions on the Earth's surface are known, the distance between them is easy calculated as:

$$\Delta\phi = \phi_2 - \phi_1 \qquad (20)$$

$$d = cos^{-1}(sin\phi_1 * sin\phi_2 + cos\phi_1 * cos\phi_2 * cos\Delta\varphi) * R \qquad (21)$$

Where R is the average Radius of Earth (6.371×10^3m). The knowledge of the distance between them and their respective altitudes, gives the ability to calculate the pitch angle by using Equations (20) and (21).

$$\Delta h = h_2 - h_1 \qquad (22)$$

$$\theta = tan^{-1}\left(\frac{\Delta h}{d}\right) \qquad (23)$$

Where θ is the Pitch angle, h_1 is the Altitude of GCS, h_2 is the Altitude of the UAV. While the values of d are always positive, θ always in the range of -90º to +90º.

5. CONTROL ALGORITHM SELECTION AND SIMULATION

There are several subsystems that work hand-in-hand to ensure the successful operation of the ATS, potentiometers used at the input and output, a power amplifier, a preamplifier, a load and a motor. The position and orientation information of the antenna mounted on the ATS at any given time with respect to the UAV being tracked is made available to the system by a specified and designed input command. This information is then transformed to a form that the system can work with to make the necessary adjustment for proper alignment. This conversion is done by a

potentiometer transducer (encoders) as shown in Figure 4 which transforms it to a voltage signal.
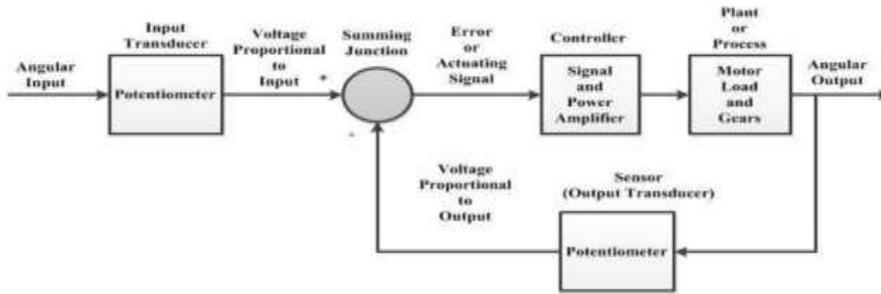

FIGURE 4. System design/makeup

From known standards the transfer function of this ATS model is given as

$$J_m = J_a + J_L(K_g)^2 = 0.3 \tag{24}$$

$$D_m = D_a + D_L(K_g)^2 = 0.02 \tag{25}$$

$$Gear\ Ratio\ Gain\ K_g = \frac{N1}{N2} = 0.1 \tag{26}$$

$$\frac{\theta_m(s)}{E_a(s)} = \frac{K_t/J_m R_a}{S(S + \frac{D_m R_a + K_b K_t}{J_m R_a})} \tag{27}$$

TABLE 2.
ATS Model Design Parameters

Parameters	Symbols	Values
Potentiometer Gain	K_{pot}	$1/\pi = 0.318$
Pre – Amplifier	K	100
Power Amplifier	K_1	100
Power Amplifier Constant	a	100
Motor and Loads Gain	K_m	2.083
Motor and Loads Gain Constant	a_m	1.71
Gear Gain Ratio	K_g	0.1
Number of Gears teeth of Motor 1	N1	25
Number of Gears teeth of Motor 2	N2	250
Moment of Inertia of armature	J_a	0.02
Moment of Inertia of load	J_L	1
Load Viscous Damping at	D_L	1
Armature Viscous Damping	D_M	0.01
Armature Resistance	R_a	8 Ω
Back EMF of the Motor	K_b	0.5 V-s/rad
Torque Constant of the Motor	K_t	0.5 N-m/A

Similarly, the transfer function of the Antenna control system from Figure 4, using the standard parameters given in Table V.1 is given by;

$$\frac{\theta_o(S)}{\theta_i(S)} = \frac{6.63K}{S^3 + 101.71S^2 + 171S + 6.63K} \tag{28}$$

5.1 Subjecting the ATS Model to a PID Control Algorithm

The ATS through a feedback loop (FIGURE 5), is continuously monitoring the input and the desired output signals. Depending on the type or level of steady-state error produced, the proportional, integral and derivative controls provide the necessary command actions to regulate and control the system to match output to the desired input whilst reducing the steady-state error to the barest minimum. Each part of the PID has specific function; the proportional part is used to change (increase mostly) the rate of the system response, the derivative part is used to produce a better transient behaviour of the response and the integral part eliminates steady-state error.
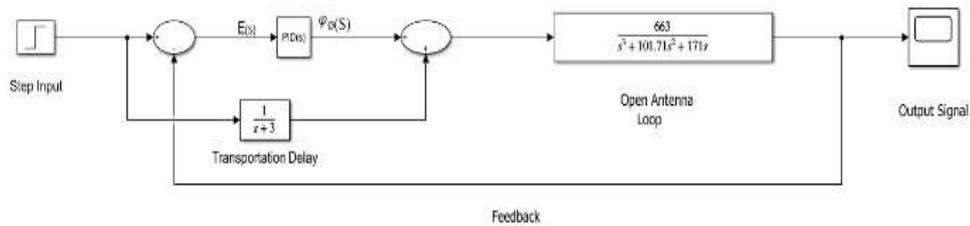
FIGURE 5. ATS Under PID Control

6. SIMULATION RESULTS

6.1 Subjecting the ATS Model to a PID Control Algorithm

Simulated radiation patterns illustrated the helical antenna's directional characteristics (Figure 6), with a peak gain of 13.2 dBi. The narrow beamwidth and consistent pattern shape across the desired frequency range confirmed the antenna's suitability for applications requiring focused and stable communication. The Simulated axial ratio and polarization measurements confirmed the helical antenna's ability to generate circular polarization with an axial ratio below 1.05dB.
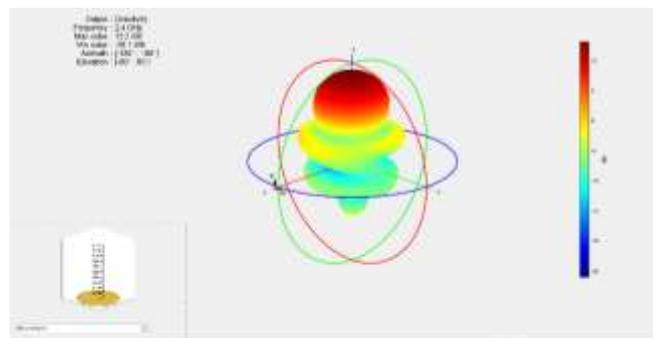

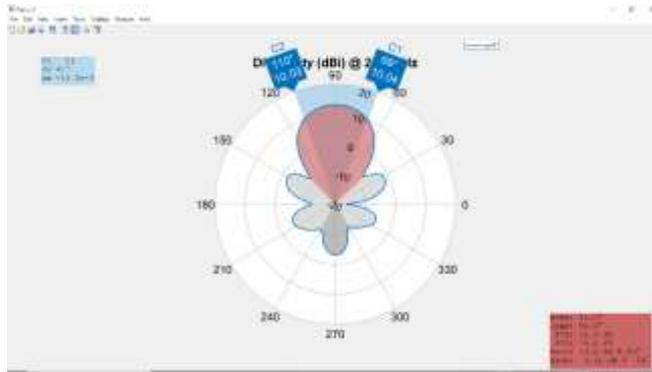FIGURE 6. 3D Radiation pattern of the Antenna

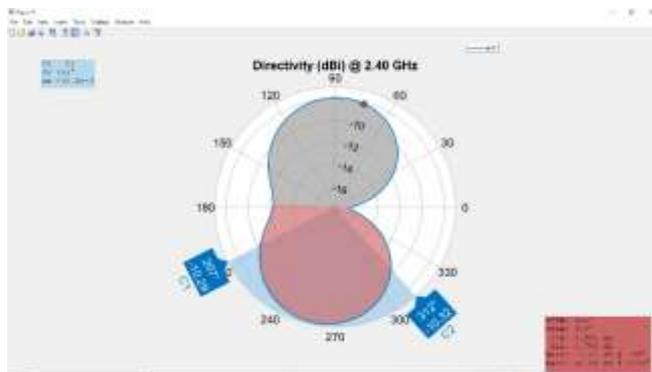FIGURE7. Elevation Radiation of the Antenna

FIGURE 8. Azimuth Radiation of the Antenna

Simulation results from the MATLAB Antenna Tool Box modelling software indicated precise adherence to the design parameters, providing confidence in the accuracy of the virtual representation.

6.2 GPS Integration and Position Accuracy

The integrated GPS module can successfully acquire and maintain satellite lock throughout the period of engagement. The Adafruit PA1616Smodule demonstrates reliable performance in diverse environmental conditions, providing real-time latitude, longitude, and altitude information with an accuracy of ±2 meters. This high accuracy is crucial for precise positioning in antenna tracking applications. The GPS-derived position information is seamlessly incorporated into the antenna tracking system's control algorithms. The tracking precision is significantly enhanced, with the system having the ability to continuously align the antenna to within 0.05 degrees of the target azimuth and elevation angles of the UAV.

6.3 Simulation of the ATS Model Transfer Function

The modelled ATS system when simulated without the control algorithm give the response shown in Figure 9. It has a peak amplitude of 1.346 that occurs after 1.276 seconds, has a relatively small steady state error and takes 4.958 seconds to be damped to the desired output. The system oscillates for a bit before coming to settle at an amplitude of 0.9877 for a step input of 1, having a steady-state error of 0.0123.
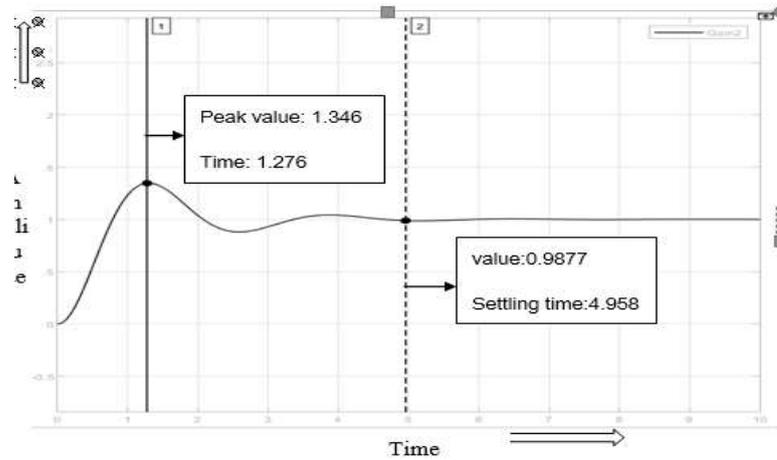
FIGURE 9. System response of the Transfer function

6.4 Simulation of the ATS Model Under Pid Control

The PID is introduced into the system with the initial values 1,1,0 respectively as shown in Figure 5. Using the MATLAB Simulink, the PID system is simulated and prior to its tunning, it causes an increase in the settling time, number of oscillations and Peak Amplitude being over 2. The system is unstable for a longer period as illustrated in Figure 9 The PID gains are tuned and gives 5.9971, 5.3682, and 1.5432 for the P, I, and D gain values respectively. The resulting response (Figure 10) gives an optimally performing system response with the smallest of response Amplitude, settling time and no steady-state error. The response moves from an amplitude of 1.204 to 1 the desired output in 2.654 seconds.
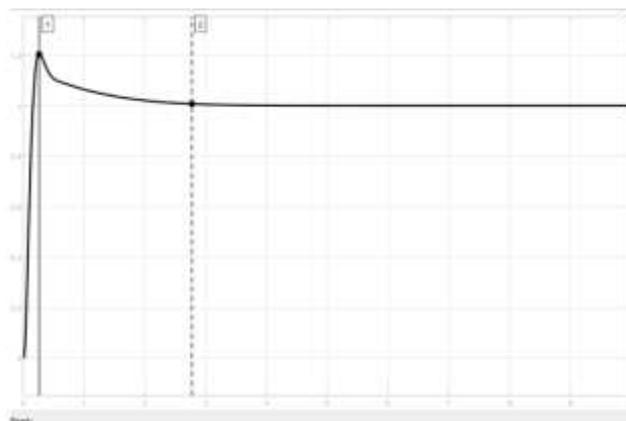

FIGURE 10. System response under a PID control Algorithm

7. CONCLUSION

The designed helical antenna showed good performance characteristics. The antenna was designed to be a directional antenna, and it had a good amount of

directivity gain in both the Azimuth and Elevation axes which affects the signal transmission and reception quality positively. The antenna had a low reflection ratio, which meant that more radiation was created towards the intended direction and therefore there was no need for the application of a reflector. The successful fusion of the antenna information (signal strength gradient for tracking), and GPS contributes to a holistic perception system, improving the system's reliability and adaptability. The information (latitude, longitude, time, heading etc.,) obtained from the GPS is easily applied using the simple but efficient tracking algorithm to give facilitate the tracking action of the ATS. The GPS module in its ability to connect to up to twenty-two (22) satellites at a time, reduces the possibility to lose track of the UAV as its able to always be connected to at least two satellites, even where GPS signals prove difficult to use or operate. PID control algorithm unlike just the proportional or derivative stand-alone controller algorithms, when simulated in the MATLAB Simulink, provided a better system control, reduced to a great level the peak amplitude, the settling time and give minimal steady-state error when the system encounters any form of disturbance (either internal or external).The ATS ability to maintain communication with the UAV even in the presence of signal interferences, and real-time adjustments contribute to its versatility in various operational scenarios.

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