STATIONARY ANTENNA TRACKER FOR UNMANNED VEHICLES

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Abstract - *As unmanned aerial and ground vehicles (UAVs and UGVs) are increasingly used in areas such as defense, research, and disaster response, having a robust and reliable communication link to ground control is more crucial than ever. Static antennas just won't fulfill the duty as they can't keep up with moving vehicles, resulting in lost signals, delays, and poor control.*

To address this, we built a smart, stationary antenna tracker (SAT) that tracks the vehicle's motion in real-time automatically. Our system takes GPS information and UAV or UGV telemetry to compute its precise position, then pivots a high-gain directional antenna directly towards the vehicle. The core of the system is a Pixhawk flight controller in conjunction with an Arduino UNO. They both drive servo motors that rotate the antenna smoothly in both the horizontal and vertical directions. We've also included a custom filter that disregards minor signal fluctuations generated by electrical noise which prevents the antenna from making unnecessary turns and keeps it locked on target.

This integration creates a much stronger, more consistent and focused signal, especially when the vehicle is travelling in undesired or challenging situations. This is a real-world solution which helps in real world applications like military operations, environmental monitoring, logistics, and beyond wherever dependable UAV/UGV communications are needed.

***Key Words*: UAV, UGV, Antenna Tracker, Pixhawk, Servo Motor, GPS, Telemetry, Autonomous Tracking.**

1. INTRODUCTION

Unmanned Ground Vehicles (UGVs) and Unmanned Aerial Vehicles (UAVs) are rapidly transforming how we defend, research, respond to disasters, and manage industry. Since they can access distant, hazardous, or inaccessible areas, they are ideally designed for use in surveillance, mapping, monitoring, and package delivery. Since autonomous vehicles now increasingly fill key mission functions, it has become crucial to their operation to be able to maintain secure, real-time communications with Ground Control Stations (GCS).

With a good communication link, however, things get progressively harder as the vehicles travel across broad or blocked terrain. Static antennas, while inexpensive and simple, are range-constrained and cannot dynamically follow a moving target. Therefore, they suffer from signal dropouts, weak transmission power, and high delay, especially when UAVs or UGVs move beyond the antenna range or make sharp turns within a very short time frame. Even operator-controlled directional antennas, while offering improved range and gain, need constant operator monitoring and are inefficient for high-speed or multi-vehicle operations.

To combat this, we used a Stationary Antenna Tracker (SAT), an intelligent, autonomous system actively following the trajectory of unmanned vehicles. SAT uses current GPS and telemetry coordinates to calculate vehicle position and drive a high-gain directional antenna using servo motors powered by a Pixhawk flight controller and Arduino UNO [2][3][4]. This allows unbroken line-of-sight (LOS) links even though the vehicle crosses complex terrain. Our SAT system can operate automatically and require no human adjustment, significantly improving tracking speed, signal stability, and communication reliability [5][7]. Its broad applications from defense operations to agricultural monitoring make it a key milestone in autonomous system communication development [6].

2. RELATED WORK & LITERATURE REVIEW

Having and keeping a strong link between ground stations and unmanned vehicles has been a challenge for years, particularly in dynamic operational environments. Various techniques have been debated over the years, from simple static antennas to more sophisticated autonomous tracking systems.

Static antennas are the simplest to use and are widely used in initial UAV communication systems because they are inexpensive and easy to use. Their fixed position, however, restricts their use significantly as UAVs or UGVs travel out of the line of sight of the antenna. Balanis [1] states that omnidirectional antennas radiate in all directions but possess a weak range and are also susceptible to interference and, therefore, are not ideal for use in applications like long range or mobile.

To counter this, manually controlled directional antennas were created. Directional antennas are more directional, have greater gain, and therefore a more powerful signal over a greater distance. However, their requirement for human control to position them [6] also comes with a set of issues. The requirement for operators to constantly monitor and reposition the antenna in relation to vehicle position is both time and error intensive especially when working with high-speed UAVs or multi-vehicle operations [2].

Semi-automatic tracking systems were the compromise. In these systems, telemetry data is manually fed into the tracking system to re-point the antenna direction. Although this is superior to static systems, the partial automation still introduces delays in response times and lower flexibility. For instance, Alemania and Huda [3] designed a bi quad antenna-based tracker that could track UAVs following a disaster, but had a 2–3 second delay in re-pointing the antenna direction.

Recent advancements have led to fully autonomous tracking systems where real-time GPS and telemetry data are used to dynamically and automatically adjust the antenna without the need for human intervention [6]. Nugroho and Dectaviansyah [7] proved a GPS-based Yagi-Uda antenna tracker with an average angular error of only 5.62° in azimuth. Riyandi et al. [5] further enhanced accuracy using fuzzy logic-based tuning to ensure stable tracking at vehicle speeds of up to 60 km/h. These systems offered the viability and importance of using smart control algorithms with real-time telemetry to ensure stable links over long distances.

We take the design of the SAT system one step further in our approach by integrating autonomous tracking [5][6][7] with real-time servo control and noise filtering to establish a stable, responsive, and low-latency communication link for a broad scope of unmanned vehicle applications.

3. SYSTEM DESIGN / METHODOLOGY

3.1 System Overview

The Stationary Antenna Tracker (SAT) system is intended to automatically point a directional antenna at an approaching unmanned vehicle to create an assured and uninterruptible communications link. The system is constructed on a modular architecture based on real-time GPS and telemetry information, rugged signal processing, and high-resolution motor control.

Central to the system is the Pixhawk v2.4.8 flight controller [2], which is provided with GPS coordinates and telemetry data from the UAV or UGV [3]. It is sent through a 433 MHz telemetry module and processed in real time. The Pixhawk determines the relative position and orientation of the vehicle with respect to the ground station and provides pulse-width modulation (PWM) signals for the target azimuth (horizontal angle) and elevation (vertical angle) of the antenna.

But PWM outputs from the Pixhawk in raw form can contain noise or jitter due to rapid vehicle position changes or electrical noise. To mitigate this, we inserted an Arduino UNO as a middleware processor. The Arduino takes the PWM input, removes the small, insignificant oscillations with a custom deadband filter, and converts the data to smooth servo motor control signals.

There are two MG995 servo motors used for mechanical motion of the antenna: panning (azimuth) and tilting (elevation). The servos are powered by a buck converter to provide safe and controlled voltage levels. This allows the system to switch antenna orientation continuously with low latency and high precision.

The overall configuration is scheduled, tracked, and visualized by utilizing the Mission Planner software that provides an interactive interface to the calibration, in-flight telemetry monitoring, and firmware integration using MAVLink protocol. This integration of hardware and software maintains the antenna in proper alignment with the UAV/UGV, no matter the high-speed and volatile motion.

3.2 Block Diagram

The functional flow of the system is illustrated in the following block diagram of the Antenna Tracker system. It highlights the coordination of the basic hardware modules and the data and power flow of the system.

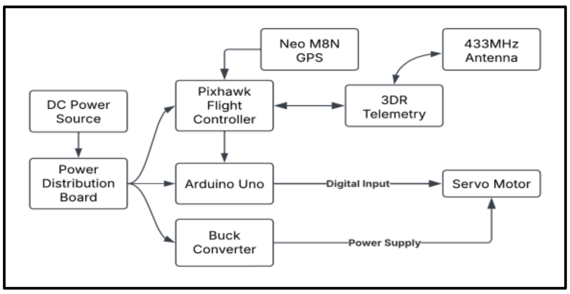

Fig 3.2.1 Block diagram of functional antenna tracker system

4. IMPLEMENTATION USING HARDWARE AND SOFTWARE

4.1 Hardware

The antenna tracker system is implemented using a set of pre-manufactured and custom modules that have been thoroughly tested for reliability, compatibility, and performance in real-time tracking situations.

1. **Power Source (4-cell 5200mAh LiPo Battery):** The system is powered by a 14.8V lithium-polymer battery, which has a high capacity for long operation. The power source is ideal for field applications where mobility and endurance are essential. The battery is input to a power distribution board, which feeds the necessary voltage rails to other subsystems.

2. **Pixhawk v2.4.8 Flight Controller:** Pixhawk is the primary controller for receiving the telemetry, processing GPS data, and issuing movement commands. The device features a 32-bit ARM Cortex-M4 processor operating at 168MHz, which provides real-time functionality and supports open-source firmware such as ArduPilot. The Main Output (PWM) pins on the Pixhawk are used to send servo control signals.

3. **MG995 High-Torque Servo Motor:** These servo motors [9] are used to change the antenna azimuth (and possibly elevation) angles. With the ability to provide 10–12 kg cm of torque and rotate 180°, the MG995 offers the power and responsiveness needed to drive directional antennas smoothly and precisely in outdoor environments.

4. **Arduino UNO (ATmega328P):** Arduino [5] acts as an intermediary between the Pixhawk and the servo motors. Arduino receives PWM signals from the Pixhawk, filters for noise with a deadband filter, scales the PWM signals into the motor's working range, and sends clean commands to the motor. All this filtering allows for smooth motion without jitter.

5. **Buck Converter:** To protect the servo motors from over-voltage, a buck converter drops the 14.8V supply to a secure level of 5–6V. This component provides stable power supply and avoids servo malfunctioning due to voltage spikes or drops.

6. **UBLOX NEO M8N GPS Module:** On the tracker, the Neo M8N captures satellite signals and delivers high-precision real-time coordinates. It features multi-GNSS capability (GPS, GLONASS, Galileo) to support quick satellite lock and better accuracy. The information is supplied to the Pixhawk to be used in calculation of orientation.

7. **433 MHz Telemetry Module with Antenna (3DR):** A long-distance telemetry system is used to provide a bi-directional communication path between the ground tracker and the UAV. The module operates in the 433 MHz frequency band and ensures telemetry data such as position, heading, and status are transmitted in real time in a reliable way. The provided high-gain antenna provides a greater signal reach and readability.

When combined, these elements produced an agile, powerful and extensible system, enabling it to operate reliably in dynamic environments where timely communications are essential.

4.2 Software Tools

A combination of open-source and purpose-built software tools were unified to run and integrate the antenna tracking system.

1. **ArduPilot Antenna Tracker Firmware (v1.1.0):** This firmware enables the Pixhawk to act as a tracker antenna. It captures GPS and telemetry information, calculates the required azimuth and elevation angles, and sends corresponding PWM signals. This release, published by the ArduPilot team in the year 2019, incorporates improvements in support for continuous rotation servos as well as in battery monitoring capabilities [1].

2. **Arduino IDE:** The Arduino UNO was programmed using the Arduino Integrated Development Environment (IDE), which is based on C/C++ semantics and allows simple uploading of control logic. A custom script was created that incorporates a deadband filter to eliminate low-level signal noise, preventing jerky servo motion. For smooth running and to achieve more accurate tracking, the deadband filter is now in its final form.

3. **Mission Planner (v1.3.80):** Mission Planner is an open-source software ground control station for Windows that configures and monitors Pixhawk-based systems. It was utilized during this project for loading firmware, calibrating, live tracking, and system diagnostics. This software has a built-in interface for MAVLink protocol that displays live UAV positioning, antenna orientation, and telemetry health and status of the system.

4. **Shapr3D (v5.830.8600.0):** Shapr3D was used to develop the physical body for the antenna tracker. The 3D-printed body was made using Hyper PLA. The design development was accomplished using Shapr3D software and was exported in STL format for 3D printing using Creality-brand 3D printers. The images of the 3D models designed in Shapr3D and the 3D printed tracker frame can be found below.

3D Models of Tracker Frame:

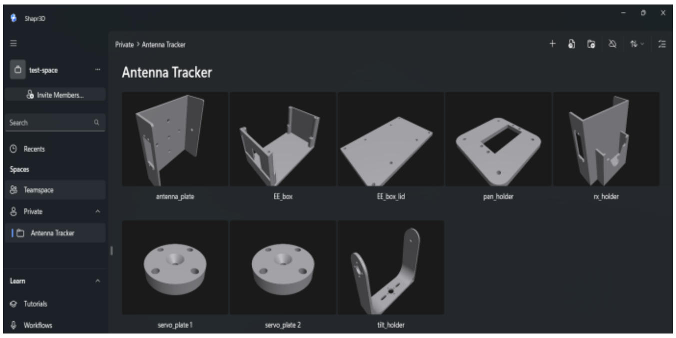

Fig 4.2.1 3D Components of Parts of the Tracker Frame

3D Printed Tracker Frame:

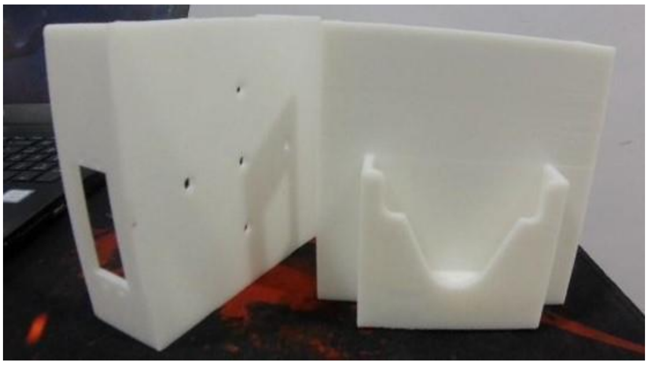

Fig 4.2.2 Printed Rx Holder and Antenna Plate

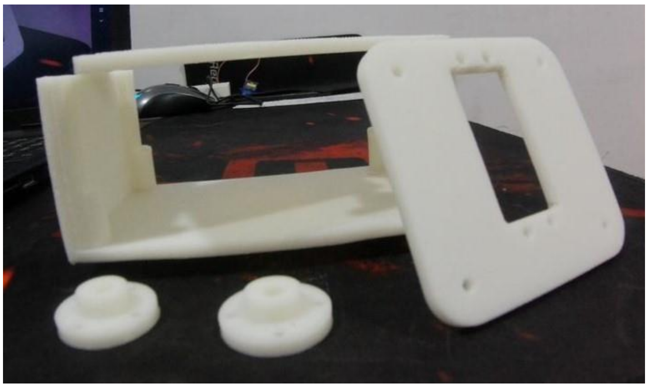

Fig 4.2.3 Printed EE Box, Pan Servo Holder, Servo Plates

These tools not only enabled strong firmware and hardware integration but also provided a solid interface for control and customization. Their open-source nature allows them to be readily updated, community-supported, and future-proofed, for example, the addition of multi-vehicle tracking or AI prediction models.

5. SIGNAL FILTERING & STABILITY ENHANCEMENT

5.1 Deadband Filter in Arduino

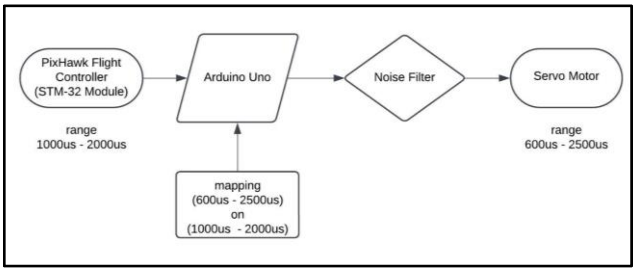

Fig 5.1.1: Block diagram of signal filtering and servo control process using Arduino UNO

One of the major difficulties with real-time servo-controlled systems is maintaining stable motor behavior in response to noisy signals. In the case of our antenna tracker, we use a Pixhawk flight controller, which transmits PWM (Pulse Width Modulation) signals to control the position of the directional antenna [5]. However, these signals are susceptible to rapid fluctuations caused by minor variations in telemetry or GPS data, as well as electrical noise. If left unfiltered, these fluctuations lead to small, unnecessary servo movements, also known as "jitter," which degrade the stability of antenna tracking.

In order to help mitigate this problem, we used a deadband filter using the Arduino UNO microcontroller. The purpose of this filter is to ignore smaller changes in input PWM values - in our case within a designated limit (e.g., ±4 units) - and allow only positive changes to pass through. This will stop the servo from reacting to every little change - hence the motion of the antenna will be smoother and the mechanical part will last longer.

The Arduino will take the PWM [5] input from the Pixhawk and compare it with the last value and only update the servo position if the difference is greater than the deadband range. This not only minimizes mechanical wear, but also enhances the responsiveness and accuracy of the tracker when the UAV or UGV actually turns.

Signal Flow & Mapping Logic

The control flow adheres to this sequence:

1. Pixhawk generates a PWM signal ranging from approximately 1000-2000 µs.

2. Arduino UNO captures the signal through a PWM capture library.

3. It passes the value to the deadband filter to see whether or not the change is substantial.

4. If significant, the value is mapped to a 0–180° range, suitable for servo control.

5. This value is converted to the MG995 servo motor used for the antenna movement.

6. RESULTS AND PERFORMANCE ANALYSIS

The Stationary Antenna Tracker (SAT) system that was planned was assessed for servo responsiveness, tracking stability, communication reliability, and future upgradeability. The testing was mainly qualitative due to limited availability of a higher degree of accuracy testing equipment, but the system performed satisfactorily in real-world applications typical for the system.

6.1 Mission Planner Visualizations [4]

The Mission Planner software was utilized as a live interface to monitor performance in real-time and validate the tracking performance. The software provided telemetry feedback in real-time, like UAV position and direction, signal level, and antenna direction. One could see the GPS position move as it responded to the headings, and there was an observable delay on the screen.

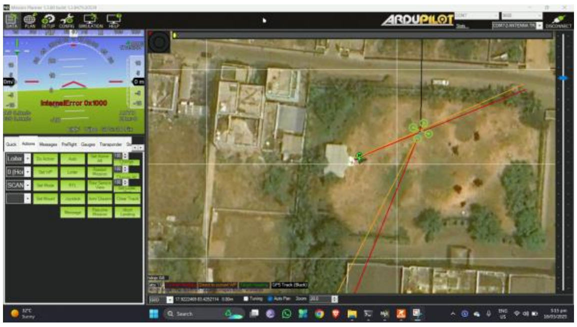

Fig 6.1.1 Tracker pointing the target at one end of the ground

Fig 6.1.2 Tracker pointing the target at another end of the ground

1. **Stability Tracking:** The system maintained a continuously aligned communication link with the moving UAV. Dynamically adjusting the azimuth of the antenna in real-time through GPS and telemetry inputs, the system was able to remove the signal dropouts typically encountered with static or manually aligned antennas. Incorporating a deadband filter within the Arduino UNO added yet another layer of smoothness, removing small jitter-induced movement and allowing the servo to operate smoothly.

2. **Servo Motion and Angular Accuracy:** The MG995 servo motor was seen to track UAV heading updates with an estimated average accuracy ±3° of azimuth. This accuracy is comparable to other similar systems described in the literature. Nugroho et al. [1] have achieved an average tracking error of 5.62° in azimuth using a Yagi-Uda antenna [7], thereby confirming the efficacy of our filtering and control logic. The servo movement was also very responsive and fluid when switching targets, plus deadband logic mitigated excessive movement due to small variations in the PWM signal. Overall, the antenna maintained a good lock on the UAV and caused little time lag or overshoot.

3. **Communication Range and Signal Reliability:** The high-gain omnidirectional antenna in the 433 MHz telemetry system ensured successful communication over a range of approximately 1–1.5 kilometers in an open environment. This would depend on interference and terrain but the omnidirectional antenna with a high-gain greatly reduced the chances of the signal getting weakened. This system in comparison to a simple omnidirectional system has an improved range and improved signal integrity.

4. **Response Time and Delay:** The system was able to process GPS inputs and control the direction of the antenna with minimal latency. End-to-end latency, from the reception of the new coordinates to servo adjustment, was typically below 200 milliseconds, which was sufficient for line-of-sight maintenance with most UAV applications. There were no cases of perceivable lag encountered at normal operating speeds.

5. **Scalability and Future Enhancements:** While the current iteration of the SAT system is designed to track one vehicle only, the SAT system is adaptable and scalable. With software-based switching logic or a multi-channel controller, the SAT system can be configured to track multiple UAVs or UGVs at once. Furthermore, there are expansive opportunities for the incorporation of predictive tracking models using AI because evidence shows these models would track the UAV's flight path using archival telemetry data and environmental variables that will allow for timely servo positioning and

confinement of the tracking latency. The results indicate the SAT system can be developed, optimized, and used as a practical and efficient system for real-time UAV communication tracking.

Following future re-engineering and improvements, the SAT system may be developed for more demanding applications such as multi-drone swarms or autonomous delivery systems in and out of obstacles, and ultimately to assist ground field monitoring purposes with UAV-UGV collaboration.

7. APPLICATIONS

The Stationary Antenna Tracker (SAT) system implemented in this project is generally applicable in the majority of industries with the requirement for extended, stable, and long-range communication with unmanned ground vehicles. With the capability to accurately track real-time UGVs and UAVs, the system enhances operational efficiency in both civilian and military uses.

7.1 Military and Surveillance Operations

In defense and tactical scenarios, prompt data transfer and situation perception are critical. SAT technology delivers faultless command centers to unmanned surveillance drone or ground robot connectivity, providing real-time connectivity. It enables round-the-clock video streaming, remote sensing, and live coordination, even in extreme or contested environments. The tracker provides a secure, two-way directive communication capability when loss of signal may compromise mission accomplishment for border monitoring or battlefield reconnaissance.

Illustration: Utilizing flying drones for survey border areas or UGVs across rugged terrain using covert operation mode.

Fig 7.1.1 UGVs monitoring terrain at border

7.2 Environmental Monitoring and Research

The research community commonly uses UAVs for analyzing climate trends, tracking animals, or undertaking geospatial studies in remote areas. Satellite-based (SAT) technology allows for continuous communication between a drone and ground station, which allows high-definition data to come in "live". An antenna link is essential if you want to avoid the risk of losing data in a long mission, when tracking animal movements, or changes in forest cover.

Illustration: UAVs gathering air quality data in mountainous areas, with the antenna tracker in sync even with environmental interference.

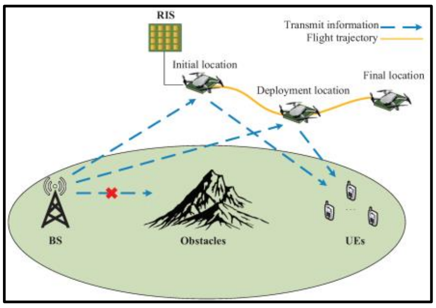

Fig 7.2.1 SAT-enabled antenna tracking UAV telemetry over obstructed terrain.

7.3 Precision Agriculture

In contemporary agriculture, UAVs are being increasingly employed to scan crop health, soil moisture, and irrigation regimes. The drones tend to traverse extensive areas of farmland, where fixed antennas are unable to provide coverage. Farmers can have good telemetry links across long stretches of land with the help of the SAT system, improving the reliability of UAV data and allowing for less human interaction in flight.

Example: Antenna-tracking drones flying above agricultural fields providing NDVI (Normalized Difference Vegetation Index) information to assess the crop condition.

Fig 7.3.1 SAT-enabled drones monitoring crop health using NDVI data over agricultural fields.

7.4. Disaster Response and Autonomous Logistics

UAVs are deployed on search and rescue operations, and in disaster zones to assess damage, aerial mapping, victim location; SAT ensures communication with these UAVs is real- time, allowing live feeds and rapid data transfer to rescue teams. Autonomous delivery drones used by logistics firms can also utilize the tracker to provide real-time telemetry connections along their delivery routes. Example: Disaster relief drones with live video over earthquake zones, or package-delivering UAVs over city streets with live ground comms.

In any of these situations, the SAT system is an important enabler of mission capability, data integrity, and operational security. With its plug-and-play functionality, and autonomous tracking, it has the potential to enable future upgrades such as AI-based trajectory prediction and tracking of multiple aircraft.

8. CONCLUSION

The Stationary Antenna Tracker (SAT) system developed in this project is efficient in offering low-cost, fault-resistant, and autonomous methods for unbroken communication with moving UAVs and UGVs. Through utilization of real-time GPS and telemetry data and implementation of a servo-controlled tracking system through Pixhawk and Arduino, the system ensures uninterrupted directional alignment among the moving unmanned vehicles and the ground antenna.

In comparison to conventional stationary or manually operated antenna systems, SAT very much improved reliability of signal, accuracy of signal positioning, range of operation, and functionality. Additionally, the deadband filter stabilizes operation by eliminating standard fluctuation or jitter of servo movement thus providing smooth and accurate tracking of the antenna while minimizing the impact of wear on mechanical hardware.

Since the system's modularity and extensibility provide room for any number of upgrades, many possibilities are laid ahead for the future. These include: a multi-UAV tracking capability through advanced telemetry switching or through coordination of a network, usage of AI technology for predictive control that can preemptively direct the antennas direction based on anticipated movement of vehicles, and solar power for increased endurance while operating away from a power supply.

In short, the SAT system bridges the performance and affordability gap in antenna tracking solutions, and has the potential to scale up to defense, research, agriculture, and disaster relief applications. Its practical application and upgradability potential are reasons why it is a highly promising platform for future development of autonomous tracking technology.

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10. BIOGRAPHIES

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