Development of active gimbal system for directional antenna on a small Remotely Piloted Aircraft (RPA)

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Abstract: This paper presents the design of an active gimbal system. The aim of this gimbal is to guide the direction of a directional antenna which is to be used on a small RPA. The system is supposed to be light weight and of high accuracy. Three different designs, which have one degree of freedom (DOF), two DOF and three DOF respectively, will be compared and discussed. An open loop control strategy will also be proposed.

1 INTRODUCTION

RPA is another name of Unmanned Aerial Vehicle (UAV). Communication system is one of the most important systems on a RPA. The performance of this system decides the maximum flight range and the adaptability in complex environment of the RPA. And in some specific missions, the information transmitted needs to be secured [1].

Advanced technologies on communication include Orthogonal Frequency-Division Multiplexing (OFDM), Active Phased Array Antenna (Smart Antenna), Multi-Input and Multi-Output (MIMO) topology and satellite repeater technology[2]. These technologies has improved the communication quality by reducing noise and interference and extended the communication range[3].

As for small RPA, typically defined as smaller than 2 kg, the “communication” often refers to the real-time video transmission (Figure 1). And for a platform in this level, the above technologies are not applicable because of their large size and heavy weight. Transmission power is another issue to be concern. The large commercial and military airplanes have the specific communication channel and frequency. Whereas for a small civil aircraft, for video transmission, only shared channels are available and the transmission power is limited by regulations (in UK, it is 10 mW for 2.4 GHz and 25 mW for 5.8 GHz)[4].

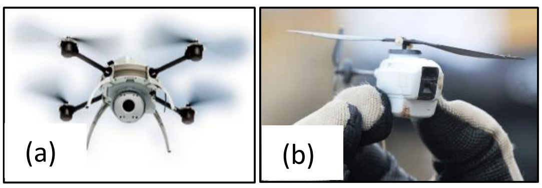


Figure 1. (a) The Datron Scout, 2 kg UAV (Courtesy of Datron World Communications). (b) The PD-100 Black Hornet 16 g nano air vehicle (Prox Dynamics)

Thus, on small RPAs, some other manners are normally taken to improve the communication quality. The most common way is to use higher frequency. This brings a lot of benefits, for example, wider bandwidth, higher bitrate, smaller size of RF devices, and a better data quality[5]. A circular polarized antenna is preferred other than the linear types. Similar as light, the received power varies with the angle between the microwave and receiver antenna. I.e. if the antenna is vertical linear polarized, the transmitted microwave is also vertical polarized, now if the receiver antenna is horizontal polarized, there is no power could be received[6] (Figure 2). Circular polarized antenna can naturally reject multipath effects[7], which makes it competitive on reducing noise and interference.

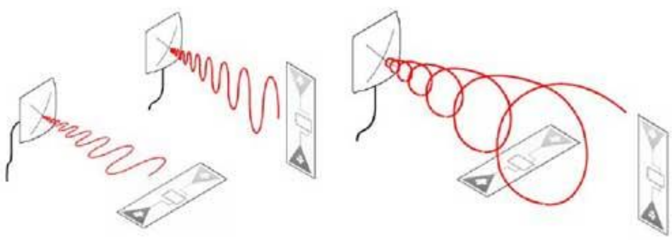


Figure 2. Illustration of linear and circular polarization. (www.ti.com)

Some hobby fans are clinging to challenging the farthest communication distance that their model plane and video transmission system could achieve. They choose to improve the ground station rather than make change to the aircraft. They choose to use super high gain directional antenna, high sensitivity receiver and directional tracker to receive the very weak signal (Figure 3). The world record now is 71 km with Skew Planar Wheel antenna on the transmitter, 850 mW power and 11 dBi helical antenna on the receiver[8].

Figure 3. Antenna tracker and ground station. (Circular Wireless)

Some people use multi antenna for a fixed wing to cancel the interference of the metal part of aircraft frame. Some people use multi transmitter in different frequency to avoid accident and interference[9]. The researchers from University of Tokyo has developed a communication system take advantage of the cellular phone network, thus you can make “video call” to the aircraft and proceed the mission. And the aircraft could be controlled anywhere beyond line of sight that is covered by the cellular network[10].

However, in all the applications above, the antenna used on the RPA tend to be of an omnidirectional type. This means that the radiation pattern is dispersed equally in all directions. RF range is therefore degraded and energy is wasted, leading to potential interception by foreign agents. A directional antenna has a radiation pattern that forms a beam in a certain direction, and on other directions, the signal is weak[11]. In this way, the power is consumed efficiently and the RF range could be increased.

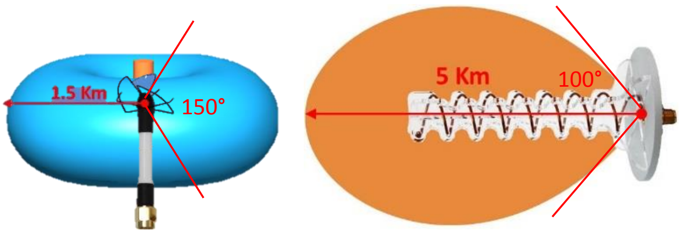


Figure 4. Radiation pattern and experience range for the two kinds of antennae. (fpvlab.com)

However, higher directivity means a narrower beam (Figure 4). To ensure the transmitter/ receiver (Tx/Rx) system matched properly when the UAV is moving around in the sky, the antenna should point at the right direction all the time. To achieve this, the radiation beam should be able to tile. The beam of antenna could be tilted electrically or mechanically. The former option is actually the smart antenna mentioned before. This kind of antennae are normally used for spacecraft and satellite[12]. The antenna itself could be miniaturized, but the matched active circuit for signal processing is also quite massive and hard to compress. Thus, the active gimbal system is introduced as a low-cost and efficient solution.

In Chapter 2, the concept design of the gimbal system would be described. The discussion of mechanical structure and control system would be presented. Chapter 3 introduced the implementation of the mechanical structure. Chapter 4 introduced the other subsystems. A discussion to the test results was given in Chapter 5 and Chapter 6 is the conclusion. Some left works are stated in Chapter 7.

2 CONCEPT DESIGN

The attitude of a RPA and its position relative to the ground station are changing all the time. They could be caused by wind gust or a mission required movement. As mentioned previously, the power transmitted is concentrating in a narrow beam. If this beam is not pointing to the receiver, the received power would be low. To ensure the directional antenna maintain the correct direction, there are some requirements to the structure and control system.

2.1 *Equipment and Operation Frequency Selection*

The movements of a RPA include 3 degree of freedom (3-DOF) planar movements and 3-DOF rotations around fixed axis. The RPA and the directional antenna is presented in two coordinate systems (Figure 5, 6).

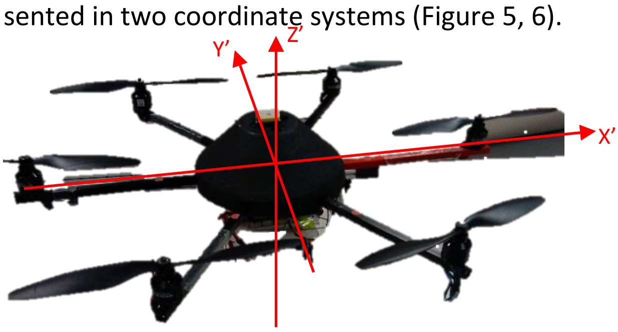


Figure 5. The coordinate system of the RPA (red arm point to the head direction).

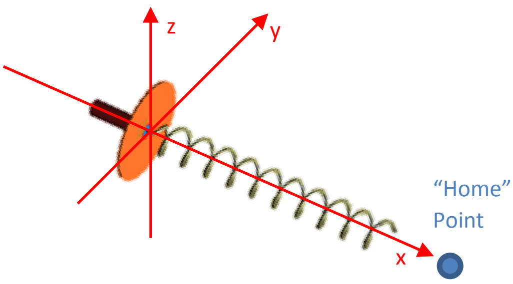


Figure 6. The coordinate system of the directional antenna.

2.1.1 *3-DOF system*

If the RPA stays stationary, the 3-DOF rotation can only be completely compensated by corresponding 3-DOF rotation: roll, yaw and pitch (Figure 7).

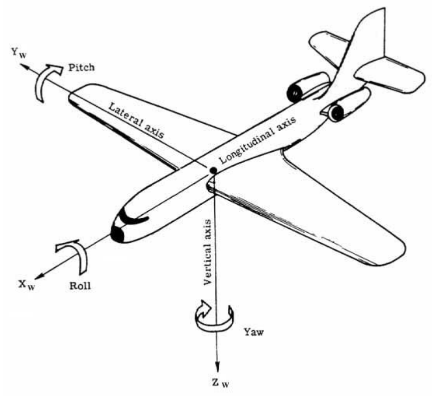


Figure 7. The conventional world coordinate system to describe aircraft attitude. (http://mtp.mjmahoney.net/www/notes/pointing/pointing.html)

For planar movements, the relative position of an object in a 3-dimensional space could be presented by polar coordinates form with two rotation (Figure 8). This is because the third parameter *r* is no longer necessarily fixed.

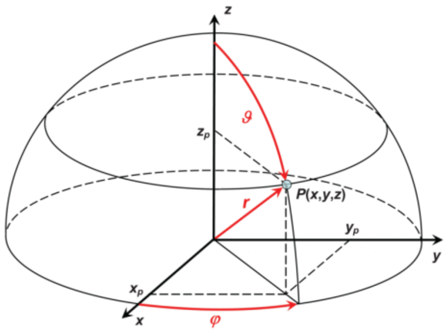


Figure 8. 3-D Polar coordinate system. (http://www.seos-project.eu/modules/laser-rs/laser-rs-c03-s01-p01.html)

The 3-DOF gimbal is then required. In reality, considering that when RPA is flying, all of its movement will cover a hemispherical area. Thus, except for the 360° rotation, 90° is enough for the other two rotation. (Figure 9)

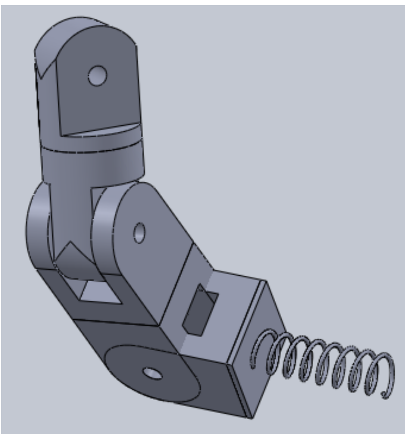


Figure 9. A schematic model in SolidWorks of the 3-DOF system.

2.1.2 *2-DOF system*

Considering the antenna, between the three rotations, there could be one that is around the central line through the antenna and the “home” point (axis x in Figure 6). This rotation changes the attitude of the antenna, but not the direction. This is related to the polarization type of antennae. So, if the transmitter antenna is linear polarized and already matched with the receiver antenna, the rotation along axis x will reduce the received power. Whereas if the antenna is circular polarized, there is no such problem. Then, the rotation of this DOF could be bypassed. And the two remaining rotations are good to compensate the planar movements. This is the concept of 2-DOF gimbal

2.1.3 *1-DOF system*

To make the structure even simpler, the concept of 1-DOF gimbal has been proposed. When a RPA is in its mission, if it is not acrobatic aircraft, the flight altitude is normally fixed. Then, only two DOF planar motion is left. For rotation, the rotation of the antenna around axis *y* (Figure 6) will still influence the direction of the antenna as the distance between the RPA and the ground station keeps changing. However, one fact is that, the further the distance, the smaller the angle of the antenna will change, and the attitude is near horizontality. This change follows the curve of the tangent of an angle. (Figure 10) The dramatic change happens when the RPA is close to the ground station. The uneven radiation makes antennae quite tolerant. In this area, even the transmitter antenna does not point to the receiver antenna directly, the transmission quality is possible to be good as well. Because of this, if make the antenna pitch angle θ fixed and select the constant angle carefully, the 1-DOF system could also ensure a good transmission quality all the way.

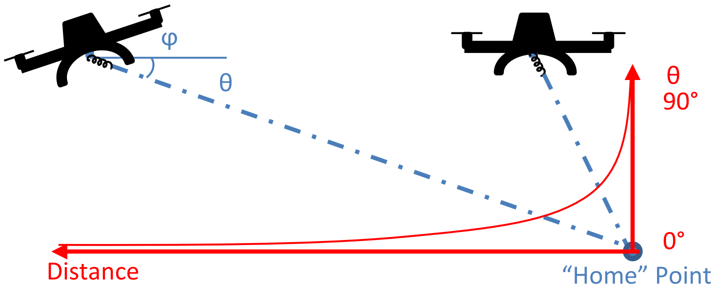


Figure 10. Antenna pitch around axis y.

2.2 *Control strategy*

A GPS module is used to supply position information (longitude, latitude and altitude), this will be used to calculate the planar movement. A 3-axial accelerometer & magnetometer is used to give information of attitude, this will be used to calculate the rotation. This is an open loop control. The calculated results will be two angles. One of them drives a servo to tilt a servo and the other drives a stepper motor. Servo could rotate accurately between two boundaries, normally the range of a servo is 200°. Stepper motor can rotate a step each time, a full circle normally contains 768 steps. So it can rotate continuously as well as be quite accurate

A “set home” button is installed. When it is pressed, the current position and head direction of the RPA will be recorded. The direction of the antenna should be pre-set to be coincident with the RPA’s head direction. Then, when RPA moves 10 m away from “home” point, the antenna starts to tilt and rotate. This is because the accuracy of the free GPS service is around 7.5 m (GPS.gov). At any time when the RPA is within 10 m to the “home”, the direction of antenna will be controlled to rotate back to the initial position (RPA’s head direction). This will help the stepper motor to start from a certain point and record the movements.

In the top view, if the original head direction of the RPA is along axis *X’* (Figure 5), the rotation angle of antenna around axis z (Figure 6) could be worked out (Figure 11). From GPS, the differences of longitude and latitude gives the expected rotation angle regarding position change. Take clockwise positive and add the two angles up, the angle to give to the stepper motor is got. For the rotation of the first servo, it is a sum of the RPA rotation angle ϕ around axis *y* and the angle ϑ caused by position and height (Figure 10). The last servo is only decided by the roll attitude of the RPA (Figure 12).

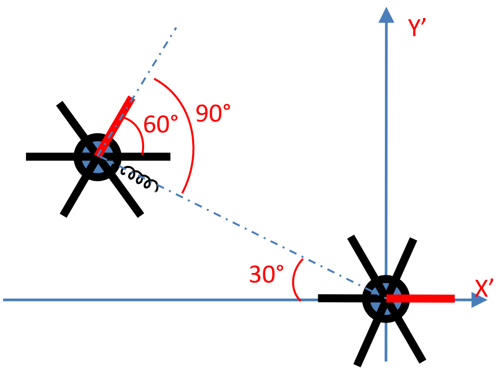


Figure 11. The relationship of angles on X'-Y' plane.

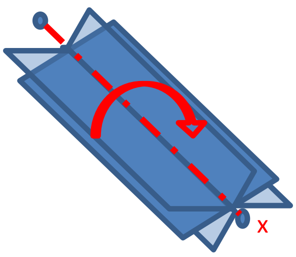


Figure 12. The roll of antenna.

3 MECHANICAL STRUCTURE DESIGN AND MANUFACTURE

Because a circular polarized directional spiral antenna has been selected for the RPA. According to the theoretical analysis, the 3-DOF gimbal system has not been manufactured. The built-up system has 2-DOF, and it could be used as 1-DOF system with different codes.

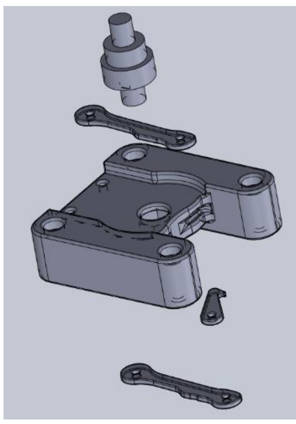
All the existing components are modelled by a software SolidWorks. Then the design is proceeding with SolidWorks. The shape and position of designed parts are based on the relationship to existing components. At last, the parts are saved as **.cmd* 3D printer layer file and **.dxf* laser cutter path file.

3.1 *360° rotation platf]orm*

This platform has to be placed at the bottom. To rotate the platform continuously, a slip ring is required. The signal to the antenna is analogue in ultra-high frequency (UHF), 5.8 GHz. While if any tilt platform is below this platform, the cable for servo should also be replaced by slip ring. However, a servo cable include two DC power wires and a digital pulse control wire. It is better not to share so different signals in one slip ring. Thus, the RJS-A8A8 Rotary Joint with SMA connectors has been selected as the slip ring (Figure13).

Figure 13. The rotary SMA connector. (www.jyebao.com.tw)

A base and lock system has been designed and manufactured to hold and lock the slip ring. Because the whole weight of antenna and gear is hang on this connector, it is supposed to be firm and tight. The base is 3D printed and the locker arms are laser cut (Figure 14).



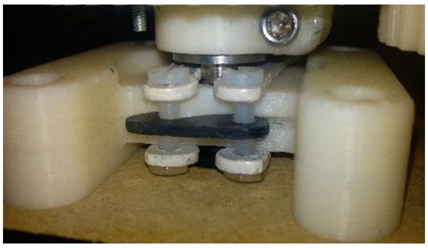


Figure 14. The models and assembled parts of the connector base and locker.

The stepper motor 28BYJ-48 drives the antenna via a pair of 1:1 gears (Figure 15). There are no mounting holes on the stepper motor, so two layer of boards are stick together to hold it. The stepper is adhered onto the second layer.

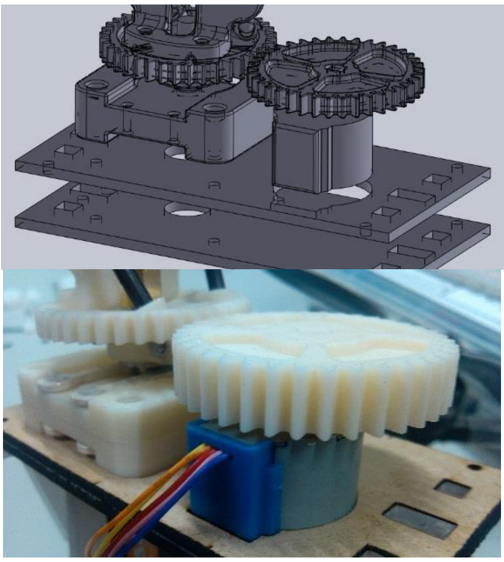


Figure 15. Models and assembled components of stepper motor and gears.

The antenna Circular Wireless HELIAXIAL58 has mounted with a small pitch angle, 3.58°, to the horizon plane (Figure 16). This angle is estimated from a spreadsheet which considered the specific data-link and fly condition for 1-DOF system (Table 1). In the spreadsheet, the received power is calculated by Friis Transmission Equation[6] (Equation 1). It is varying according to the distance and the Tx gain. The Tx gain is changing according to the radiation pattern of the antenna (Figure 17). With the estimated received power, combined with the sensitivity of the receiver, it could be seen whether the signal is received or not on a specific distance.

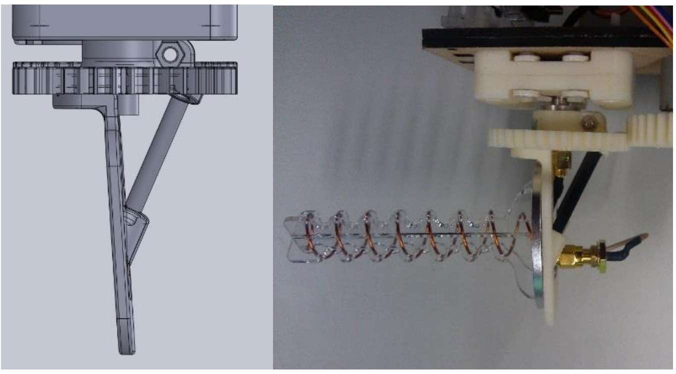


Figure 16. The models and assembled components of the antenna and the mounting board.

Table 1. TX/RX and Operation Frequency Selection

Tx Gain (dBi)	Rx Gain (dBi)	Tx Power (mW)	Tx Frequency (GHz)	Flight Heigh t (m)	Mission Maximum Range (m)
12	10.5	25	5.74	100	3000

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2} \quad (1)$$

In which, P_T, P_R are transmitted and received power.
G_T, G_R are the gain of Tx and Rx antennae.
λ is the wavelength of the microwave.
And R is the distance between Tx and Rx.

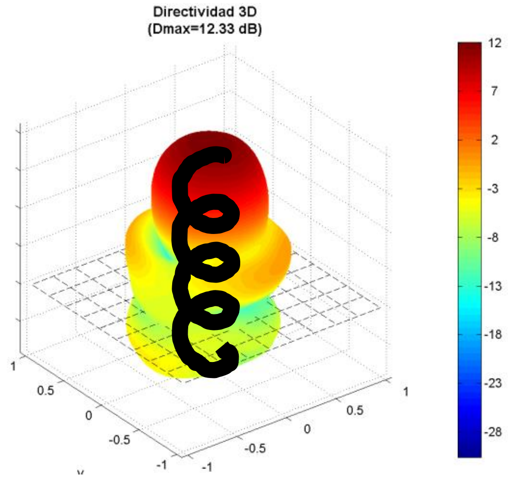


Figure 17. Radiation pattern of the helical antenna. The gain varies with the angle. (Circular Wireless.com)

To reduce the burden of the tilt servo, the components of this platform are better to be light weight. Thus the platform boards are cut by Medium Density Fibreboard (MDF).

3.2 *90° tilt platform*

A digital servo SAVOX SC-1268SG was selected for this platform. The torque is @6.0v 13 kg-cm.

The servo axis is coincident with the tilt axis. One support beam of the 360° platform is connected the servo arm, the other is mounted on a bearing. (Figure 18)

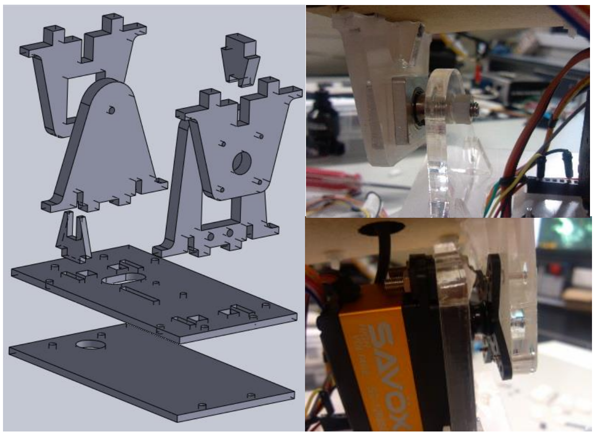


Figure 18. The models and assembled components of the tilt platform.

The components are laser cut and mortised, mortised structure makes the platform more stable and firm.

Since this platform is hang on the RPA frame and has load of the weight of 360° platform, the components are better to be light on the premise of enough strength. Here Acrylic has been selected as the material.

3.3 *Controller platform*

Since the accelerometer needs to be accurately at the centre of the RPA and point to the head position, and the rest space is not enough for the controller board, they are therefore placed separately on two boards. All other modules are also placed on the same board of accelerometer in order to save space for the controller.

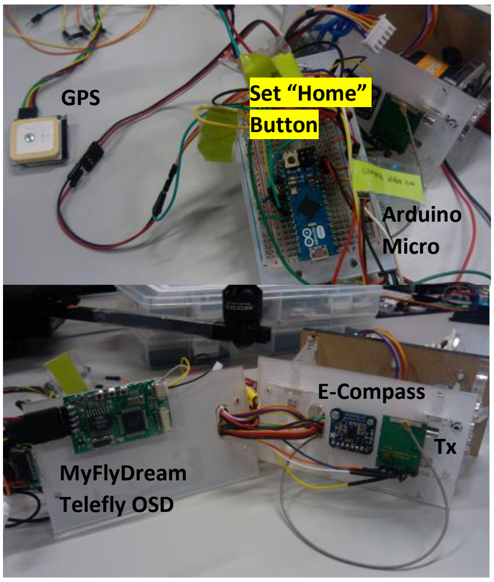


Figure 19. The controller platform.

4 SUBSYSTEMS

Except for the mechanical structure, the system also include the control system and an entire video transmission system.

4.1 *Control System*

An Arduino Micro Controller Board was used for the control system (Figure 19). The LSM303 E-COMPASS is a matching product to this Arduino development board and is supported by the library. With pre-defined functions, this sensor is quite easy to use. The U-Blox 5Hz GPS module is not a matching product. It uses the standard NMEA code. A program is written to parse the codes. A button was used to "set home" (Figure19). The control pins of the servo and the stepper motor is connected to the board.

The open loop control program has been written. The servo and stepper motor has their own internal feedback loop to ensure the accurate positioning. But there is no feedback to correct the GPS data and accelerometer readings.

4.2 *Communication System*

The communication system include the following components (Figure 20) and the flow chart (Figure 21) shows how the system work.

- *2G NANO 520TVL CAMERA*
- MyFlyDream Telefly On Screen Display (OSD)
- Tx: Airwave Wireless Transmitter Module AWM661TX 7CH 5.8 GHz 25mW 11g
- Airwave Receiver *7CH 5.8GHz*
- 4.3" TFT LCD Car Rear-view Monitor Screen
- MyFlyDream Autonomous Antenna Tracker (AAT)
- MyFlyDream AATDriver

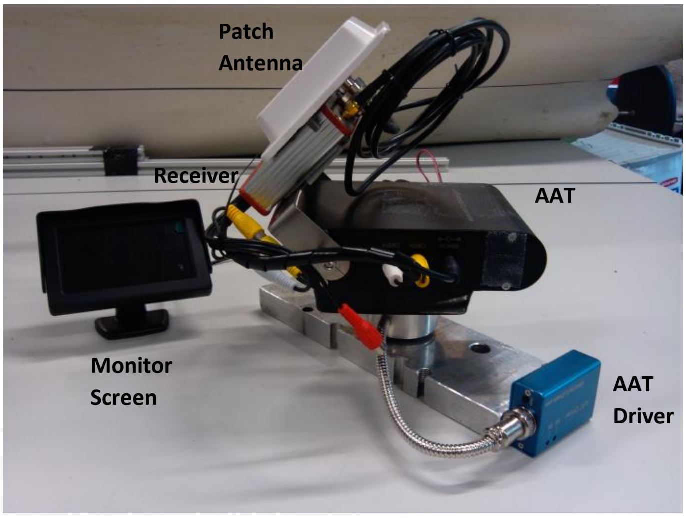


Figure 20. The ground station.

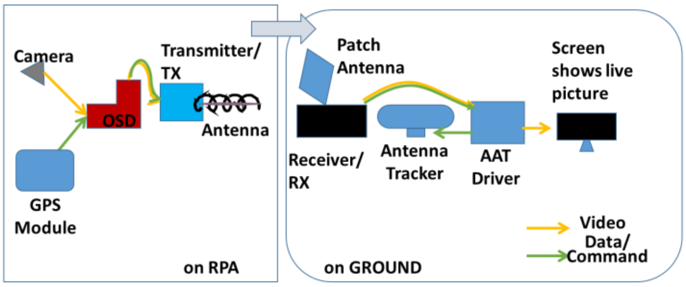


Figure 21. Communication system connection.

There are two path of data. The video signal is generated by the camera, go through the OSD, transmitted via the video channel, then pass the AAT driver and get to the monitor. The GPS data is collected by the GPS module, it also goes through the OSD, then is transmitted via the audio channel. When it is received and pushed to the AAT driver, the position will be calculated and a command will be generated to driver the antenna tracker.

4.3 *RPA Platform*

This is a commercial platform, Mikrokopter. It has an autopilot and central distributed speed controllers. The Pure mass without payload is 1.2 kg. The maximum payload is 1 kg. (Figure 22)

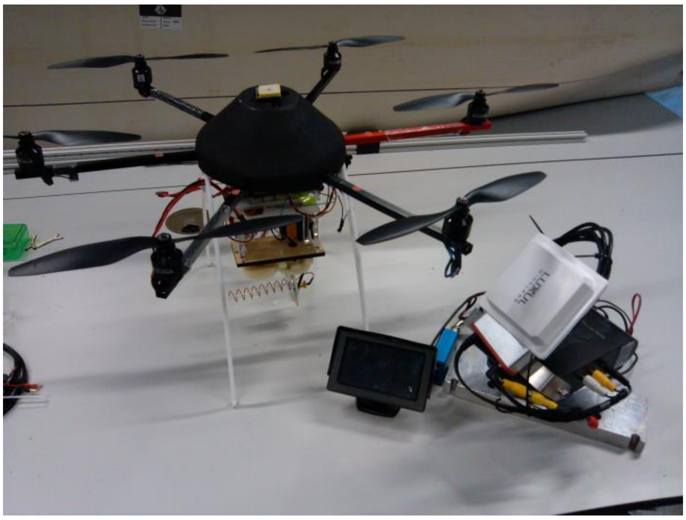


Figure 22. Picture of the whole system.

5 TEST AND ANALYSIS

The gimbal system has been installed to the RPA. Some tests has been operated including mass measurement, components functionality and control system test.

5.1 *Mass*

The physical features of the system has been measured. (Table 2)

Table 2. TX/RX and Operation Frequency Selection

Position	Fnctionality	Mass (g)
Bottom Layer	360° Rotation	170
Second Layer	90° Tilt	190
Top layer	Controller Board	140
Total mass		500
Total height		260 mm

The bottom layer is the rotation platform. Since use stronger material and strong servo, the second layer is heavier in order to hold and tilt the bottom layer. If there would be a third layer, in order to tilt the previous two layers, it could be expected that the servo needs to be even larger, which will make this layer heavier.

Considering that the third layer actually has no benefit since it is much easier to use a circular polarized antenna, so the 3-DOF system is not recommended.

For 1-DOF and 2-DOF systems, it is compromises. The selection depends on specific requirements of the missions. 2-DOF system is larger and heavier, more power consuming, but it gives a better accuracy in near "home" area. And for normal missions such as target observation and routed surveillance, the 1-DOF system is enough.

5.2 *Control*

In separate tests, each components works well independently. The data from GPS and accelerometer is examined. The servo and stepper motor can rotate the right angle as commanded.

The fly test is still not operated since there was no suitable place and chance. Thus, the impact of GPS could not be tested. However, when randomly move the RPA at a fixed point, the antenna successfully tracked the "home" point.

6 CONCLUSION

This paper described the design process and implementation of an active gimbal system for guiding the directional antenna on small RPA. The completed gimbal system is combined by mechanical structure and control system. The mechanical design is light weight and satisfactory to all the movement requirements. While all the modules of the control system can work properly. It is seen that this system has the capability of being a low-cost solution to improve the communication of small RPSs.

7 FUTURE WORK

There are still some works left before the active gimbal system get to a standard of being suitable for practical applications.

- The searching for smaller directional circular polarized antenna will be continued.
- The design of the platforms could be lighter and more compact, especially the size along z' axis.
- Lighter and stronger material will be searched as a replacement to currently used materials.
- A more stable landing gear is required by the RPA.
- A neat and tidy PCB board is required to rearrange the connection between the connector and other modules.
- A fly test is required to verify the functioning capability of the whole system.
- More accurate positioning technology with easy access will be searched other than GPS service.

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