Development of Autonomous UAV Systems for Low Light Surveillance Applications Using Night Vision Camera

[1*]Swee King Phang, Muhammad Ali-Adi Hassan, Zhin Yue Wong, Zhi Yuan Ng, Yen Ling Lai

School of Engineering, Taylor's University
1 Jalan Taylor's, 47500, Subang Jaya, Selangor, Malaysia

Abstract-This paper describes the development of an autonomous UAV that could contribute to a better, safer and a much-advanced security surveillance system. The UAV in quad-copter form is installed with a night vision camera for low light surveillance applications, while embedded with high performance flight controller. Real-time image processing and live video streaming is powered up by a Raspberry Pi Module, and the resulting bird-eye view of the surveying system can be monitored through the ground station. The UAV is first designed through 3D rendering software SolidWorks, and then fabricated through additive and subtractive manufacturing technologies. The flight controller of the UAV is designed based on mathematical model identified with first principle. The results of the surveying system and the robustness of the UAV has been verified through extensive flight tests that have been done at an open area.

Keywords: UAV, Flight Control, Surveillance

1 Introduction

Unmanned Aerial Vehicle (UAV) or widely known as drone, is a flying petite robotic invention that could be piloted manually via transmitter or autonomously via flight control software. Despite being small, UAVs are more often to be equipped with information gathering sensors to assist users with different kind of purposes such as surveying or image and object scanning [1], search-and-rescue missions [2] and many more. The rapid development of UAV technology has grabbed attention from the industries on how they are able to supersede conventional commercial types of surveillance system [3]. Currently, surveillance system on UAVs are mostly used either for personal or business related such as photography, videography and delivery services [4].

Nowadays, surveillance is a common operation in many industries and offices to record down critic areas in facilities to avoid accident happen. The operation consists of observing, identifying, recording, tracing and tracking the surroundings and convert it into useful data [5]. The traditional surveillance system that commonly employed by industrial site are patrols and closed-circuit television camera (CCTV) that proctored by using a centralized remote monitoring facility. CCTV often required a well-developed integrated system to operate so that every video recorded by different CCTV can be viewed by security guard and response accordingly [6]. The turnover rate of patrols and the cost of hiring patrols annually have troubled the industrial site. Not only that, with the application of CCTVs, in the same time it represents that substantial investment in video cameras are required in order to scout and cover all critical areas of industrial site [7]. The cost of maintenance fee on CCTVs cannot be overlooked too when it is combined with the cost of hiring patrols.

Besides that, false alarm as well as missed condition which are the limitations of conventional surveillance system will both caused inefficiency in cost and time to industrial company and police departments [8]. Therefore, a method of utilizing UAVs on surveying facilities is suggested and explained. A planned path which cover critical areas of facilities by setting multiple waypoints that are realized by using global position tracking (GPS) module has been uploaded to UAVs [9]. The drone is navigated by the pre-set waypoints and executed its mission by surveying around the industrial area. There is usually a camera attached on the drone to perform the surveillance function [10].

With the camera mounted and SD card built in on the on-board processor, not only the live streaming function can be performed, the live streaming video will also be saved and stored in SD card so that it can easily be retrieved and extracted out using ground station [11]. Once the path is decided by user, the UAV will operate autonomously. Once intrusion is detected at the facility, it can be switched to manual control mode which enable

*Corresponding Author: Swee King Phang,Email id : Sweeking.Phang@taylors.edu.my Article History:
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user take control on the UAV to stay on the intrusion spot providing feedback to relevant department until incident occurred is evaluated and solved.

When UAV surveillance compared to traditional surveillance system that used by industrial site, it is found that UAV surveillance is more cost efficient because it reduces manpower demand. Moreover, with the utilization of capability of the UAV which is air-borne, it can provide better coverage in terms of critic area surveyed compared to using CCTVs installed. Wastage of money and time due to false alarm and missed conditions can be reduced by using drone surveillance system as it can provide real time information to prepare relevant department act against incident happened.

In this manuscript, development of an autonomous UAV surveillance system will be discussed and documented. Besides the Introduction, Section 2shows the UAV platform design which includes mechanical and electronic design. Section 3 details the camera subsystems that will be attached to the UAV for live-feed of surveillance images to ground station. UAV mathematical model and flight controller design will be discussed in Section 4, while flight trials results will be discussed in Section 5 followed by concluding remarks in Section 6.

2 UAV Design

In this section, detail design on the proposed UAV system for autonomous surveillance application will be discussed. It is divided into two subsections, first the electronics component selections and integration, then the mechanical design of the UAV's fuselage.

2.1 Electronics Integration

Fig. 1 shows the overview integration of the electronics for the proposed UAV design. According to the figure, a 4 cells LiPo battery will be connected to a power module with a built in 12 V and 5 V voltage regulators. The 12 V voltage will provide power to the camera subsystems which include a microprocessor, a gimbal and an IR camera, whereas the 5 V voltage will provide power to the flight controller, telemetry units and RF receiver. The detail selection criteria for the peripheral components will be shown next.

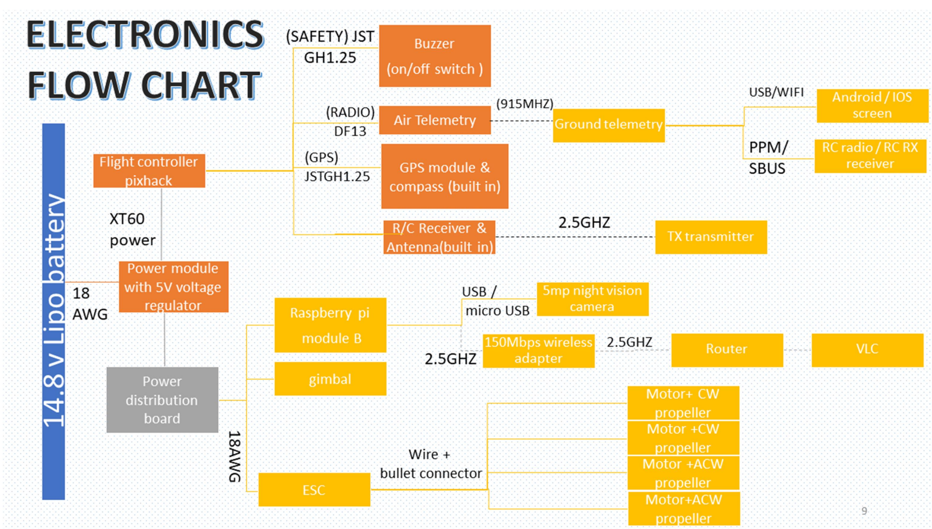

Figure 1: Overview on UAV electronics integration

2.1.1 Flight Controller

Pixhawk 32-bit Flight Controller was selected as the primary processor for the implementation of flight control algorithm. It is an open source program to provide variety of functions which the operating procedure is based on PX4 structure. It has built in gyroscopic sensors, accelerometers, barometer and magnetometers, which are crucial for flight control. It can provide up to 8 PWM output ports which are sufficient for the proposed UAV in this work. It is light (15.8 g) and small (44 × 84 × 12 mm) to be easily carried by the UAV of any sizes.

2.1.2 Propulsion System

Propulsion system consists of the electronic speed controller (ESC), T1045 polymer self-tightening propellers, and AIR2216KV880 brushless motors. ESCs are used to control the speed, direction and braking of the brushless motor. Propellers are attached on the motor which the blades will spin in or-der to push the air down so that thrust is created. Two of the motors will spin clockwise direction whereas another two will spin in anticlockwise direction in order to obtain four degree-of-freedom movement (mathematical derivation will be shown in Section 4. Brushless DC motors and self-tightening propellers are used as it produces high efficiency, high torque and can be easily mounted to the drone. On the other hand, ESCs are used to control the motor speed by sending PWM signals to the motors. Change in motor speed will contribute to different kind of motions and movements of the UAV [12].

2.1.3 GPS Module

UBLOX Neo M8N GPS module measures the drone location by feedback from the satellite signals. It shows the drone longitude, latitude and elevation points, and is crucial for autonomous drone navigation. The GPS module is selected on the criteria of how quick it can search for satellite, where in this model, it requires merely 10 s to find at least six satellite in open space. It also includes a built-in compass, which measures the heading direction of the UAV more accurately than the sensor provided in the flight controller mentioned above.

2.1.4 Battery

4000 mAh 14.8V 4S Li-Po battery supply power to all the electronics components of the drone. The total power of each components was calculated from its respective information of voltage supplied and current. All the power consumed by the components were summed up to a total of 230.85 W. By using the calculated total power consumed and the total voltage supplied, the current drawn from the battery can then be calculated as 15.6 A, where it is then converted to 15.4 minutes of theoretical flight endurance using a4000 mAh battery.

2.2 UAV Fuselage Design

In general, for multi-rotor UAV, especially quad-copter, the center hub should support all the necessities while the X-shaped arms are extended outwards to support the propulsion system. This design is desired as the center of gravity can be maintained to be within the center of the UAV. With this concept in mind, a fuselage for the proposed UAV was designed and simulated using a 3D rendering software, SolidWorks. The overall design of the platform can be seen in Fig. 2.

The size of the drone is 37 cm across the lateral direction, and 31 cm along the forward axis, as shown in Fig. 3. The fuselage will be constructed with carbon fiber sheet as the material is rigid and not easy to be bend when force is applied on it. Despite having strong characteristics, carbon fibers are lightweight. Thus, it contributes to good flight thrust-to-weight ratio. The rotor was placed in X-shaped frame due to the reason that the frame will give less blockage to the camera view. A landing skid will also be included on the UAV. This will support the overall weight of the UAV besides absorbing the landing impact. It will also protect the UAV body and the propellers from directly touching the ground when landing or taking-off. Flight controller is installed on a layer of Kyosho Zeal sheet for good vibration isolation. With higher compression set, Kyosho Zeal sheet will drastically decrease the vibration on the flight controller during flight and landing respectively [13].

The UAV was fabricated according to the design in SolidWorks. A complete UAV platform with all peripheral components connected can be visualized in Fig. 5.

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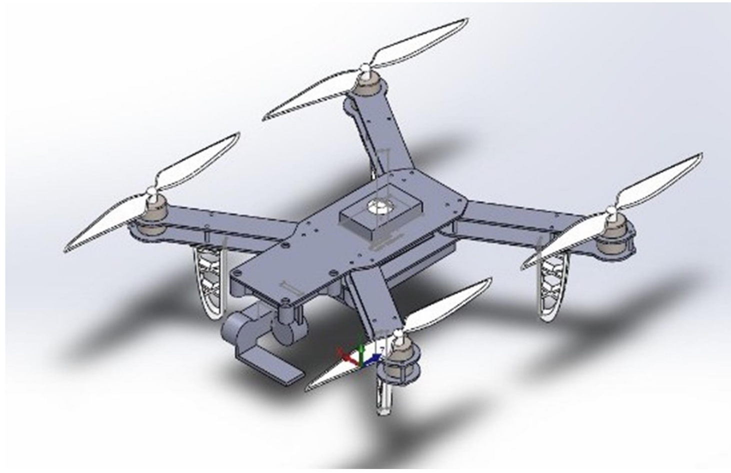

Figure 2: Designed UAV in SolidWorks software

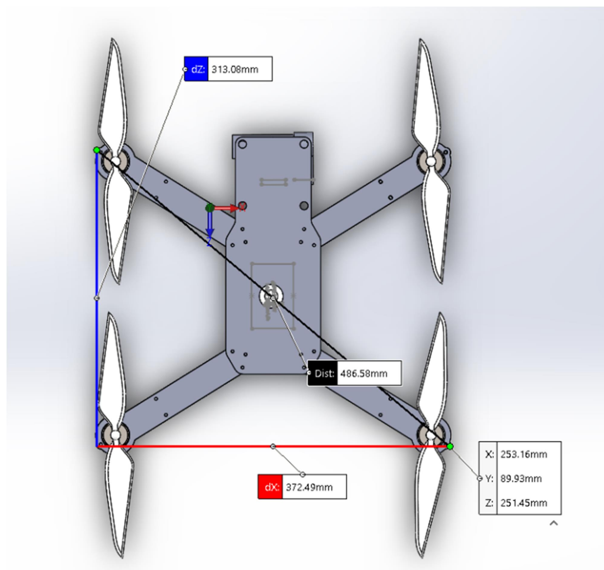

Figure 3: Top view of the UAV with its dimensions

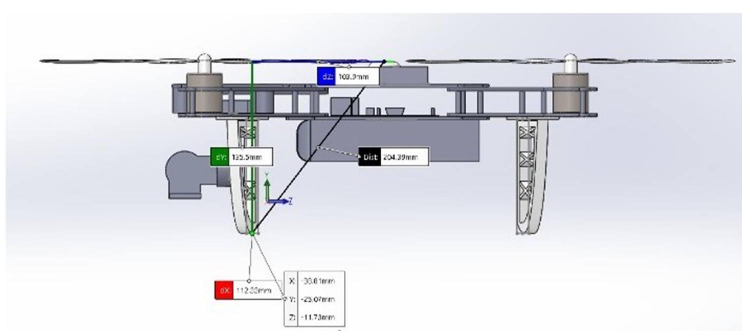

Figure 4: Side view of the UAV with its height dimensions

Figure 5: Fabricated UAV with full on-board systems

3 Camera Surveillance System

Site surveying operation is a daily task that must be done at all time, from daylight to night time. As a security or surveillance camera system, functioning by taking clear images even in low light conditions is very important. Fora UAV to totally replace patrols or CCTV, night vision camera is installed to the UAV so that it could visualize and operate at any light density without affecting the image quality. The camera comes with infrared sensors, that detects the radiation from the surroundings. The lens will transmit light to the sensor and covert it to electronic signal, which it is then create images out of it and analyzed to show the image on the video monitor [14]. Equip-ping IR technologies in the surveillance system in low-light applications will be very useful to optimize the quality of the video recorded.

In surveillance system, the vision of the camera is clear and vivid to ensure the survey operation is done without having its vision quality affected. As the UAV vibrates and moves constantly during flight, DJI Phantom 3 FPV 2-axis gimbal is installed to the drone so that the camera is always in static position and orientation. Flight controller will indicate the current position of the UAV and the gimbal will counteract the motion to ensure that the camera remains stable. This phenomenon occurs due to the independent characteristic between the gimbal angles and the aircraft attitude that causes it to be continuously adjustable [15].

To process images then sending it to the ground station, a Raspberry Pi embedded computer was utilized as the on-board processor. In the design, the Raspberry Pi was programmed to send live feed video to the ground station. While streaming on-line, the video is also recorded and saved into raw h264 file, that was then converted to mp4 file for ease of viewing and sharing. To improve the communication range between the UAV camera subsystem and the ground station, a high-powered router was place near the ground station. A field experiment was carried out to identify the true range of the communication, and it is found to be at least 110 m on the ground as shown in Fig. 6. It is believed that the distance will increase drastically while the UAV is airborne due to the lack of obstacles between the UAV and the router.

Besides the range, a latency test was carried out to identify the latency of the transmission. The tested latency for the live feed video streaming is about 0.2 s as shown in Fig. 7. A screenshot of the 1080p HD video as seen on the ground station while the UAV is flying can be seen in Fig. 8.

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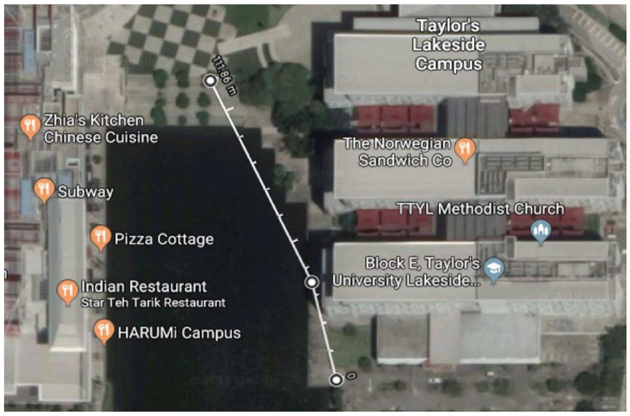

Figure 6: Google Map indication of communication range between the UAV and the ground station

Figure 7: Latency of the wireless transmission of video images

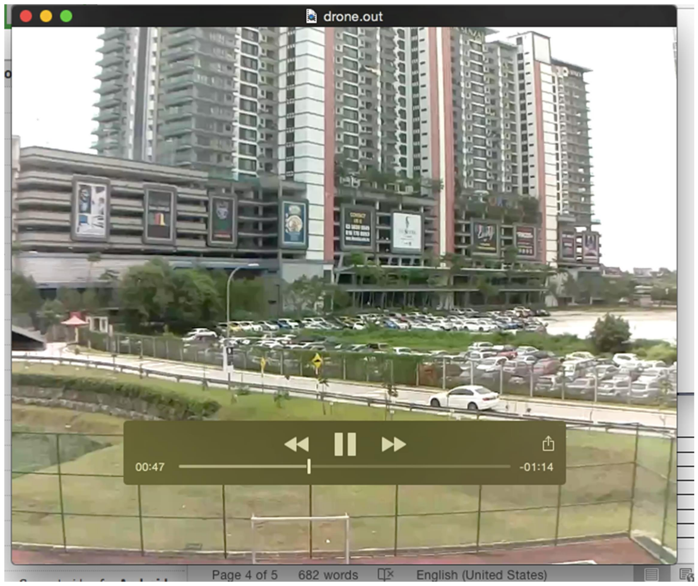

Figure 8: Live video streaming with the quality of 1080p

4 UAV Model & Flight Control

In this section, the mathematical model of the designed quad-copter UAV system is identified, followed by flight controller design. Mellinger *et. al.* has shown that a quad-rotor UAV system is a differentially flat system, meaning its states and inputs can be written as an algebraic function of four flat outputs together with their derivatives [16]. With this definition, the quad-copter model could be assumed as a double integrator linear system. However, to study the behavior of the UAV in high speed motion, a linearized model of double integrators would not be sufficient. In this manuscript, a nonlinear quad-copter UAV mathematical model was derived.

Nonlinear quad-copter UAV models have been developed and revised by many researchers. Examples include, [17, 18]. A principle difference between the derived models by different researchers is the coordination of the initial frame and the body frame. In model proposed in this manuscript, the standard practice of having a fixed ground frame as the initial frame is adopted. Besides the ground frame, and a moving body frame that is attached to the UAV will rotate and translate along with the UAV movements. More information on the frame assignment can be found in [19]. An overview block diagram of the quad-copter UAV model is shown in Fig. 9.

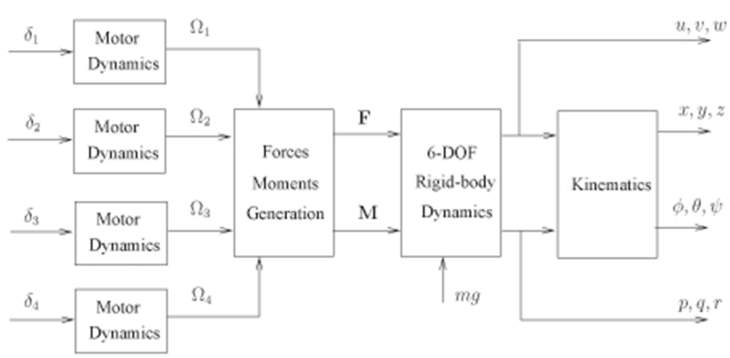

Figure 9: Overview block diagram of the quad-copter UAV model

4.1 Kinematics and Rigid-Body Dynamics

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The motions between the ground frame (in this case, it is the North-East-Down NED frame) and the body frame are related with Newton navigation equations.

$$\dot{P}_n = R_{n/b}V_b$$

$$\dot{\Theta} = S^{-1}\omega$$

where $R_{n/b}$ is the rotational matrix, and S^{-1} is the lumped transformation matrix. They are given by

$$R_{n/b} = \begin{bmatrix} c_\theta c_\psi & s_\phi s_\theta c_\psi - c_\theta s_\psi & c_\phi s_\theta c_\psi + s_\phi s_\psi \\ c_\theta s_\psi & s_\phi s_\theta c_\psi + c_\theta s_\psi & c_\phi s_\theta c_\psi - s_\phi s_\psi \\ -s_\theta & s_\phi c_\theta & c_\phi c_\theta \end{bmatrix}$$

$$S^{-1} = \begin{bmatrix} 1 & s_\phi t_\theta & c_\phi t_\theta \\ 0 & c_\phi & -s_\phi \\ 0 & s_\phi / c_\theta & c_\phi / c_\theta \end{bmatrix}$$

with $s_* = \sin(*)$, $c_* = \cos(*)$, and $t_* = \tan(*)$. To describe the translational and rotational dynamics of the UAV, we have

$$m\dot{V}_b + \omega \times (mV_b) = F$$

$$J\dot{\omega} + \omega \times (J\omega) = M$$

where F and M are the forces and moments acting on the UAV. As the designed quad-copter UAV is symmetrical, the inertia matrix, J, was approximated to be diagonal, i.e.,

$$J = \begin{bmatrix} J_x & 0 & 0 \\ 0 & J_y & 0 \\ 0 & 0 & J_z \end{bmatrix}$$

Moment of inertial J can be obtain via trifilar pendulum experiments as shown in [20], or through the SolidWorks simulation itself.

4.2 Forces and Moments

The quad-copter UAV movements are mainly influenced by the forces and moments generated by the UAV itself, and partially due to external forces and moments acting on the UAV fuselage when it moving. In general, there are two main sources of forces and moments in UAV, i.e., the gravitational force and the rotor thrust.

The gravitational force acts directly towards the Earth, thus it is assumed to be acting along the ground frame z-axis. To transform it to the body frame, we get

$$F_g = R_{n/b}{}^{-1} \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} = \begin{bmatrix} -mgs_\theta \\ mgc_\theta s_\phi \\ mgc_\theta c_\phi \end{bmatrix}$$

Forces and moments generated by the quad-copter UAV mainly come from the rotors. Assume that each rotating rotor creates a thrust, T_n, and a moment, Q_n, for $n = 1,2,3,4$ along its axis. From the aerodynamics consideration, the thrust and torques produced are modelled as

$$T_n = \frac{1}{4\pi^2} C_T \rho (2r)^4 \Omega_n^2$$

$$Q_n = \frac{1}{4\pi^2} C_Q \rho (2r)^5 \Omega_n^2$$

where C_T and C_Q are the aerodynamic coefficients of the rotor, ρ the density of the air, r the radius of the rotor blade. In the proposed UAV design, the collective pitch angle of the blade is fixed, thus one could simplify the equations in an intuitive way. These two equations can be re-expressed as

$$T_n = K_T \Omega_n^2$$

$$Q_n = K_Q \Omega_n^2$$

where the constants k_T and k_Q were obtained through experiments. Finally, the total thrust and moments of the UAV due to the interactions between all the motors could be formulated as follows:

$$F_r = \begin{bmatrix} 0 \\ 0 \\ \sum_{i=1}^{4} T_i \end{bmatrix}$$

$$M_r = \begin{bmatrix} \frac{l_1}{2}(T_1 + T_3 - T_2 - T_4) \\ \frac{l_2}{2}(T_2 + T_3 - T_1 - T_4) \\ Q_1 + Q_3 - Q_2 - Q_4 \end{bmatrix}$$

In the equations above, l_1 is the motor-to-motor length of the UAV, in this case, 0.31 m. l_2 is the motor-to-motor lateral distance of the UAV, which is 0.37 m.

4.3 Flight Control

The UAV control problem can be separated into the attitude stabilization loop and the position control loop. The attitude stabilization (or the so called inner-loop control) ensures the UAV roll, pitch and yaw dynamics are stable with relatively fast dynamics. The inner-loop controller was implemented in the flight controller board, where an attitude stabilizer was tuned towards fast closed-loop dynamics with a simple software framework.

From the mathematical formulation of the UAV dynamics shown in previous section, the attitude dynamics of the quad-copter UAV can be expressed as

$$J_x\dot{p} = u_1 + (J_y - J_z)rq$$

$$J_y\dot{q} = u_2 + (J_z - J_x)pr$$

$$J_z\dot{r} = u_3 + (J_x - J_y)pq$$

where $[u1, u2, u3] = u$ is the normalized moment input to the system. Here, the angular rate dynamics of the quad-copter can be easily linearized by a feedback linearization at

$$u_1 = \bar{u}_1 - (J_y - J_z)rq$$

$$u_2 = \bar{u}_2 - (J_z - J_x)pr$$

$$u_3 = \bar{u}_3 - (J_x - J_y)pq$$

Feedback linearization applied here is perfectly fine as long as the quad-copter system gives a low-noise estimation of angular rates of the UAV, which is usually the case with the help of an extended Kalman filter (EKF). With this technique applied on the controller, the system has approximated an ideal double integrator on each axis. Taking the x-axis (rolling angle) as an example, we have

$$\dot{\mathrm{x}} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\mathrm{x} + \begin{bmatrix} 0 \\ \frac{1}{J_x} \end{bmatrix} u_1$$

$$y = \mathrm{x}$$

where the state $x = (\phi, p)^T$. To completely eliminate steady-state error, one can introduce an augmented state

$$\dot{\phi}_i = \phi_r - \phi$$

We then have the augmented system as

$$\dot{\mathrm{x}}_a = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{bmatrix}\mathrm{x}_a + \begin{bmatrix} 0 \\ 1/J_x \\ 0 \end{bmatrix} u_1 + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \phi_r$$

$$y_a = \mathrm{x}_a$$

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and flight controller can be designed as

$$u_1 = -k_1\phi - k_2\phi_i - k_3 p$$

Where k_i, k_2, k_3 are essentially the PID controller gains, respectively. All three poles for the closed loop system can be selected arbitrary by tuning the PID gains. Similar design methodology can be applied to the other two channels.

5 Results

Extensive flight trials were carried out with the designed quad-copter UAV to test the feasibility of the system in

1. Live transmission of video images to ground station; and
2. Autonomous GPS waypoint flight.

An open-source ground control software QGC was utilized for command upload and data monitoring of the UAV. GPS waypoints was selected on the built-in Google Map in QGC with the specific GPS coordinates, height of flying, and speed of flying indicated. The waypoints are then uploaded to the UAV as a mission command. Fig. 10 shows a snapshot of the UAV flying at 10 m height with camera images downloaded to the ground station in real-time (see Fig. 8). The full envelope of the autonomous waypoints flight data is plotted in Fig. 11.

As reference to Fig. 11, the UAV took-off from the ground at the point close to local coordinate (0,0) to a height of 10 m. It is then navigating to the first waypoint about 10 meters away from it, subsequently to the final waypoint that is approximately at (−25,5) coordinate value. It is then landed on the spot. The whole process was autonomous where no human pilot was needed. Fig. 12 shows the position response of the UAV with respect to its reference, Fig. 13 shows the velocity response of the UAV in the same flight, whereas Fig. 14 shows the attitude angle response of the UAV together with its references.

Figure 10: Designed UAV flying autonomously with GPS waypoints

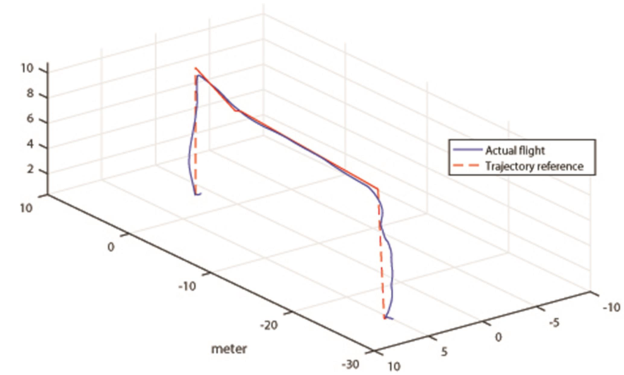

Figure 11: Flight path of the UAV in autonomous waypoints flight

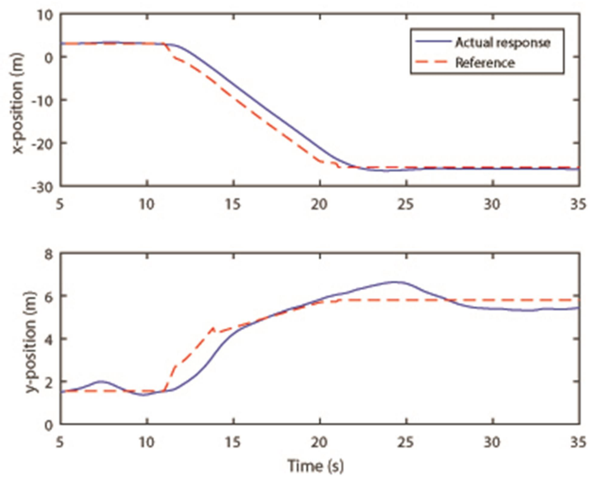

Figure 12: UAV position response with its reference

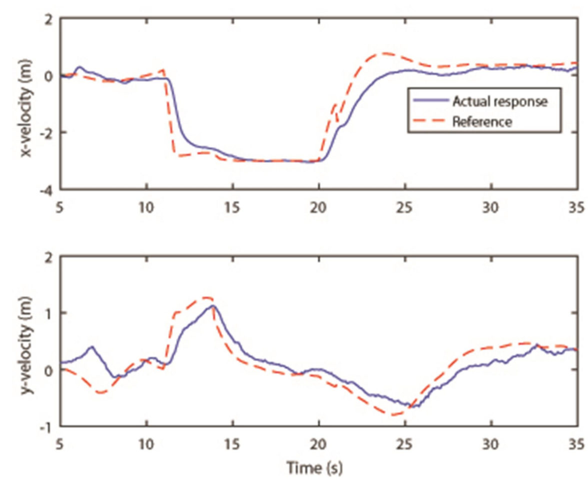

Figure 13: UAV velocity response with its reference

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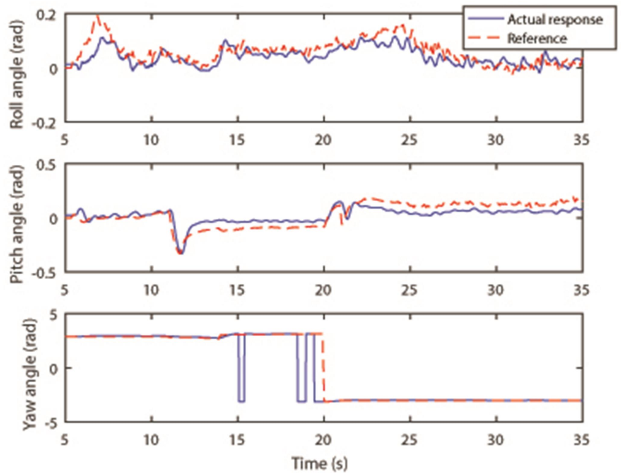

Figure 14: UAV attitude angle response with its reference

6 Conclusion

This manuscript has documented the development of a proposed autonomous UAV surveillance system. It is an efficient alternative to improve the security surveying system by deploying a real-time video streaming system on a robust yet rigid UAV. With the guidance of a GPS, surveying path on an open space and area can be decided via the command from ground station, and thus allowing the UAV to fly autonomously. Built-in infrared sensor on the night vision camera assured that surveillance can be done either during day or night. Extensive flight tests were completed to verify the overall performance of the UAV and its respective camera subsystem. With advance technology is within our reach, security surveying system led by an autonomous UAV is very much possible to be implemented and can be further improved from time to time.

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Corresponding Author: Swee King Phang,Email id : Sweeking.Phang@taylors.edu.my Article History:
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