Modelling and Control of Quad Hybrid Engine Levitating Platform

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Abstract. This research aims to develop trajectory controls for a levitation platform which is powered by rocket fuel. This control task is to regulate the platform for 3D trajectory followings and suspension in the air, which is different from that of the most rocket systems. To cope with the challenges of slow thrust response and coupled vehicle dynamics, we proposed a control system that consists of 4 independent loops for the height, yaw angle, x-position, y-positions, respectively. The developed controllers include 4 PID compensators for the flow rate throttling system, and four double phase lead and two lead-lag compensators for the vehicle dynamics. According to the simulation results, the levitation platform can follow a designated trajectory well when there exist external torques disturbance (both 1 N-m step inputs and 0.1 N-m Gaussian distributed input) and 2% thrust force oscillations.

1. Introduction

More and more applications require air vehicles to have either a short runway or the capability of being suspended in the air, for example, urban area delivery [1], object detection [2], rugged terrain take-off and landing [3], etc. That is why quadcopter drones are getting popular these days. However, quadcopters only operate in the atmospheric environment, and have to carry a heavy battery to travel around. These fuel-related issues limit electricity-powered quadcopter to certain applications such as short distance, lightweight payload, etc. In this project, we want to develop an air vehicle that moves in 3D space, which is similar to what conventional quadcopters do, but replace the electric motors with rocket propulsions. In this way, we may benefit from the rocket propulsions for more applications of air vehicles.

Rocket propulsions rely on the chemical reactions to generate large thrust force while consuming a small amount of the fuel mass. It is preferred for applications such as long-distance, heavy payload, etc. Due to the chemical reactions, the generated thrust force may not be uniform and its response time is slower compared to electric motors. Therefore, most of the rocket systems employ gimbal-type mechanical structures to regulate its flight trajectory [4][5] instead of force throttling. Unfortunately, the gimbal-type mechanism is not suitable for flying an air vehicle that is required to be suspended in the air.

A conventional quadcopter consists of 4 motors, and each electric motor would generate both torque and lift force simultaneously when the voltage applies. When a quadcopter stably suspended in the air and move freely in 3-D space, both the resultant force and toques from motors have to be carefully engineered. It means these four motors have to work co-ordinately to achieve requested vehicle
dynamics. Both light-weight and fast response of the thrust force generation are main merits of the electric-motor-powered quadcopter. Therefore, it is not difficult to distribute the work to each motor in a quadcopter system. In this project, we proposed a trajectory control system for a novel levitation platform with rocket propulsions. This platform, which has a similar force-output configuration as conventional quadcopters, consists of four thrusters. There are several challenges in designing a trajectory control system for this platform. (1) The response time of the thrust is about 1 sec, which is much slower than that of an electric motor (6 ~ 8 Hz) [6]. (2) The lift-to-weight ratio is about 1.4 in the current design while it is usually larger than 2 in electric-motor-powered quadcopters. (3) The generated thrust force and torques are coupled together and the dynamics of the force generation is highly nonlinear. (4) The fuel is consumed with the time of operation and thus the mass, center-of-gravity (C.O.G), and many system properties vary with time. Due to the above challenges, the control system design is much more difficult than a conventional quadcopter drone. Particularly, the work distribution has to be finished in a much precise manner. To solve these problems, instead of using very complicated control algorithms to work with these four propulsion thrusters, we design a multiple-loop control system for each controllable vehicle dynamics. Furthermore, we design the bandwidth of each loop carefully and use the bandwidth as a guideline to distribute the workload. The design procedures of the proposed trajectory control system, simulation, and partial experimental results are elaborated in the following contents.

2. A prototype design of the 4-HELP system

Figure 1 shows the proposed Quad Hybrid Rocket Engine Levitating Platform (4-HELP). The total height and width of the system are 1.705m and 2.125m, respectively. This system consists of four hybrid rocket engines, six composite tanks, four flexible legs, etc. These four legs are designed for the platform to take-off and land on rugged terrains. Each hybrid rocket can produce thrust force with its maximum values of 60 kgf for 30 seconds [7]. The total weight of the platform is 170 kg, which accounts for the lift-to-weight ratio of 1.4. The fuel of the 4-HELP system is solid hydrocarbon compounds, while the oxidizer is H2O2. The mass flow rate of the H2O2 is 210 g/s and the consumption rate of the hydrocarbon compounds is 40 g/s. This implies that the mass of the whole system would vary at approximate 7% during the flight.

This platform is designed to have similar maneuvering capability as the quadcopter drone. Four rocket engines are installed with a cant angle of 15 degrees, two in clockwise-direction and two in counter clockwise direction. These four thrusters are located 0.54 meters away from the COG. Consequently, these control inputs (forces and torques) are all coupled in every axis.

Figure 1. A schematics of the proposed quad-hybrid-engine-levitating-platform
3. Dynamics modelling of the 4-HELP system

3.1. Attitude Definition

This research uses inertial frame (E-frame), body frame (B-frame), and Euler angles \((\phi, \theta, \phi)\) to describe the attitude of 4-HELP. Figure 2 shows the definition of these Euler angles and the origins of the E-frame and B-frame (COG of the platform). The rotation order of the Euler angles is chosen to be “yaw-pitch-roll”. In addition, the corresponding rotation matrix can be obtained as follows [9].

\[
C^B_E = \begin{bmatrix}
\cos \theta \cos \phi & \cos \theta \sin \phi & -\sin \theta \\
-\sin \phi \sin \theta \cos \phi + \cos \phi \sin \phi \sin \phi & \cos \phi \cos \phi \sin \phi \sin \phi + \sin \phi \sin \theta \sin \phi & \cos \phi \cos \phi \\
\sin \phi \sin \phi \cos \phi + \cos \phi \sin \phi \cos \phi & \cos \phi \sin \phi \cos \phi \sin \theta \cos \phi & \cos \phi \cos \phi \sin \theta \cos \phi \sin \phi \sin \phi
\end{bmatrix}
\]  

(1)

Where \(C^B_E\) is the conversion matrix between the inertial frame and body frame.

![Figure 2](image)

**Figure 2. Coordinates and Euler angles for describing the attitude of 4-HELP**

3.2. Thrusters with cant angles

These four rocket engines are installed with a cant angle \((\delta)\). Therefore, to the COG of the platform, the resultant forces in B-frame \((F^B_x, F^B_y, F^B_z)\) and the resultant torques in B-frame \((M^B_x, M^B_y, M^B_z)\) can be obtained as follows.

\[
\begin{bmatrix}
F^B_x \\
F^B_y \\
F^B_z
\end{bmatrix} = \begin{bmatrix}
\sin \delta & 0 & -\sin \delta & 0 \\
0 & \sin \delta & 0 & -\sin \delta \\
\cos \delta & \cos \delta & \cos \delta & \cos \delta
\end{bmatrix} \begin{bmatrix}
f_1 \\
f_2 \\
f_3 \\
f_4
\end{bmatrix}
\]  

(2)

\[
\begin{bmatrix}
M^B_x \\
M^B_y \\
M^B_z
\end{bmatrix} = \begin{bmatrix}
-b\cos \delta & a\sin \delta & b\cos \delta & -\sin \delta \\
-a\sin \delta & b\cos \delta & a\sin \delta & -b\cos \delta \\
b\sin \delta & -b\sin \delta & b\sin \delta & -b\sin \delta
\end{bmatrix} \begin{bmatrix}
f_1 \\
f_2 \\
f_3 \\
f_4
\end{bmatrix}
\]  

(3)
Where \( f_1, f_2, f_3, f_4 \) are the forces produced by each thruster, \( a \) is the distance from a thruster to COG in \( z \)-axis, \( b \) is the distance from a thruster to COG in \( x-y \) plane.

### 3.3. 6 DOF dynamics equations

The linear and angular motions of the 4-HELP system can be described as follows.

\[
\begin{align*}
\begin{bmatrix}
\dot{X}^E \\
\dot{Y}^E \\
\dot{Z}^E
\end{bmatrix} &= \frac{C_E}{m} \begin{bmatrix}
F_x^b \\
F_y^b \\
F_z^b
\end{bmatrix} - \begin{bmatrix}
0 \\
0 \\
g
\end{bmatrix} \\
\begin{bmatrix}
\dot{\omega}_x^b \\
\dot{\omega}_y^b \\
\dot{\omega}_z^b
\end{bmatrix} &= \frac{w_x^b w_y^b (I_y^b - I_z^b) + M_y^b}{I_x^b} \\
&- \frac{w_x^b w_z^b (I_z^b - I_x^b) + M_z^b}{I_y^b} \\
&- \frac{w_y^b w_z^b (I_x^b - I_y^b) + M_x^b}{I_z^b}
\end{align*}
\]

(4)

Where \((X^E, Y^E, Z^E)\) is the position of the 4-HELP in E-frame, \((w_x^b, w_y^b, w_z^b)\) are the angular velocity of the 4-HELP in B-frame, \(g\) is the gravity, \(m\) is the total mass of the 4-HELP, and \((I_x^b, I_y^b, I_z^b)\) are the moments of inertia. According to the rotation order stated in section 3.1, the relation between the Euler angle change rate and the angular velocity show as follows.

\[
\begin{bmatrix}
\dot{\phi} \\
\dot{\theta} \\
\dot{\psi}
\end{bmatrix} = \begin{bmatrix}
1 & \sin \phi \tan \theta & \cos \phi \tan \theta \\
0 & \cos \phi & -\sin \phi \\
0 & \sin \phi \sec \theta & \cos \phi \sec \theta
\end{bmatrix} \begin{bmatrix}
w_x^b \\
w_y^b \\
w_z^b
\end{bmatrix}
\]

(6)

### 4. A proposed trajectory control system for the 4-HELP

Under the current system configuration, we control the force output of four thrusters. These control inputs (forces and torques) are all coupled in every axis. We can control four DOF of the vehicle dynamics at most. Hence we can choose these dynamics as the yaw, pitch, roll, and the height of the platform. The yaw motion is controlled to minimize the coupling between pitch and roll dynamics. Consequently, the controller design for the pitch and roll motions can be simplified. The controlled pitch and roll motions then enable the subsequent position to be controlled in the x-y plane. With the control of four thrust forces, we can regulate the trajectory of 4-HELP system in 3-D space. Besides, we develop controllers for the force-throttle subsystem. Therefore, the thrust force would have linear input-output dynamics, which would greatly simplify the work for the control system development. The architecture of the proposed control system is shown in Figure 3.

According to Figure 3, we need to develop 6 controllers for the trajectory controls, 4 controllers for the force-throttle subsystems. These 6 trajectory controllers are developed based on the linearized dynamics of the system and experimentally calibrated dynamics of the force-throttle subsystem. According to the proposed control architecture, the trajectory controllers would calculate the values of control inputs of one lift force in B-frame \(F^b_2\) and 3 torques in B-frame \(M^B\). These control inputs are converted via a conversion matrix to obtain the force command of each rocket engine. And then these force commands are realized by the force-throttle systems.
4.1 Linearized vehicle dynamics

Assuming the attitude of the platform is small during the trajectory controls, Eqs. (2) to (6) can be linearized and simplified to obtain the decoupled dynamics for the controller design. To achieve this aim, Eq. (4) is linearized as follows.

\[
\begin{bmatrix}
\dot{x}_E^E \\
\dot{y}_E^E \\
\dot{z}_E^E
\end{bmatrix} =
\begin{bmatrix}
1 & -\phi & \theta \\
\phi & 1 & -\phi \\
-\theta & \phi & 1
\end{bmatrix}
\begin{bmatrix}
\frac{F_x^B}{m} \\
\frac{F_y^B}{m} \\
\frac{F_z^B}{m}
\end{bmatrix} -
\begin{bmatrix}
0 \\
0 \\
g
\end{bmatrix}
\]

(7)

According to the symmetric design of the platform, the magnitudes of the \( F_x^B \) and \( F_y^B \) are relatively small as compared to that of \( F_z^B \) (Eq.(2)). Therefore, Eq. (7) is simplified as follows.

\[
\begin{bmatrix}
\dot{x}_E^E \\
\dot{y}_E^E \\
\dot{z}_E^E
\end{bmatrix} =
\begin{bmatrix}
\theta \\
-\phi \\
1
\end{bmatrix}
\begin{bmatrix}
\frac{F_z^B}{m} \\
0 \\
g
\end{bmatrix}
\]

(8)

In addition, assuming the yaw motion is controlled successfully, \( w_z^B \approx 0 \). The angular motion of the system can be simplified as follows.

\[
\begin{bmatrix}
\dot{\phi} \\
\dot{\theta} \\
\dot{\psi}
\end{bmatrix} =
\begin{bmatrix}
M_x^B & M_y^B & M_z^B \\
I_x^b & I_y^b & I_z^b \\
I_x^b & I_y^b & I_z^b
\end{bmatrix}
\begin{bmatrix}
\phi \\
\theta \\
\psi
\end{bmatrix}
\]

(9)

4.2 Force conversion matrix

As shown in Figure 3, the \( M_x^B, M_y^B, M_z^B \) and \( F_z^B \) are chosen as the control inputs of the system. These four variables are converted by a force conversion matrix to obtain the desired force output of each thruster (\( f_{1-4} \)). This conversion matrix can be obtained from Eq. (2) and (3) as follows.
4.3 Dynamics of the force-throttle control system

Figure 4 shows a block diagram of the force-throttle control system. The purpose of this system is to control the flow rate of the oxidizer to obtain the requested force. It is realized by the inner/outer loop controls, where the inner loop controls the opening of the valve, the outer loop controls the flow rate. And, the flow rate is measured by the pressure difference of a flow meter (balanced flow meter, BFM).

\[
\begin{bmatrix}
1 & -\cos \delta \\
1 & -\sin \delta \\
-\sin \delta & 1 \\
\cos \delta & 2
\end{bmatrix}
\begin{bmatrix}
\frac{1}{2} (b \cos \delta)^2 - (a \sin \delta)^2 \\
2 (b \cos \delta)^2 - (a \sin \delta)^2 \\
2 (b \cos \delta)^2 - (a \sin \delta)^2 \\
1
\end{bmatrix}
\begin{bmatrix}
\frac{1}{4} \\
\frac{1}{4} \\
\frac{1}{4} \\
\frac{1}{4}
\end{bmatrix}
\begin{bmatrix}
1 \\
1 \\
1 \\
1
\end{bmatrix}
\begin{bmatrix}
F^b \\
M^b \\
M^b \\
M^b
\end{bmatrix}
\]

(10)

Figure 5 shows the experimental results of the above throttle control system. The blue lines are the flow rate command while the orange lines are the measured flow rate from BFM. As shown in the plot, the flow rate controls are quite successful. The flow rate command is multiplied by a scale to obtain the corresponding force command (pink lines). The measured thrust forces are drawn in green. According to the plot, the force output is not that linear with the flow rate of the oxidizer. Besides, the force response is a bit slower than the flow rate of the oxidizer. The force commands and force measurements are utilized to obtain a transfer function shown as flows.

\[
Thr(s) = \frac{1.108s + 19.914}{s^2 + 5.863s + 19.96}
\]

(11)

Figure 6 shows the response of the identified model and measured data for comparison. The blue line is the response of the identified model \((Thr(s))\) while the green line is the measured data. The identified system bandwidth is approximate 1 Hz.
Figure 5. The thrust force of the hot fire test

4.4 Controller design

4.4.1 Height controller design.
Figure 7 shows the block diagram of the z-axis (height) control loop excerpted from Figure 3. The throttle system is replaced with the experimentally identified transfer function shown in Eq. (11). According to the Bode plot shown in Figure 8, the uncompensated system (red line) has a gain crossover frequency of 0.02 Hz and the phase margin -1.05o.

In this controller design, we want to have the z-axis dynamics as fast as possible while not saturating the control input. The phase margin ≥ 40° is for a damped response. The fast response is requested because the z-axis dynamics is the most critical one for the stability of the entire levitation platform. To attenuate the high-frequency noise, we design a double phase-lead controller rather than a single phase-lead one. The height controller \( G_{cz} \) is designed as follows.

\[
G_{cz} = 266.5 \times \left( \frac{0.815s+1}{0.114s+1} \right)^2
\]  

(12)

Figure 6. System identification of the thrust dynamics
4.4.2. Attitude controllers design.

The yaw control is designed to enable the proposed pitch and roll controls of the system. And, this is done by having the bandwidth of the yaw dynamics faster than that of the pitch and roll dynamics. The design procedures of these three controllers are similar to those of the z-axis controller. To save the length of the paper, we show the final design of these controllers.

\[
G_{c\phi} = 38.1 \times \left(\frac{0.813s+1}{0.114s+1}\right)^2 \quad (13)
\]

\[
G_{c\psi} = G_{c\theta} = 29.85 \times \left(\frac{1.064s+1}{0.169s+1}\right)^2 \quad (14)
\]
where $G_{c\phi}$, $G_{c\Phi}$, and $G_{c\theta}$ are the controller for the yaw, pitch, roll, respectively. When these controllers are included, the bandwidth of the yaw dynamics is 0.94 Hz, while its phase margin is 45°. The bandwidth of the pitch and roll dynamics are both at 0.8 Hz, while their phase margin is 57.7°.

4.4.3. Position controllers design.

According to Eq. (8), the pitch and roll angles of the platform would produce forces that affect the vehicle dynamics in the x-axis and y-axis. Therefore, we design inner-outer control architecture to achieve the trajectory controls. Figure 9 shows an example of x-axis position controls.

Figure 9. The block diagram of the x-axis position controls

Figure 10 shows the bode plot of both uncompensated dynamics and compensated dynamics. According to the plot, before the compensation, the gain crossover frequency is 0.4 Hz while the phase margin is -99.8°. After the lead-lag compensator design, the gain crossover frequency of the compensated system (bandwidth of the closed loop system) is about 0.27 Hz while the phase margin is 18.4°. The designed lead-lag controllers for the x-axis and y-axis positioning are shown in Eq. (15).

$$G_{cx} = G_{cy} = \begin{pmatrix} 3.053s+1 \\ 0.366s+1 \\ 26.316s+1 \\ 993.16s+1 \end{pmatrix} \begin{pmatrix} 3.053s+1 \\ 0.366s+1 \\ 26.316s+1 \\ 993.16s+1 \end{pmatrix}$$ (15)

Figure 10. The bode plot of x-axis position controls

5. Numerical simulations and discussions

In the following simulations, the commercial software Matlab/ Simulink is used to verify the performance of the proposed control system. The 4-HELP dynamics in the simulations are described by Eqs. (1) to (6). The dynamics of the controllers and force-throttling systems are from Eqs. (11) to (14). The verification task is to let the 4-HELP fly a pre-set trajectory: take off from the ground for 2 meters, move 1 meter in y-direction, move 1 meter in x-direction, and then land on the ground.
To verify the robustness of the proposed control system, the external torques with unknown magnitudes are utilized to mimic the wind disturbances, including step torques in each direction and noising torques during the entire flight. These disturbance torques are listed in Table 1. In addition, we also include the effect of the thrust force oscillation (Table 2). According to Figure 6, the oscillation consists of 3 major frequencies with different amplitudes, which are 1 Hz, 5 Hz, and 7.5 Hz. These effects are included in the simulation with the random pickup phase delayed.

Table 1. Disturbance torques in the simulations

| Value       | Time       | Direction |
|-------------|------------|-----------|
| Gaussian noise | 0.1 Nm    | 0~50 sec  | X, Y, Z    |
| Step torques | 1 Nm      | 10~15 sec | X, Y, Z    |

Table 2. Thrust oscillations in the simulations

| Value       | Time       | Thrusters |
|-------------|------------|-----------|
| Content 1   | F(1.2%) sin(2πt + φ₁) | 0~50 sec | 1~4 |
| Content 2   | F(1%) sin(10πt + φ₂)  | 0~50 sec | 1~4 |
| Content 3   | F(0.5%) sin(15πt + φ₃) | 0~50 sec | 1~4 |

5.1 simulation result

Figure 11 shows the trajectory of the 4-HELP system under the proposed control method. The vehicle trajectory follows its designated values well even under the interferences of both distance torques and thrust force oscillations. The position oscillates in x and y direction because of the relatively small bandwidth of x-axis and y-axis dynamics (designated values of 0.27 Hz). The overshoot of the positioning is 3.63%, 16%, and 21.1% in the z-axis, y-axis, and x-axis, respectively. These values also agree well with the designated phase margin stated above.

Figure 12 shows the thrust force commands and their corresponding output values. Due to the plot visibility, we show one thruster only. According to the simulation results, the thrust does not saturate as requested. In addition, the thrust force decreases slowly to maintain the z-axis position of the vehicle (flight height) when the fuel is consumed continuously and the mass of the system gradually reduces. One may find that the force commands and their output values both oscillate. The oscillations in commands are generated in response to the unfavorable force oscillations existing in the real force output.

Figure 11. The trajectory of the 4-HELP under the proposed control system
According to the force output shown in Figure 12, one may find that the force outputs starting from 50 kgf slowly decreases to 40 kgf in the second half of the flight. This 40 kgf force-output corresponds to 2/3 of the maximum thrust force value. This suggests that we may have enough forces to improve the force response time and the robustness of the system in the second half of the flight. In that case, we may have a more complicated control system to optimize the performance of the 4-HELP system. More studies in this line are still ongoing.

6. Control system implementation
We have developed a completed hardware system for the flight controls of the 4-HELP. The schematics of the system is shown in Figure 13.

Figure 12. The thrust command and their corresponding output values of one thruster

Figure 13. The block diagram of 4-HELP system
The sbRIO-9637 from National Instruments is utilized as the main core computer of the 4-HELP. It can communicate with the ground computer upload and download data through wi-fi channels. As the core of 4-HELP, sbRIO is connected with various valves and sensors as well as two DSP boards. We use three sensors to detect 6DOF information, namely IMU, magnetometer and RTK GPS. The IMU is connected to the sbRIO through RS485, and the magnetometer and RTK are connected to it through RS232. We have written a Kalman filter that can integrate these three kinds of information for filtering and fusion, and have been experimentally proved to be feasible. The information calculated by the sensor fusion will enter the Flight controllers designed in previous pages. The four thrust commands output will pass to the two DSPs through the CAN-BUS protocol. The control architecture of Figure 3 has been written in these two DSP boards. One DSP connects to two thrusters and that is regarded as a throttle control system. In addition, there are 10 valves on the 4-HELP connected to sbRIO. 4 differential pressure meters and 10 pressure meters will send the pressure into the tube back to sbRIO, and finally, pass through the network to go back to the ground station for monitoring. The control board is shown in Figure 14. IMU and magnetometer are shown in Figure 15. RTK GPS module is shown in Figure 16.

Figure 14. sbRIO-9637 control board  
Figure 15. IMU (left, DMU10) and magnetometer (right, HMR3300)  
Figure 16. RTK GPS, antennas and RF transmission module

7. Conclusion
This research proposes a trajectory control system for a novel rocket-engine, levitation platform. The rocket engine generates its thrust force via the fuel of solid hydrocarbon compounds, and the oxidizer of H_2O_2. Compared to conventional electric-motor powered by quadcopter drones, there are four major challenges in designing a trajectory control system for this platform. It includes slow response of the thrust force generation, the small lift-to-weight ratio, the highly coupled vehicle dynamics, and the time-varying system properties.

The above problems are solved by the following proposed methods: (1) It develops 4 controllers for the throttle-force dynamics so that the response of the thrust force becomes linear; (2) It designs a multiple-loop control system for each controllable vehicle dynamics. Moreover, using the bandwidth of each loop as a guideline distributes the workload. Stemming from these design concepts, the bandwidth of the throttle-force subsystem is designed approximately 1 Hz, the z-axis position is 0.98 Hz, the yaw dynamics is 0.94 Hz, and the x-axis and y-axis dynamics are 0.27 Hz. In a simulation task, the 4-HELP system is requested to follow a pre-set trajectory: take off from the ground for 2 meters, move 1 meter in y-direction, move 1 meter in x-direction, and then land on the ground. The interferences in mentioned simulations include disturbance torques in each direction (1 N-m), Gaussian distributed noise torques during the entire flight (0.1 N-m), and unexpected thrust force oscillations. The vehicle follows its designated trajectory well with the overshoot of 3.63%, 16%, and
21.1% in the z-axis, y-axis, and x-axis, respectively. These values also agree well with the controller designs.

References

[1] Md R Haque, M Muhammad, D Swarnaker and M Arifuzzaman 2014 Autonomous Quadcopter for Product Home Delivery
[2] Nils Gageik, Paul Benz and Sergio Montenegro 2015 Obstacle Detection and Collision Avoidance for a UAV With Complementary Low-Cost Sensors
[3] W Zheng, J Wang and Z Wang 2016 Multi-sensor Fusion based Real-time Hovering for A Quadrotor without GPS in Assigned Position
[4] B L Berrier, J G Taylor, H Virginia 1990 Internal Performance of Two Nozzles Utilizing Gimbal Concepts for Thrust Vectoring
[5] Clinton B F Ensworth 2013 Thrust Vector Control for Nuclear Thermal Rockets
[6] H L Chan and K T Woo 2015 Design and Control of Small Quadcopter System with Motor Closed Loop Speed Control
[7] Y L Liu and J S Wu 2018 Development of the Quad Hybrid Rocket Engine Levitating Platform Propulsion System
[8] T Bresciani 2008 Modelling, identification and control of a quadrotor helicopter
[9] David H. Titterton and. John L. Weston 2004 Strapdown Inertial Navigation Technology 2nd Edition