Simulation Research of Extra-Vehicular Activity Based on Virtual Reality Technology

Weilin Li, Jian Wen*, Zeyu Hu, Wenkai Ma

***Abstract*—**In order to solve the problem that six degree of freedom movement and automatic attitude holding of the simplified aid for extravehicular activity rescue (SAFER) on the ground simulation of astronaut's operation cannot be achieved accurately due to the influence of gravity, friction and other conditions. The dynamic simulation model of the device is established by using virtual reality technology. And in the MATLAB/Simulink environment to establish a hybrid control system model, its core concept is based on the Bang-bang control. Under different conditions, the SAFER attitude control process is simulated, and then the scene simulation animation and control process curves are obtained. The simulation results verify the accuracy of the mathematical model and control strategy. Application of virtual prototyping technology model simulation method can describe the device control process accurately and make the design process more efficient. And provide certain theoretical basis and guiding significance to the practical application of SAFER.

***Keywords*—**virtual reality technology, six-freedom degree, hybrid control system, automatic attitude holding, extra-vehicular activity

INTRODUCTION

When performing a space mission, the astronauts always need to complete many extravehicular activities (EVA). However, the activities in the space environment will be affected by weightlessness. Therefore, the astronauts must use a certain type of tools to achieve extravehicular, extravehicular walking, return and other activities. And this kind of mobile tools need to be able to "guarantee astronauts' safe return after leaving the cabin". This problem has been paid much attention by scientists in the field of extravehicular technology [1, 2]. Compared with the traditional tether device and mechanical device, the jet propulsion device has the advantages of wide range of activities, high flexibility and strong operability. After several manned space trials, Simplified Aid for Extravehicular Activity Rescue（SAFER）are gaining more and more attention [1, 4].

In order to control the automatic attitude holding of the SAFER, many solutions have been put forward by scholars both at home and abroad. Patrick M. Handley presents a method of bang-bang control [5]. Handley designed a control method based on sliding mode control theory to achieve automatic attitude keeping of astronauts [6]. And Lin Taiming proposed a control method based on Udwadia-Kalaba constrained motion theory [7]. However, the above control algorithm is applied to the motion control of the six degree of freedom device. Generally, there are some problems such as long control time and large fuel consumption, so the control effect is not satisfactory. Moreover, the device works in the outer space, which is a special case, so the control system needs to be extremely robust.

A hybrid control system is a controller and / or a controlled object that contains both continuous and discrete models, both of which act together in the system, thus regulating system performance. Compared with the continuous or discrete event dynamic system alone, the system has better performance and can realize the control performance that some traditional controllers cannot achieve.

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ANALYSIS OF SAFER MATHEMATICAL MODEL

A. SAFER physical structure parameters

The device is compact and simple, and the quality is only 38.25kg. There are 24 xed-position thrusters (GN2) that exert thrust forces on the astronaut for manoeuvring. And each thruster produces thrust of 2N. Each valve is coordinated with each other, and the device is provided with a space six degree of freedom manoeuvre control capability(X, Y, Z, Roll, pitch and yaw). The SAFER body and the simulation design are shown in figure 1.

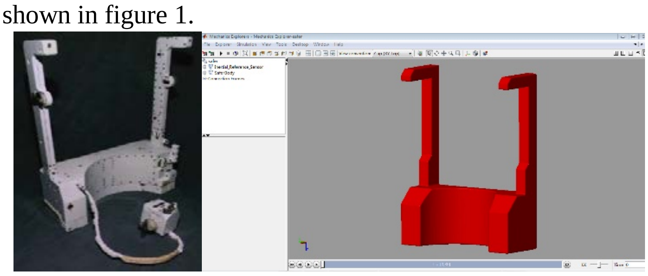

Fig.1 Physical Diagram and Model of SAFER

B. Establishment of Device Attitude Movement Model

First, a rectangular coordinate system of the SAFER is required. The origin coincides with the centre of mass and the positive direction is determined by the right-hand helix rule. Let $\theta 1$、$\theta 2$、$\theta 3$ be the X roll angle, Z yaw angle, and Y elevation angle of the device; k1、k2、k3 respectively are the angular rate of rotation of the device around the X axis, Z axis and Y axis. J1、J2、J3 represent the rotating inertia of the body about the X axis, the Z axis and the Y axis respectively; L1、L2、L3 are external torques that are subjected to the X axis, the Z axis, and the Y axis. According to the literature [8], the kinematic equations and dynamic equations of the write device can be analysed, as shown below.

$$\begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} = \begin{bmatrix} k_1 - \cos\theta_1 tg\theta_3 \cdot k_2 + \sin\theta_1 tg\theta_3 \cdot k_3 \\ \dfrac{\cos\theta_1}{\cos\theta_3} k_2 - \dfrac{\sin\theta_1}{\cos\theta_3} k_3 \\ \cos\theta_1 \cdot k_3 + \sin\theta_1 \cdot k_2 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \dot{k}_1 \\ \dot{k}_2 \\ \dot{k}_3 \end{bmatrix} = \begin{bmatrix} \dfrac{J_2 - J_3}{J_1} k_2 k_3 + \dfrac{L_1}{J_1} \\ \dfrac{J_3 - J_1}{J_2} k_3 k_1 + \dfrac{L_2}{J_2} \\ \dfrac{J_1 - J_2}{J_3} k_1 k_2 + \dfrac{L_3}{J_3} \end{bmatrix} \tag{2}$$

From the upper analysis, we can know that the attitude equation of the device is nonlinear, and there is some coupling between the channels.

C. Linearization and Decoupling of Attitude Equations

To ensure the stability and reliability of SAFER during completion of the operation. Therefore, it is important to linearize the system and realize the decoupling of single degree of freedom between the control-channels [9, 10].

The state space of the attitude movement control system is described as (3) and (4).

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \end{bmatrix} = \begin{bmatrix} x_4 - x_5 \cos x_1 tg x_3 + x_6 \sin x_1 tg x_3 \\ \dfrac{\cos x_1}{\cos x_3} x_5 - \dfrac{\sin x_1}{\cos x_3} x_6 \\ x_6 \cos x_1 + x_5 \sin x_1 \\ \lambda_1 x_5 x_6 + u_1 \\ \lambda_2 x_6 x_4 + u_2 \\ \lambda_3 x_4 x_5 + u_3 \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} I_{3\times3} & O_{3\times3} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \end{bmatrix} \tag{4}$$

As shown in (5), the middle parameter Z is set.

$$\begin{bmatrix} z_1^0 \\ z_1^1 \\ z_1^0 \\ z_2^1 \\ z_3^1 \\ z_3^0 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_4 - x_5 \cos x_1 tg x_3 + x_6 \sin x_1 tg x_3 \\ x_2 \\ \dfrac{\cos x_1}{\cos x_3} x_5 - \dfrac{\sin x_1}{\cos x_3} x_6 \\ x_3 \\ x_6 \cos x_1 + x_5 \sin x_1 \end{bmatrix} \tag{5}$$

The equation of state can be decoupled into (6).

$$\dot{z} = \begin{bmatrix} 0&1&0&0&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&1&0&0 \\ 0&0&0&0&0&0 \\ 0&0&0&0&0&1 \\ 0&0&0&0&0&0 \end{bmatrix} \cdot z + \begin{bmatrix} 0&0&0 \\ 1&0&0 \\ 0&0&0 \\ 0&1&0 \\ 0&0&0 \\ 0&0&1 \end{bmatrix} \cdot v \tag{6}$$

$$y = \begin{bmatrix} 0&0&0 \\ 1&0&0 \\ 0&0&0 \\ 0&1&0 \\ 0&0&0 \\ 0&0&1 \end{bmatrix} \cdot z$$

By formula (6), the system has been decoupled into three independent control channels. And each channel is a critical, stable, controllable, canonical form. Therefore, the control rate of the single channel controller can be designed independently.

D. SAFER Automatic Attitude Holding System

Because of the particularity of the jet propulsion system itself, there are only two (1) and 0 (closed) states. And considering that the device works in a special area of outer space, it is necessary to combine the two special indexes, "advancing the process with less gas consumption" and "fast control time" [7]. To sum up, in the simulation, the control channels of six degrees of freedom in the space should be divided into two groups, the translation and rotation, respectively, to control them. Different control means are designed to meet the above design requirements. Considering the control characteristics of jet propulsion device and the control method of six degree of freedom mobile device. [6, 15]. The bang-bang control rate based on sliding mode structure is designed for the rotation control group (pitch, roll and yawl). For the translational control group (up and down, left and right, front and rear), a multi parameter hybrid control algorithm is designed.

2.4.1 Angle Control Subsystem

The definition of angle error $e_{rs} = \xi - \xi_0 = \Delta\xi$, The angular velocity error of $e_{rv} = \omega - \omega_0 = \Delta\dot{\xi}$ Design control rate is:

$$\begin{cases} s_r = e_{rv} + c e_{rs}{}^2 sgn(e_{rs}) \\ U_r = -U_{max} \cdot sgn(s_r) \end{cases} \tag{7}$$

In (7): U_{max} is the open valve output value; e_{rv} is the error between the current state and steady-state angular velocity; e_{rs} is the error of attitude angle; c is a control constant that changes the characteristics of the control system; $sgn()$ is the symbol function. Because of the existence of the sliding mode, the condition $s\dot{s} < 0$ must be satisfied so that the relative condition of the variable structure control is guaranteed to be in a state of upward sliding in the switching surface. In the group of rotating control channels, the valves can be divided into two groups of positive and negative directions, providing thrust for a single control channel. When the forward group air valve is opened then $U_r = U_{max}$. While the reverse group air valve is opened then $U_r = -U_{max}$.

2.4.2 Displacement Control Subsystem

Device can obtain axial direction thrust and no interference from the couple when the four of jet nozzles are at the same time in the same axial working. Define displacement error $e_{ls} = d - d_0 = \Delta d$, velocity error $e_{lv} = v - v_0 = \Delta v = \Delta\dot{d}$, acceleration error $e_{la} = a - a_0 = \Delta a = \Delta\ddot{d}$. In control, try to make e_{ls}, e_{lv} and e_{la} tend to 0. According to the characteristics of displacement control, a multi parameter hybrid control algorithm, such as (8), is designed

$$U_l = \frac{U_{max}}{2} \cdot \left[1 - \mathrm{sgn}\left(c_1 \cdot e_{lv} + e_{ls}\right)\right] \cdot \left[\begin{array}{l} sgn\left(c_3 \cdot e_{ls} + c_4 \cdot e_{lv}\right) - \\ sgn\left(c_2 \cdot \left|c_1 \cdot e_{lv} + e_{ls}\right| + c_3 \cdot e_{ls}\right) \end{array}\right] \tag{8}$$

C_1, C_2, C_3 C_4 are the control constants and takes the positive value. U_{max} is a single axial four valves open at the same time, the resulting reverse force. The output signal U_1 selects the corresponding nozzle through the jet nozzle sequence selection subsystem, thereby generating axial force to keep the displacement unchanged.

BUILD SIMULATION EXPERIMENT

SAFER has a total mass of 37.6 kg and is designed to be foldable. The size of the folded state is 356 mm, 660 mm wide and 250 mm thick, and the height is increased to 889 mm after the expansion. The center of mass and the moment of inertia[6] are shown in table 1.

Tab.1 SAFER Mass Properties table

One	Two
Centroid	$\begin{bmatrix} 165.6 & 8.6 & 21.8 \end{bmatrix} mm$
Moment of inertia	$\begin{bmatrix} 50.41 & 0.11 & 0.07 \\ 0.11 & 54.65 & -5.14 \\ 0.07 & -5.11 & 16.61 \end{bmatrix} kg \cdot m^2$

The thrust of all valve thrusters is 2 N, ignoring the nonlinear region of valve starting and closing time. The simulation system of setting the control delay time is 2S, the displacement for dead $|\Delta d|$<0.15m, and the angle for dead $|\Delta\xi|$<0.2rad.

The six degrees of freedom for the SAFER are as follows: X axial (front and back), Y axial (left and right), Z axial (upper and lower), pitch, roll, and yaw. The position of the air valve is shown in figure 2.

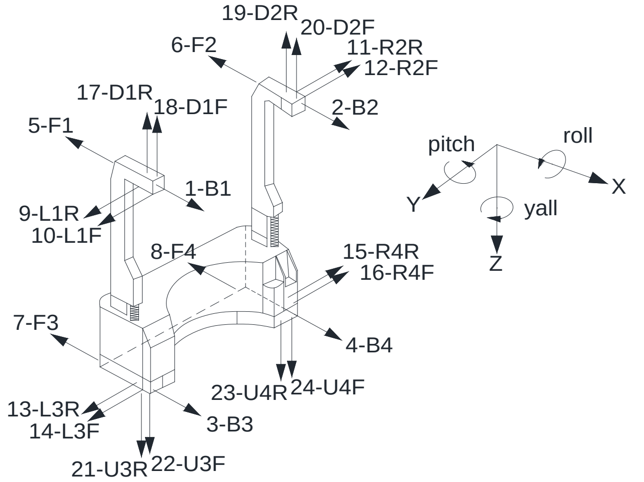

Fig.2 Position arrangement of jet nozzle

Use the Simulink in MATLAB2014a software to build a control simulation environment as shown in figure 3. As shown in figure 3.

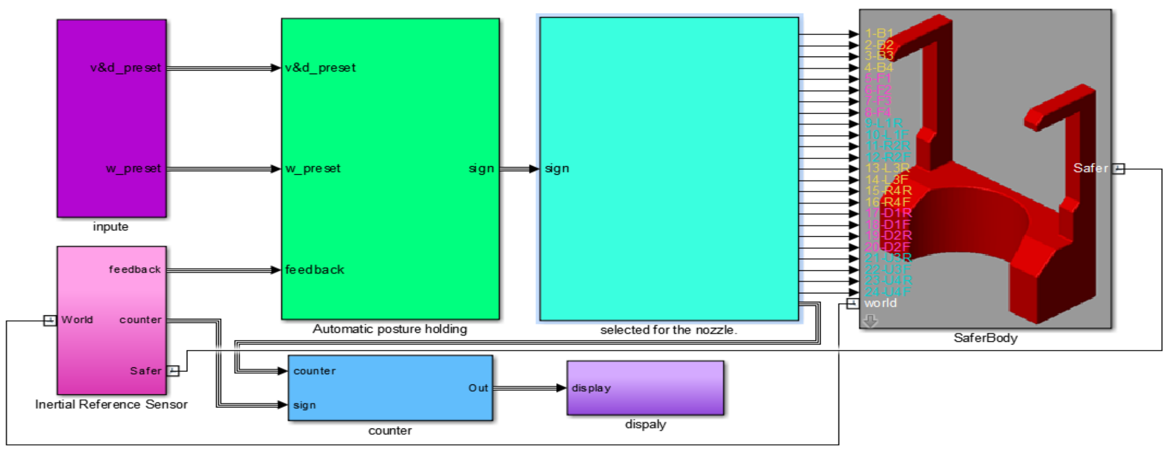

Fig.3 Closed-loop simulation test system

A. Automatic Attitude Holding Submodule

The attitude automatic control module is used to control the attitude stability, and the six degrees of freedom closed-loop control is adopted. The bang-bang control and the multi parameter adjustment control are used to control the translation and rotation of the system respectively. The module passes 24 valve state parameters to the SAFER Body submodule, obtaining angular velocity error Δw, displacement error Δd, velocity error Δv, acceleration error Δa from input submodule and Sensor submodule, and uses these variables as parameters to control the movement state of the device.

B. SAFER Body Submodule

SAFER Body submodule is used to describe the animation of the control process, so that the simulation effect is more intuitive. The stereo model is drawn by Inventor2014 software. Use the SimMechanics toolbox provided in MATLAB to set the quality, centroid, and moment of inertia of the SAFER model.

C. Input / Output Submodule

The input submodule and output submodule (counter & display) are used for human-computer interaction. Among them, the input submodule is used to set the desired system steady state value to simulate the astronaut's attitude stabilization, fixed-point flight and other specific activities in the off shore activities. The output module is used to record the state curve of SAFER, to complete the task time and the percentage of active fuel consumption. Fig. 4 is a schematic diagram of the graphical user interface (GUI) layout of the SAFER hand controller.

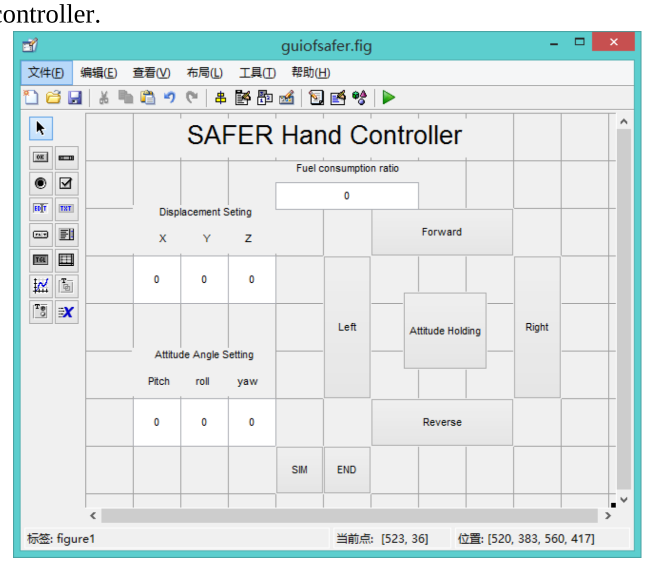

Fig. 4 The GUI of SAFER hand controller

Results and Analysis

A. Experiment of Automatic Attitude Holding

In order to adapt to the specific working environment in outer space, a simulation experiment was designed to simulate the attitude keeping process of an astronaut through SAFER under the condition that the device has non-zero initial speed.

The relevant parameters are defined as follows: the initial velocity of the roll angle is 130° /s, the initial velocity of the pitch angle is 120° /s, the initial velocity of the yaw angle is 140° /s. The initial speed of X axis is 0.75m/s, the initial velocity of Y axial 0.75m/s, axial Z initial velocity is 0.75m/s. The expectation device returns the initial position in a still position and maintains the original angle. Considering that the actual pneumatic device has the presence of delay, the simulation system starts to control after 1s.

The device was initially affected by the initial speed and flew out quickly. Then the control system takes the centre of mass displacement, velocity and angular velocity as the input parameters to control the attitude of the device. The control curve is shown in figure 5.

In the displacement and velocity diagram, the solid line shows the curve of the X axis control, and in the angular velocity diagram represents the roll angle change control process curve; in the displacement and velocity diagram, the dotted line shows the curve of the Y axis control, and in the angular velocity diagram represents the pitch angle change control process curve; in the displacement and velocity diagram, the dot-dash line shows the curve of the Z axis control, and in the angular velocity diagram represents the yaw angle change control process curve.

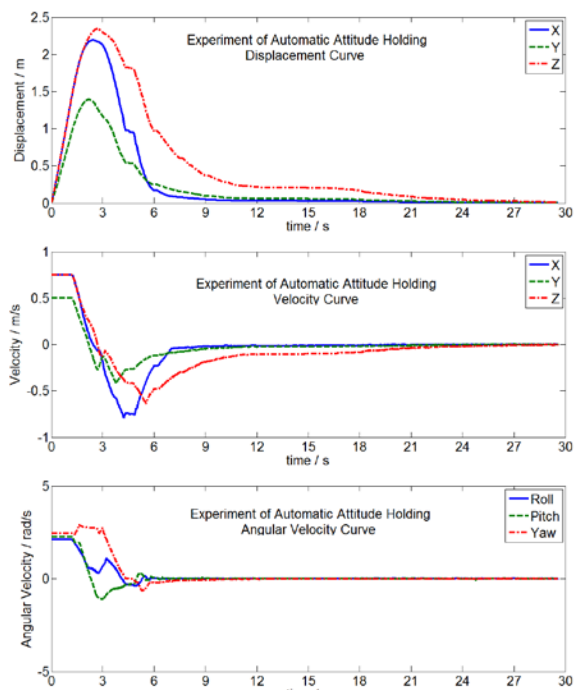

Fig.5 Experimental result of automatic attitude holding

The experimental results show that the task completion time is t = 18.4s, and the fuel consumption percentage is f = 37.23%.

B. Experiment on Robustness of Test Systems

In order to simulate the change of the rotary inertia and the mass centre caused by the elements such as the astronaut's limb movements, the simulation test of the system robustness is designed.

The relevant parameters are defined as follows: the initial velocity of the roll angle is 30° /s, the initial velocity of the pitch angle is 40° /s, the initial velocity of the yaw angle is 50 ° /s. The initial speed of X axis is 1m/s, the initial velocity of Y axial 1m/s, axial Z initial velocity is 1m/s. And in the control process, the 40N X axis of the continuous 0.5s of the upper right corner of the device is perturbed by the positive pulse force. The expectation device returns the initial position in a still position and maintains the original angle.

The device was initially affected by the initial speed and flew out quickly. Then the attitude control is started, and the device tends to be stationary. In 15s, the system has a large fluctuation due to the disturbance factors, and the system quickly controls the disturbance. The device tends to be stationary and return to the initial position. The control curve is shown in Figure 6, and the control system is robust.

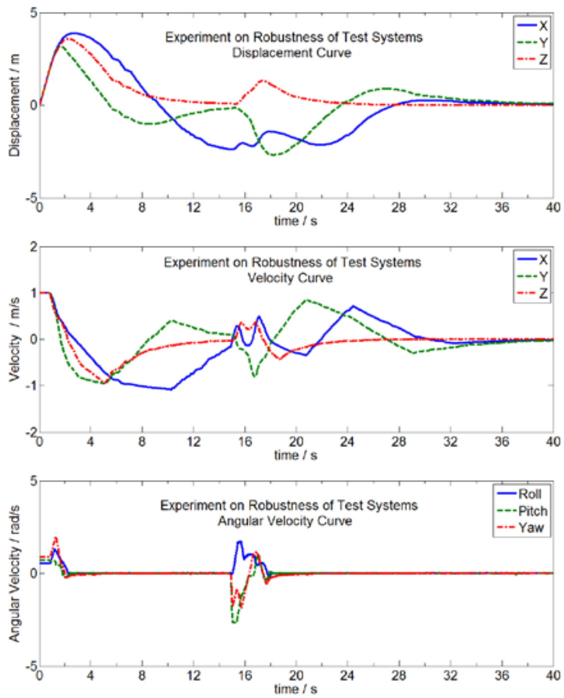

Fig.6 Experimental result of system robustness test

The experimental results show that the task completion time is t = 32.3s, and the fuel consumption percentage is f = 30.49%.

C. *Experiment of Fixed Position Movement*

In order to simulate the device during extra-vehicular activities, SAFER is controlled by an astronaut hand controller to move to the specified position. The simulation experiment of the fixed position movement is designed.

The relevant parameters are defined as follows: the initial velocity of the roll angle is 30° /s, the initial velocity of the pitch angle is 20° /s, the initial velocity of the yaw angle is 10 ° /s. The initial speed of X axis is 0.5m/s, the initial velocity of Y axial 0.5m/s, axial Z initial velocity is 0.5m/s. The final target position for (x, y, z) is (2, 4, 5) m. And when moving to the target position, the device remains stationary and the attitude angle remains unchanged.

In the course of moving, the device has a certain deviation from the initial adjustment stage due to the initial speed. After the sensor detects the deviation, the system is adjusted in time, then the controlled variable is gradually stabilized, and the 12s reaches the preinstall position approximately, then fine tuning. The manipulated variable control curve is shown in figure 7.

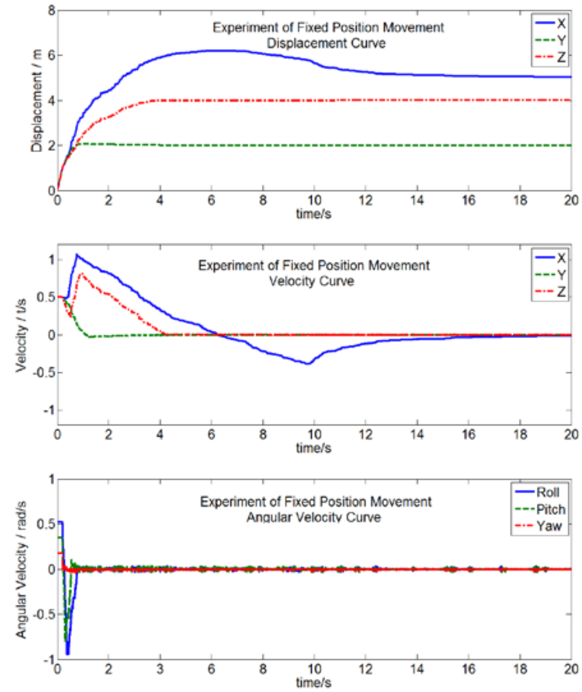

Fig.7 Experimental result of fixed position movement

The experimental results show that the task completion time is t = 14.9s, and the fuel consumption percentage is f = 51.04%.

CONCLUSION

Using virtual prototyping technology, taking SAFER as an example, the simulation analysis of hybrid control system in automatic attitude holding process is realized. The simulation results show that the hybrid control system is suitable for solving the attitude control problem of six degree of freedom mobile devices. The steady-state error in a reasonable range, control system model and system dynamics model established is reasonable, able to accurately describe the process control system; the task completion time and fuel consumption in the acceptable range, the control methods are proved to be effective; three sets of scene simulation experiments were designed by using virtual prototype technology to verify the feasibility and effectiveness of the simulation design of astronaut extravehicular manoeuvring device, and greatly improved the efficiency of device design.

The core control idea of hybrid controller in this paper is still based on time optimal control method, and this method still wastes a lot of fuel consumption. How to optimize the fuel consumption under the condition that the time is guaranteed is the key problem of the following research. The follow-up work requires a systematic analysis of the problem, thus enabling the high performance control simulation of the six degree of freedom mobile device.

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