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Modeling and Simulation of Simplified Aid for EVA Rescue Using Virtual Prototype Technology

Jian Wen[1,*], Junguo Zhang[1], Lin Gao[1] and Xinlei Li[2]

[1]*School of Technology, Beijing Forestry University, Beijing, China*

[2]*Department of Computer Science and Engineering, The Chinese University of Hong Kong, Hong Kong SAR, China*

Abstract: The Simplified Aid for EVA Rescue (SAFER) System uses 24 GN2 thrusters to achieve six degree-of freedom maneuvering control and Automated Attitude Hold (AAH) control. It is a typical hybrid control system and difficult to model. In this article, we applied the virtual prototyping technology; and used MATLAB/Simmechanics for modeling and simulation of the SAFER system. The implementation model of hybrid control system for SAFER is demonstrated, including kinematic and dynamic model, and logical status for Automated Attitude Control (AAH). The model of SAFER is modeled by 3D modeling software, and then imported in Simmechanics as a virtual machine. Together with other Simulink module such as STATEFLOW, Look-up Table block, etc, the virtual SAFER hybrid control system can be modeled and simulated in Simulink. The result shows the validation possibilities of such a combined tool. Simulation result verifies the effectiveness of the method.

Keywords: Virtual Prototype Technology, SAFER, Automated Attitude Control, Bang-Bang Control, Simmechanics.

1. INTRODUCTION

The astronaut extravehicular activity (EVA) is the key technology of manned space flight. Because of the influence of complex extravehicular environment and weightlessness, the astronaut in extravehicular activity faced with many problems such as movement difficulty, attitude hold, pin reorientation, and even have drifted away from the spacecraft. Manned Maneuvering Unit (MMU) is to ensure the effective scheme for astronauts EVA [1-3].

The technology of MMU in the United States, Russia and other developed countries is well developed. Some of them have been through space flight experiment verification, such as MMU, SAFER in USA, YMK in Russia, and HERMESS in European Space Agency. As compared with other developed countries, China's MMU technology lags fairly far behind [4-5].

Modern control applications usually execute more and more complex control logic, and the complexity is increased by the fact that control software interacts with a physical environment through different actors and sensors. Such systems are called Hybrid systems due to the hybrid evolution of their state: One part of the state or variable changes discretely, the other part changes continuously over time [6-8].

The Simplified Aid for EVA Rescue (SAFER) System uses 24 GN2 thrusters to achieve six degree-of freedom maneuvering control and Automated Attitude Hold (AAH) control. It is a typical hybrid system, the command logical statues, selected thruster valve state, change discretely, while the physical vectors like angular velocity or acceleration change continuously over time.

As an aerospace product, the process of development for MMU is influenced by many problems, such as experimental conditions, experimental cost and safety problem. It is very difficult to test the MMU in the ground applying the physical prototype [9-11].

In this article, we applied the virtual prototyping technology, used Formal language MATLAB/SIMU-LINK for modeling and simulation of SAFER. In this method, SIMMECHANICS was applied for generated 3D animation makes the system dynamics visualization. This method can overcome the problem of real effect of weightlessness condition could not be simulated on the ground. It can be used to simulate and validate SAFER hybrid system including control subsystem, dynamic and kinetic model. The result shows the validation possibilities of such a combined tool.

2. THE SIMPLIFIED AID FOR EVA RESCUE (SAFER) SYSTEM

The following SAFER system model in this article is based on, and partly copied from, the NASA guide book[12], and can be found in the Similar literatures, like[13,14], which describes a cut-down version of a real SAFER system.

2.1. Overview of SAFER System

The simplified Aid for EVA Rescue (SAFER) is a small, self-contained, backpack propulsion system enabling

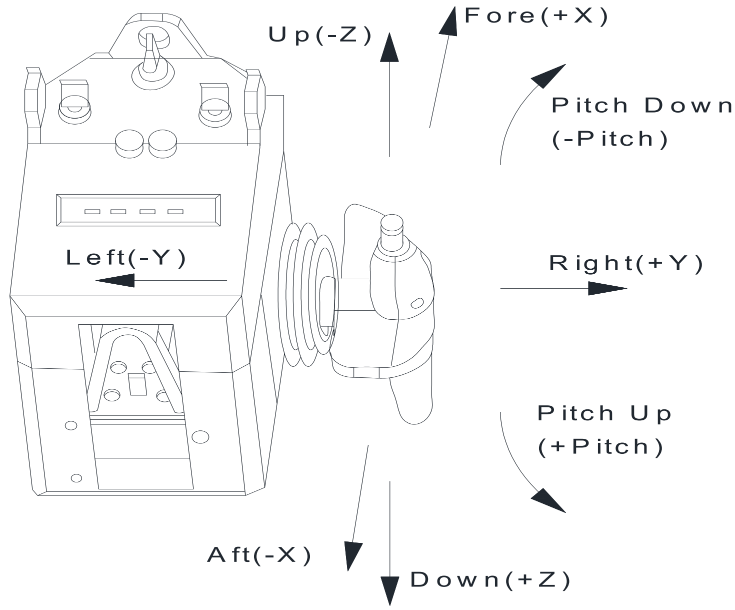

Fig. (1). Hand Controller Module of SAFER.

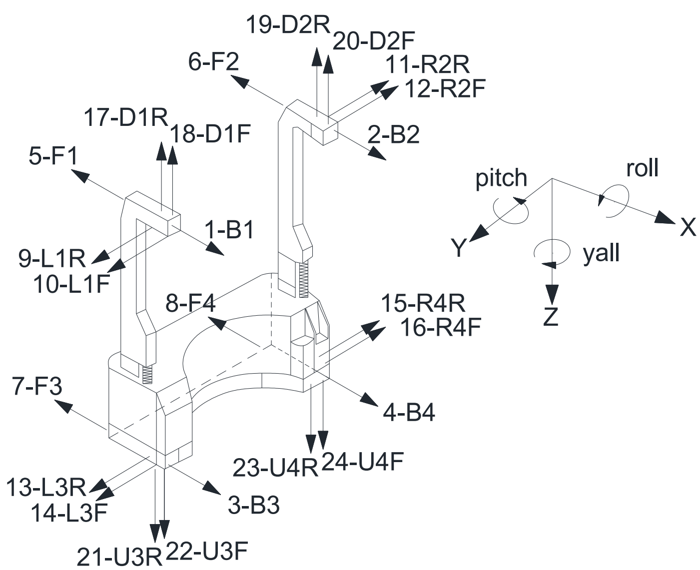

Fig. (2). SAFER Thrusters and Axes.

free-flying mobility for a crewmember engaged in extravehicular activity (EVA). It is intended for self-rescuing on Space Shuttle missions, as well as during Space Station construction and operation, in case a crewmember got separated from the shuttle or station during an EVA.

SAFER attached to the underside of the Extravehicular Mobility Unit (EMU) primary life support subsystem backpack and is controlled by a single hand controller module (HCM), shown in Fig. (**1**). The HCM is a four-axis mechanism with three rotary axes and one transverse axis using a certain hand controller grip. The HCM can operate in two modes, selected via a switch, either in translation mode, or in rotation mode. The arrow in Fig. (**1**). shows the rotation mode commands. There are various priorities among commands that make the thrusters selection logic rather complicated. Translation commands issued from the HCM are prioritized with the priority X first, Y second, and Z third. When rotation and translation commands are present simultaneously from the HCM, rotations take higher priority and translations are suppressed. Moreover, rotational commands make the corresponding rotation axes of the AAH remain off until the AAH is reinitialized. However, if rotational commands are present at the time when the AAH is initiated, the corresponding hand controller axes are subsequently ignored, until the AAH is deactivated.

Fig. (**2**). illustrates the thruster layout, designations, and directions of forces. SAFER uses 24 GN2 thrusters to achieve six degree-of freedom manoeuvring control. After

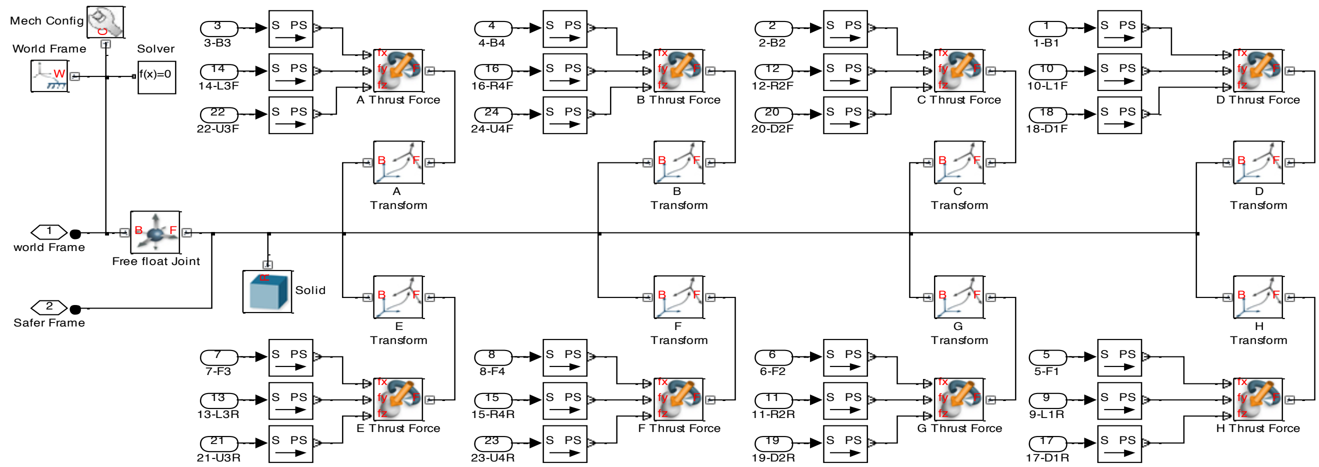

Fig. (4). Parts of the Scheme to SAFER Body.

passing through the regular valve, GN2 is routed to four thruster manifolds, each containing six electric-solenoid thruster valves. Thruster valves open when commanded by the avionics subsystem. When a valve opens, GN2 is released and expanded through the thruster's conical nozzle to provide force. A total of 24 thrusters is provided, with four thrusters pointing in each of the $\pm X$, $\pm Y$ and $\pm Z$ directions.

2.2. Model of SAFER System

For SAFER, translation and rotation equations from mechanics are sufficient for modelling the motion of a crewmember using the propulsion system in the body's own coordination system. Also absolute coordinates have to be determined to visualize the SAFER movement. In order to combine translation and rotation in a single model of motion, coordinate transformation are necessary. All the mathematics needed can be found in the standard literature of mechanics.

The translation of a crewmember wearing SAFER is described by Newton' second law of expressed by

$$F = m\dot{v} = \dot{p} \tag{1}$$

Where F , m , v and p denote force vector, mass, velocity vector and impulse vector.

The rotation is modelled by equation known as the Euler's equations of the motion for the rotation of a rigid body, which is given by

$$I \cdot \dot{\Omega} + \Omega \times I \cdot \Omega = Q \tag{2}$$

Where, Ω denotes the angular velocity vector defined with respect to the centre of mass, and Q denotes a torque vector causing a rotation around the corresponding axis, I is a diagonal matrix defined by the moments of inertia. SAFER does not use proportional gas jets, but thrusters whose valves are open or not, which is simplifies the calculation.

As Ω is calculated in the body's own coordinate system, they have to be transformed back to the absolute coordinate system. Given the Euler angles ϕ, θ and ψ that denote the deviation of the absolute x, y and z axis, the angular velocities vector can be calculated according to the following formula.

$$\Omega = D_3(\psi) \cdot D_1(\theta) \cdot (\dot{\theta}, 0, \dot{\phi})^{\mathrm{T}} + (0,0,\dot{\psi})^{\mathrm{T}} \tag{3}$$

$$D_1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} \tag{4}$$

$$D_2 = \begin{pmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{5}$$

Where D_1 and D_2 are rotation matrices that turn the coordinate system by a given angle. Solving equations with given thruster forces result in SAFER's position $x(t)$ and the angular velocity $\Omega(t)$ used for AAH.

3. SAFER HYBRID SYSTEM MODEL IN MATLAB

3.1. SAFER Body Model

The body of SAFER was modelled by the Autodesk Inventor Professional (AIP), including mass, inertia, and 3D geometry properties. All the properties were followed the actual SAFER. Then the model was imported into MATLAB/SIMMECHANICS. And an automatically generated 3D animation makes the system dynamics visualization. The SAFER model was shown in Fig. (**4**) and Fig. (**5**).

As shown in Fig. (**4**) and Fig. (**5**), the safer body's own coordination system is connected the absolute coordination system by a 6-DOF joint block, which allows three translational degrees of freedom and three rotational degrees of

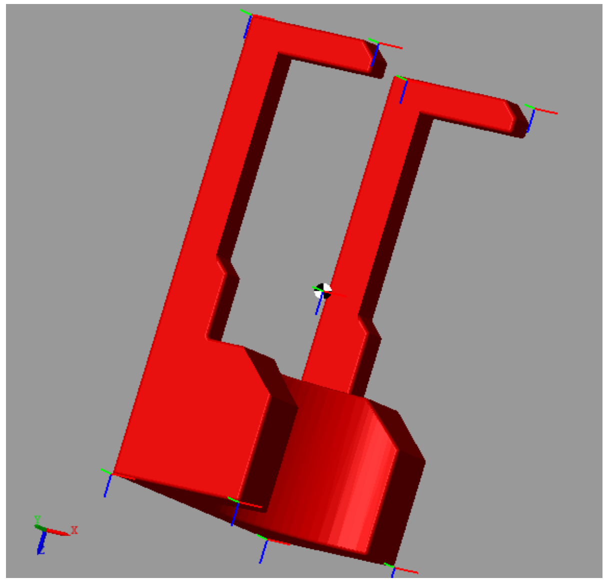

Fig. (5). SAFER Body in Simmechanics.

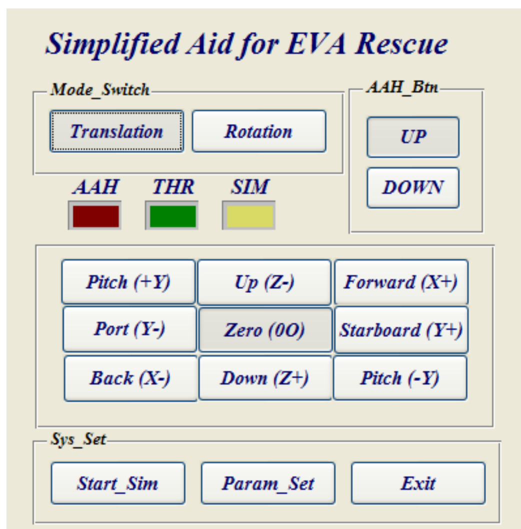

Fig. (6). The GUI for the HCM.

freedom. 6 external force and torque actuator blocks are set as thruster force shown in Fig. (**2**).

The block acts directly on the origin of the attached body's own coordinate frame. With these Thrust force actuators were set to FN or 0N, the states of thruster valves open or off were simulated. Then SIMMECHANICS formulates and solves the equations of motion (Position, Rotation Angle, and Rotation velocity) for the complete mechanical system based on absolute coordination system.

3.2. STATEFLOW for Hand Controller Module (HCM)

As shown in Fig. (**6**), a GUI to the Hand Controller Module (HCM) is provided in MATLAB. All buttons for all the hand controller states as well as for manual input of the AAH output are contained.

Two radios buttons Up and Down are set to simulated AAH Button. If the button is pushed down once the AAH is initiated, while the AAH is deactivated if the button is pushed twice. The STATEFLOW for AAH state change was shown in Fig. (**7**).

When pressing one of the controlled buttons in GUI of HCM, the current time and pressed button ID were recorded by a global variable. Pressing Start_sim button, the trajectory of the astronaut path is plotted in a 3D plot, as shown in Fig (**8**). unit is meter.

3.3. Bang-Bang Control for Automated Attitude Hold (AAH)

Proportional gas jets for attitude control are impractical, however, and the more typical method is to use thrusters

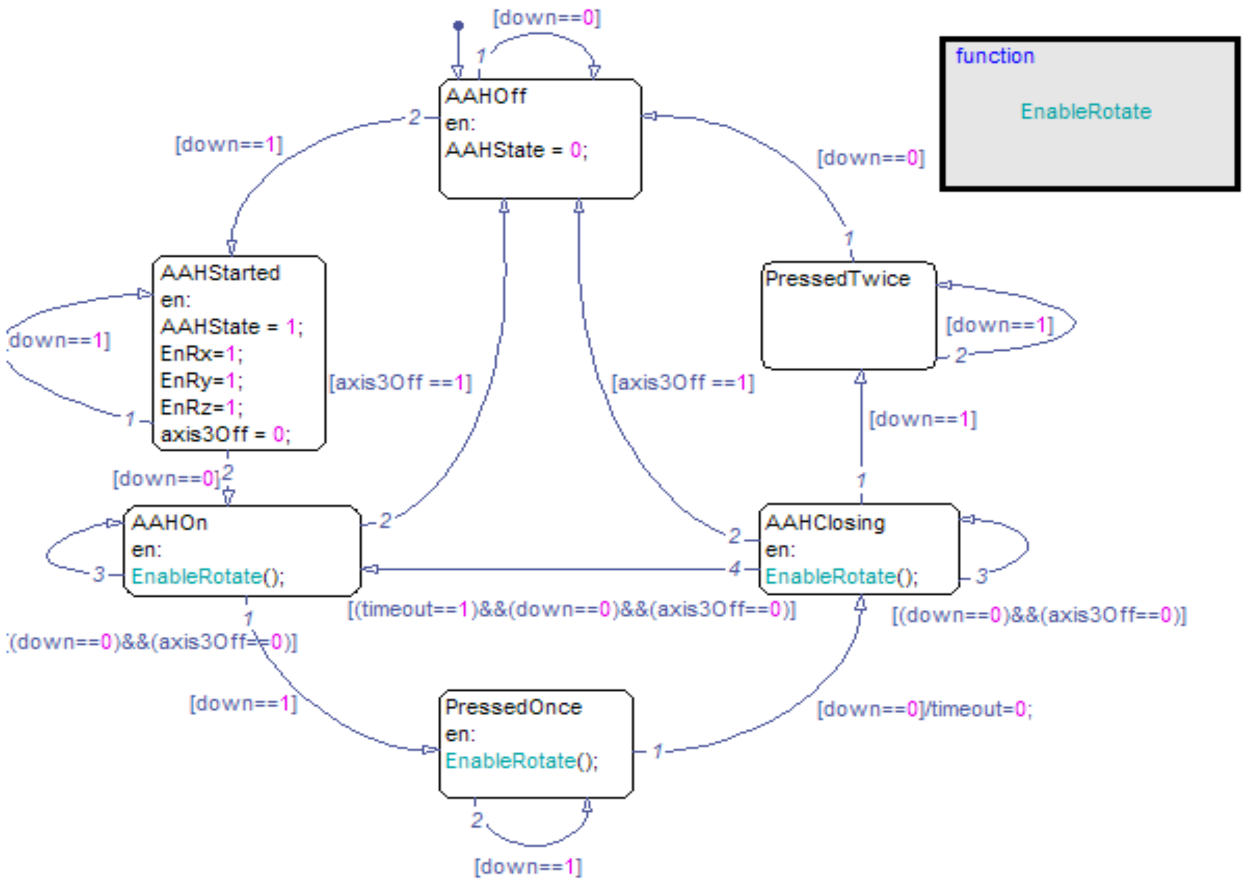

Fig. (7) The SATEFLOW for the AAH State.

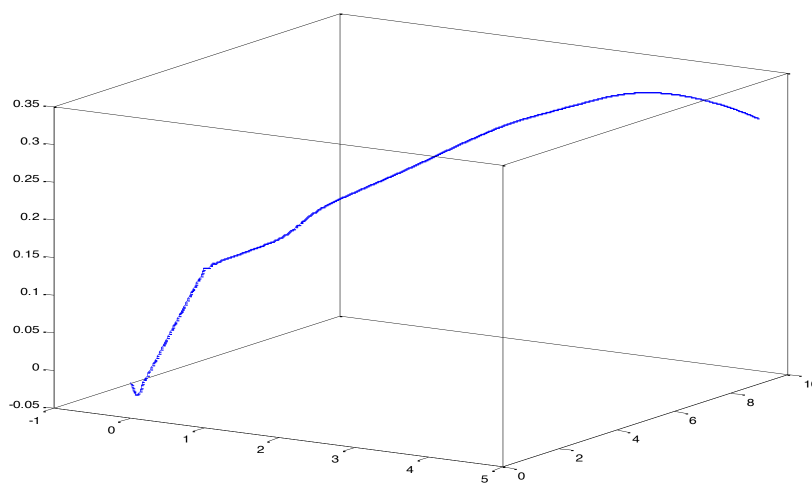

Fig. (8). A Sample Trajectory of the SAFER Using HCM.

whose valves are either completely open or completely closed. So the Automatic Attitude Hold mechanism is simulated by a simple Bang-Bang algorithm.

In Bang-Bang Control for Automated Attitude Hold (AAH), take the tracked pitch angle for example, tracking errors were given by:

$$\begin{cases} e_s = \xi - \xi_0 \\ e_v = \dot{\xi} \end{cases} \tag{6}$$

Where ξ_0 is tracked pitch angle, ξ is current real pitch angle. The ideal attitude control system ensures e_s and e_v

Table 1. Parameters selection.

$s > 0$		$s > 0$	
$e_v > 0$	$e_v < 0$	$e_v > 0$	$e_v < 0$
$c < 0$	$c < 0$	$c > 0$	$c < 0$
$\dot{s} < 0$		$\dot{s} > 0$	

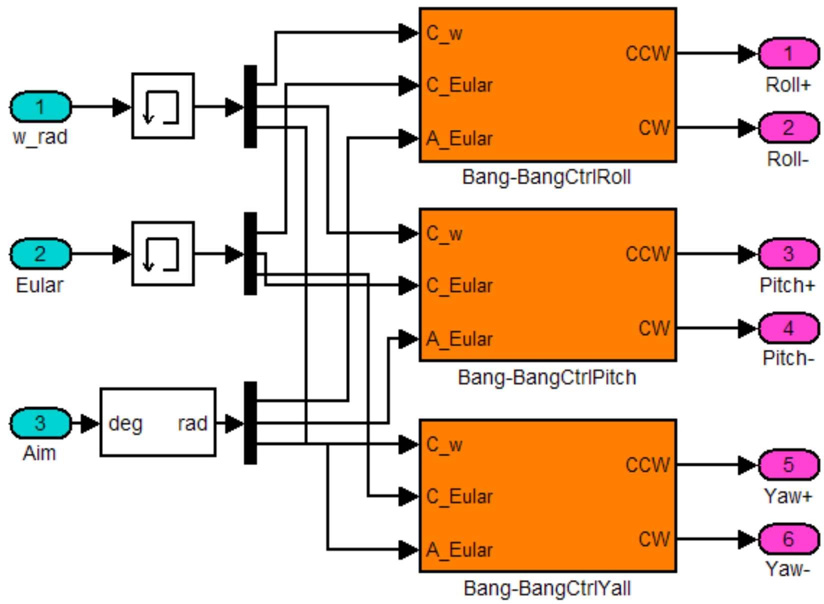

Fig. (9). Bang-Bang Control Scheme for AAH.

become zero at the target point. Therefore, switch function and control function based on variable structure Bang-Bang attitude control were given by:

$$s = e_v + ce_s^2 \operatorname{sgn}(e_s) \tag{7}$$

$$U = -U_{\max} \operatorname{sgn}(s) \tag{8}$$

Where $U_{\max}$ denotes the pitch engine opening output, e_v denotes angular velocity error, e_s denotes pitch angle error, c is taken to be constant, which will change characteristics of the system. sgn() is sign function. In the Phase plan, e_s and e_v will become nearly zero, when S is becoming origin point.

To ensure the existence of sliding mode, it is must be satisfied $s\dot{s} < 0$. The derivation of expression 7 is given by

$$\dot{s} = \dot{e}_v + 2ce_s e_v \operatorname{sgn}(e_s) \tag{9}$$

Designed parameters are shown in Table **1**. The parameter c can be selected by measurable parameters s and e_v. Selecting appropriate parameter c, can satisfy the reaching condition of variable structure control, so as to ensure the system of sliding on the switching surface.

There are six groups' attitude control nozzles, for pitching direction, rolling direction and yelling direction. Each direction has two groups, positive and negative respectively. In positive direction is $U = U_{\max}$, while in negative is $U = -U_{\max}$.

With the parameters shown in Table **1** the Automated Control Hold (AAH) for SAFER Module can be modelled by Simulink show in The Bang-Bang control scheme for AAH is shown in Fig. (**9**).

A Sample result for AAH is shown in Fig. (**10**). It is must be noted that the AAH can only work in a small angle change in less than 90 degree for astronaut to hold his posture for suitable work condition. Together with Hand Control

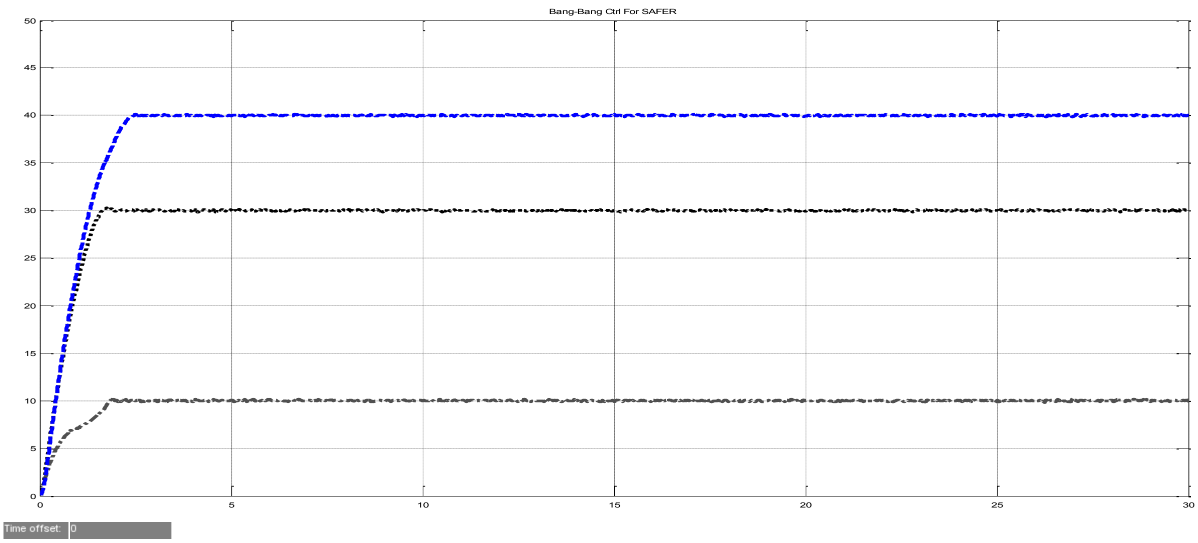

Fig. (10). A Sample Result of AAH.

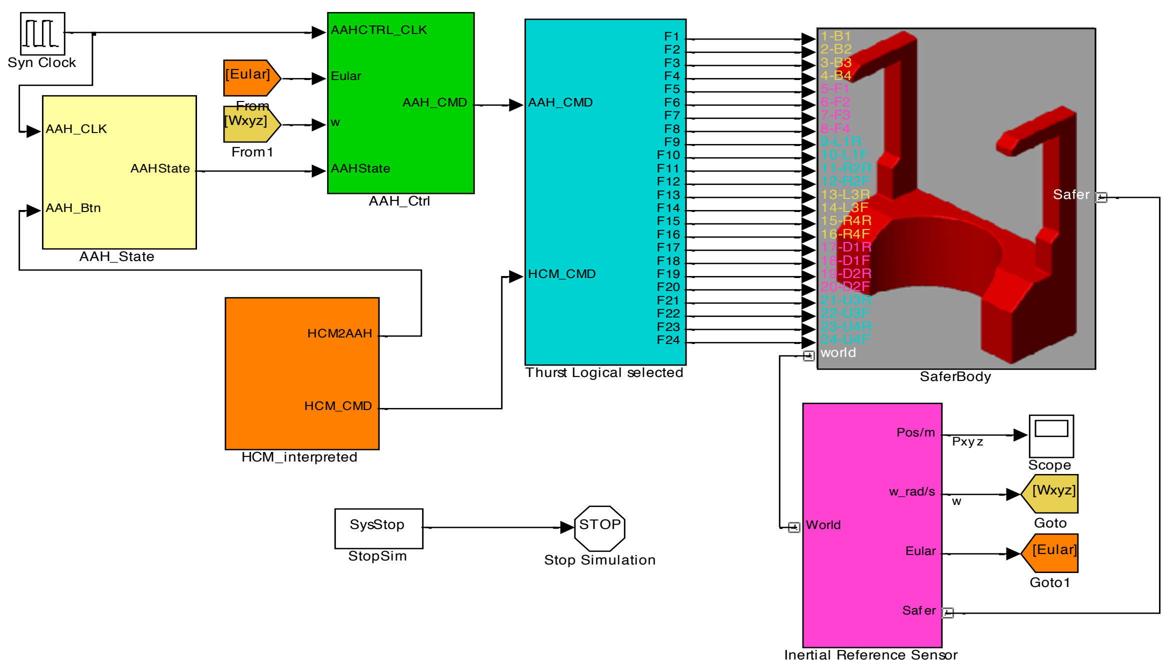

Fig. (11). Hybrid Control System for SAFER.

Module (HCM) for big angle changing attitude of posture, astronaut can move and hold freely in weightlessness environment during extravehicular activity.

3.4. Hybrid System in MATLAB/Simulink

The whole hybrid control system for SAFER is shown in Fig. (**11**). Including Automated Attitude Hold (AAH) State analysis module implemented by STATEFLOW, Hand Control Module (HCM) by GUI and global variables, Thrust Logical Module by Look-up Table blocks, and Safer body module and Inertial Reference Sensor Module simulated by SIMMECHANICS 2nd.

With the model of SAFER virtual hybrid control system, many features such like AAH control, HCM control, functional verification, fault simulation, can be simulated and validated during the development of the product.

4. CONCLUSION AND DISCUSSION

In this article the system model of SAFER has been presented using MATLAB/Simulink. We demonstrated that the implementation models of SAFER body, HCM, and AAH control. The result shows the validation possibilities of such a combined tool. Such a hybrid validation is more suitable for finding unjustified domain assumptions made in the discrete model. Compared with other modelling method for hybrid system in literature, the method in this article is more simple, easy and effective.

The modelling method for SAFER system proposed in this article provides a simple and effective modelling analysis means to the hybrid control system. All the work is accomplished in the MATALB/Simulink environment. At first The model of SAFER can be easily modelled by three dimensional modelling software such as the Autodesk Inventor Professional (AIP), PROE, SOLIDWORKS, CATIA etc., including mass, inertia, and geometry properties, then imported in SIMMECHANICS as a virtual machine. Together with other Simulink module such as STATEFLOW, Look-up Table block, etc., the virtual SAFER hybrid control system can be modelled and simulated in Simulink. Using such a virtual reality technology in the development of the motion hybrid control system in this article provides a new research method for the future

This is a cheap and effective technique for raising the confidence of right control model during the development of product, especially such an aerospace product like SAFER which is difficult to model and validate in ground environment. Furthermore the visualization features of Simmechanics provided a convenient way to communicate a mathematic control model to a customer.

	< Jian WEN>, <born in 1981>,<Shanxi, China> Current position, grades: lecturer, Institute of Technology, Beijing Forestry University, China Scientific interest: automatic control, robot, and nondestructive testing Publications: 10 papers Experience: Jian WEN received doctor degree in Engineering from Beijing Jiaotong University, He has completed seven scientific research projects
	<Junguo Zhang>,< born in 1978>,< Hebei, China> Current position, grades: Associate professor, Institute of Technology, Beijing Forestry University, China Scientific interest: Forestry information collection and intelligent processing Publications: 20 papers Experience: Junguo Zhang received the D.E. degree in Beijing Forestry University. He visited the Forest Product Laboratory, USDA in 2012. He is the director of the department of automation now. He is committed in the research on the forestry information collection and intelligent processing. In addition, he has led nearly ten scientific projects supported by the National Natural Science Foundation of China, State Forestry Administration, etc.
	< Lin GAO >, < born in 1958>,< Beijing, China> Current position, grades: Associate Professor, Institute of Technology, Beijing Forestry University, China. University studies: received her Bachelor of Engineering on Automation from University of Science & Technology Beijing in China. She received her doctor degree in Engineering from Beijing Forestry University in China. Scientific interest: Her research interest fields include automatic control, nondestructive testing. Publications: 25 papers Experience: She has teaching experience of 30 years, has completed four scientific research projects.
	< Xinlei LI >, < born in 1992>,< Shanxi, China> Current position, grades: Master of science, The Chinese University of Hongkong, China. Scientific interest: Computer Science, Automatic control. Publications: 2 papers Experience: Xinlei LI received his Bachelor degree in City University of Hongkong, has completed two scientific research projects.

CONFLICT OF INTEREST

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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