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A Common Ground Experiment Testbed for Synthetic Mission Demonstration of Small Satellites

Xiaoqian Chen, Wen Yao, Yiyong Huang and Yong Zhao
College of Aerospace and Materials Engineering,
National University of Defense Technology,
Changsha, China
chen12302@vip.sina.com

ABSTRACT

***A*This paper introduces the development of a ground experiment testbed for synthetic mission demonstration of small satellites in National University of Defense Technology (NUDT). This testbed consists of five parts: test platform, small satellite simulator, monitoring and control system, data collecting and simulation system, and displaying system. It can simulate small satellite motion with two or three degree of freedom by means of smooth granite platform and air bearing system, and support hardware-in-the-loop simulation. This experiment testbed has been applied to several multi-satellite mission demonstration projects, including the formation flying of three small satellites, the rendezvous and docking of two small satellites, the on-orbit refueling demonstration, etc. The experiment processes as well as the results of these experiments are given in this paper.**

Keywords- Small Satellite; Ground Experiment Testbed; Mission Demonstration

I. INTRODUCTION

With development of space technology, many new concepts and missions related to small satellites are proposed.

To realize the function of large monolithic satellite with small satellites which have volume, power and weight constraints, the concept of small satellite formation flying which constitutes a virtual large satellite is proposed. Take Orion-Emerald mission for example [1], this experiment planned to demonstrate the key technologies of formation flying and provide support for future development of small satellite formation constellation which posses much more powerful radar or optical earth observation capability. This concept is also mentioned as satellite cluster. This new form of satellite has greater advantage over the traditional large satellite. Firstly, the small satellite is much easier to develop and launch. Secondly, the formation can flexibly reconfigure and degrade to use with one of them being failed. To replace the failed one is also cheaper and applicable. So the formation flying satellite cluster is more reliable and with less risk and cost.

As the wireless communication technology and spacecraft modularization technology gradually become mature, and wireless energy transfer becomes technical applicable, a fresh new concept of fractioned modular satellite is proposed [2-3], such as the project named System F6 (Future, Fast，Flexible，Fractionated，Free-Flying Spacecraft united by Information eXchange) led by DARPA, USA [4-5].

Figure 1. F6 Diagram

In the fractioned module satellite, the large satellite is partitioned into several small satellite modules. Each module is a subsystem of the whole satellite system, such as power subsystem and communication subsystem, and plays the role of the specific subsystem to the fractioned whole system just likes the one in the traditional monolithic integrated satellite. All the subsystem modules can both integrate into a large satellite by physical connection (via docking system) and integrate into a virtual large satellite through wireless communication and energy transfer in a fractioned formation. This concept is a big breakthrough to the traditional satellite concept. By utilization of modularization, serials of modules can be developed and manufactured massively, so as to reduce the research cost and risk. By combination of these modules to meet different requirements, fast space response can be realized. The on-orbit module can be flexibly replaced for repair or upgrade, and new module can be added to enhance function of the satellite system. Strictly speaking, each module is not a complete satellite as it only has partial function such as providing power or communication, and can’t run independently, for example the data handling module can’t run without the power provided from the power module. So in this paper, we treat it as the small satellite module which has some similarity to small satellite. This new concept satellite will bring great impact on the aerospace engineering.

As the need for on-orbit servicing becomes more and more urgent, the development of small servicing satellite, such as free-flying space robot, becomes the frontier field of aerospace research [6]. The small satellite with maneuverability can get close to the target satellite, and inspect, repair and refuel it. A small satellite can even been used as a fuel tank and attached to a target to provide it with extra fuel. Small satellite can also dock with each other and construct a large space structure which also means on-orbit assembly.

All the aforementioned new concepts are very useful for the application of small satellites. But on the other hand, the combination of many small satellites is very complex because it needs plentiful information exchange as well as collaborative control. To reduce research risk and cost, it’s very important to validate key technologies and demonstrate mission functions synthetically in the research and developing procedure. Several hardware-in-loop spacecraft experimentations in laboratory are developed by universities, such as ground experiment system of reconfigurable robot satellites [7], micro-satellite ground test vehicle for proximity and docking operations [8], the test bed for proximity navigation and control of spacecraft for on-orbit assembly and reconfiguration [9], and experimental demonstration of technologies for autonomous on-orbit robotic assembly [10].

Since 2005, we began to build a ground experiment testbed which is capable of demonstrating integrated small satellite mission, especially for the mission constituted of several small satellites. The testbed is already completed and we have finished several experiments on it. The result shows that this testbed is very useful for studying the key technologies of small satellites cluster, and demonstrating the cooperation effect of the group and the synthetic function of the whole system. In this paper, this testbed and three typical small satellite mission demonstration experiments carried out on it will be introduced thoroughly.

II. GROUND EXPERIMENT TESTBED

The schematic diagram of the testbed is shown in fig. 2. It mainly consists of five parts: test platform, small satellite simulator, monitoring and control system, displaying system, and data collecting and simulation system.

A. Test platform

The test platform has three parts. One is a rectangle granite platform with size of 6×8 meters, one is a rectangle granite platform with size of 2.5×1.8 meters, and another one is a slide rail with length of 8 meters. The platforms have very smooth surface and act as a frictionless base for the movement of satellite simulator. Each platform has a group of pillars, which can be used to support the platform and can roughly level the flatness of the bed. Its non-flatness will be compensated by the control algorithm in the experiment. The size of the largest platform is sufficient to simultaneously run several small satellite simulators. The smaller rectangle platform with two small satellite simulators on it is shown in fig. 3.

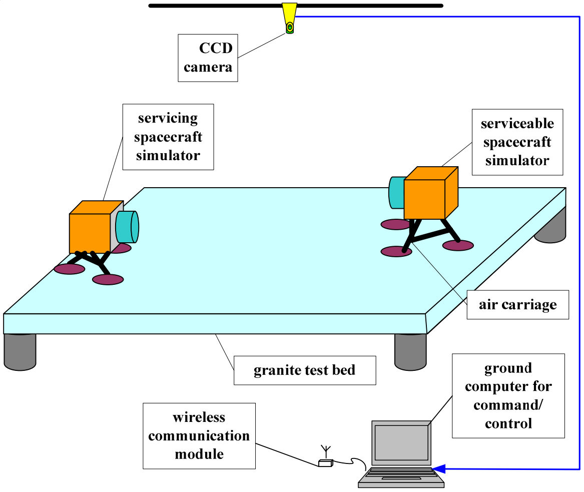

Figure 2. Schematic diagram of ground experimental system

Figure 3. Test platform

B. small satellite simulator

Small satellite simulator is the key component of this system as depicted in fig. 4. It is a modular satellite with air bearing system. The satellite simulator can move with three degrees of freedom on the rectangle platform and two degrees on the slide rail. The main subsystems of the small satellite simulator include a propulsion module, a wireless communication module, a measure module, an on-board computer module, a docking mechanism (for demonstration of satellite docking and assembly, optional for specific experiment requirement), a frame structure and an air bearing system. The simulator adjusts the position and attitude by six cold-gas thrusters. The vision guidance system gets image and calculates relative position, velocity and attitude data for the movement control software installed in the ground computer. Then, the ground computer estimates parameters according to the data and gives the control command to the wireless communication module, which sends the command to the wireless communication module installed on the simulator and further transfer to the on-board computer module. After the on-board computer module receives the command, it will open or close the electromagnetism valve, so as to control the motion of the simulator.

The main parts are listed in the following.

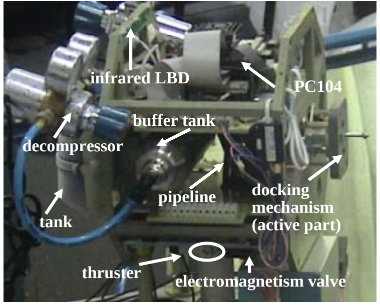

Figure 4. Small satellite simulator

1) Propulsion module

The propulsion module consists of two cold-gas tanks with decompressor systems, one buffer tank used to hold air pressure, six cold-gas thrusters with electromagnetism valves, and pipelines. The propellant is liquid carbon dioxide. Both of the simulators' translation and rotation movement on the test bed can be controlled by the cold-gas thrusters. The Layout of thrusters in the propulsion module is described in fig. 5. The thruster 1 and 2 push the simulator to move forward, while the thruster 4 and 5 push the simulator to move backward. The thruster 3 pushes the simulator to move rightward, while the thruster 6 pushes the simulator to move leftward. The thruster 1 and 4 turn the simulator to right, while the thruster 2 and 5 turn the simulator to left. The thrust of each thruster is 0.4N.

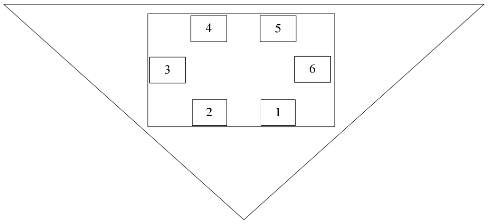

Figure 5. Layout of thrusters in the propulsion module

2) On-board computer module

The on-board computer module is an embedded standard architecture. In this module, PC104 is used considering its open and abundant resources, and its size and weight features etc. The frequency is 500MHz, and the internal memory is 256MB. It has RS-232/485, USB, LCD/CRT and KEY standard interfaces. It is used to handle all of the data and command, which is the core of the whole simulator system. It implements attitude and propulsion control, docking and undocking control, data communication, state display and feedback, power control and so on.

3) Wireless communication system

The wireless communication system includes two parts: one is installed on the ground and the other one is installed on the simulator. As the calculation capability of the on-board computer is limited, the complex calculation task is run in the ground computer and the results and commands are sent to the simulator by wireless communication system. The baud rate is 9600bps. The experiments showed that this data rate is sufficient for all the complex mission demonstrations.

4) Docking system

The docking system is mainly for the experiment of on-orbit servicing and assembly, etc. It is divided into two homologous parts: an active part installed on one simulator and a passive part installed on another simulator. As shown in fig. 4, the active part consists of a docking plate, a capture spear, a tolerance cone-hole and a lock device. Since both the active and passive parts have a spear and a cone-hole, one puts its spear into the other's cone-hole during docking. And then, the lock device driven by motor locks each other and finally two parts are connected rigidly. The docking system is compact designed with small size and light weight. It can be flexibly installed and disassembled on the simulator so as to meet the specific mission requirement.

5) Air bearing system

The air bearing system is composed of three air pads and an electromagnetism valve. Air used by pads originates from one of the two cold-gas tanks. The air bearing system can lift the experiment satellite with a thin air film, and reduce the friction between satellite and platform nearly to zero. Each air pad can support 70 kg.

To sum up, the main parameters of the small satellite simulator are listed in table 1.

Table 1. Main parameters of small satellite simulator

size	length & width	0.3 m
	height	0.5 m
	mass	20 kg
propulsion	propellant	Liquid CO_2
	tanks	0.5L/15MPa
	buffer tank	0.7L/0.4MPa
	thrust of each thrusters	0.4 N/ 0.2 N
electrical & electronic	power	24V lithium
	computers	PC104 PIII
docking /capture tolerances	max lateral	+/- 2 mm
	max angular	+/- 1 deg

C. Monitoring and control system

The monitoring and control system mainly includes a video guidance system, which comprises a CCD camera hanged on the ceiling, infrared LED on the simulator and an image solver installed in the ground computer. The system is used to measure the relative position and attitude between the satellite simulators. The images acquired by the CCD camera are transmitted to the ground computer and the solver calculates the relative position and relative attitude for the movement control algorithm. The measure accuracy is 1mm.

Figure 6. CCD camera hanged on the ceiling

D. Data collecting and simulation system

The data collecting system includes several sensors installed on the simulators and around the testbed platforms, which can collect the experiment data and transmit to the ground computer simultaneously for analyzing. With this system, the simulation software and the physical experiment data can be integrated and support the hardware-in-the-loop simulation.

E. Displaying system

The displaying system is constituted of a large globose screen as well as projectors, which can simultaneously display the sky background as well as the operation status.

III. MISSION DEMONSTRATION EXPERIMENTS

This experiment testbed is already applied to several project of our group. For example, the formation flying of 4 small satellites, the rendezvous and docking of two small satellites, the on-orbit refueling demonstration, etc. The process as well as the results of these experiments will be given in this paper.

A. Rendezvous and docking experiment

In the rendezvous and docking experiment, we assume that the friction drag can be neglected based on the air bearing system. The chaser simulator receives the docking command from the ground computer, and then approaches the target simulator and finally completes the autonomous docking by changing its position and attitude via six cold-gas thrusters. The relative guidance data of the two simulators is obtained by the measurements from the CCD camera vision guidance system.

We use PID controller in the experiment. The controller is based on Back-Propagation Neural Network (BPNN) using Automatic Differentiation Method (ADM) [11-12]. This controller is quite robust and can overcome the disturbance induced by the inclination or roughness of the testbet surface, and the uncertainty in image processing and data transmitting delay time. To avoid frequent control, it is with dead zone and limiting output. Unscented Kalman Filter (UKF) is adopted to reduce the effect of measurement noise. The controller flowchart is shown in the fig. 7.The distance error of measurement is no more than 2 mm while the angle error is less than 1 degree.

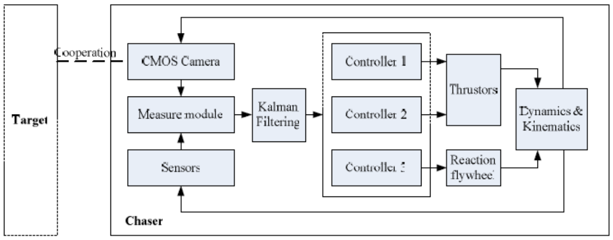

Figure 7. Controller flowchat of rendezvous and docking experiment

The control method proposed above is applied to numerical simulation and physical experiment. To demonstrate the experiment, we should firstly define the coordinate system, as shown in fig. 8.

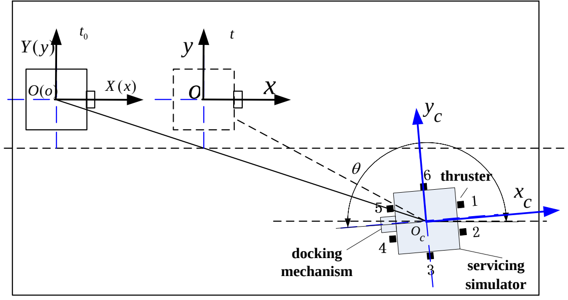

Figure 8. Coordinates definition

oxy is defined as the body coordinate system of the target, centered in its centroid; and OXY is defined as its body coordinate system at the initial time, whose origin is the centroid of the target at the initial time. As the maneuver process is relatively short to the orbital period, OXY can be assumed to be inertial in this experiment and will align with oxy only through translation.

The definition of $o_c x_c y_c$ is similar to oxy, but its origin is the centroid of the servicer. It is obvious that the relative attitude angle θ depicted in fig.8 should be 180 degree, when the requirements of docking are satisfied.

The dynamic equations of servicer are given by

$$\begin{cases} \ddot{x} = a_{cX},\ \dot{x} = v_{cX} - v_{oX},\ x = X_c - X_o \\ \ddot{y} = a_{cY},\ \dot{y} = v_{cY} - v_{oY},\ y = Y_c - Y_o \\ I\ddot{\theta} = M_c \end{cases}$$

where (X, Y), (v_X, v_Y) and (a_X, a_Y) are the position, velocity and acceleration respectively along the X and Y axis. The subscript *c* denotes servicer while *o* denotes the target. *I* is the moment of inertia of the servicer.

In the experiment, we assume that the target neither rotate nor translate in our experiments. So the oxy coordinates frame coincides with the OXY reference frame.

a) Numerical simulation

In the experiment, the chaser is controlled to make the relative attitude and relative position component along axis Y under the allowed values firstly, and then approaches the target along x axis. x*, the terminal relative position along axis X, is desired to be 0.35m owing to sizes of the docking mechanism and the simulator. The whole simulation lasts about 69 seconds and the results are shown in fig. 9. The initial and desired relative parameters in present analysis are as follow:

x_0=2.5m, y_0=0.5m, θ=135°, x^*=0.35m, y^*=0 m.

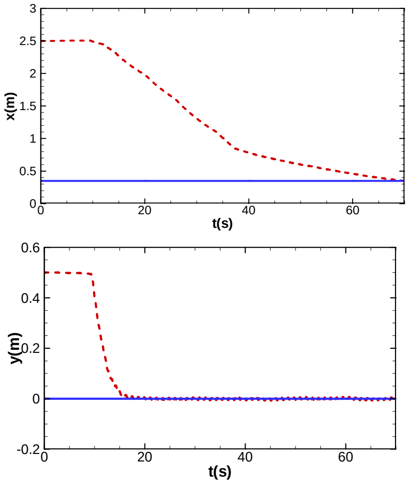

Figure 9. Curves of relative parameters in numerical simulation

b) *Physical experiment*

The aforementioned PID controller has been coded in C++ and run in real time on the onboard computer of the chaser spacecraft simulator. During the experiment, the target vehicle is kept fixed. The maneuver consists of autonomously approaching the target and then docking to it. In this experiment, the chaser, which starts from an offset position and attitude, first reduces the angular error by attitude maneuver and then approaches the target. The process is shown in fig.10, and the curves of relative parameters are shown in fig. 11. The entire maneuver lasts about 71s. The initial and the expected relative position parameters of the chaser are:

x_0=1.95m, y_0=0.43m, x^*=0.35m, y^*=0 m.

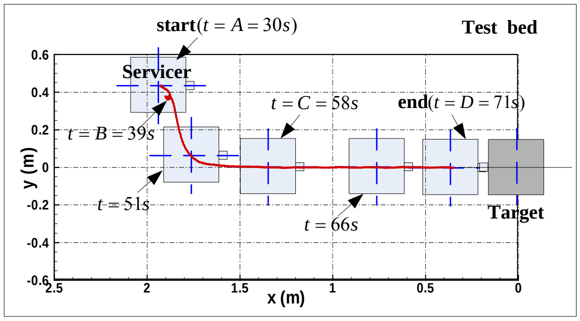

Figure 10. The motion of the chaser viewed from the top

It can be seen from the figure that the controller algorithm is quite effective.

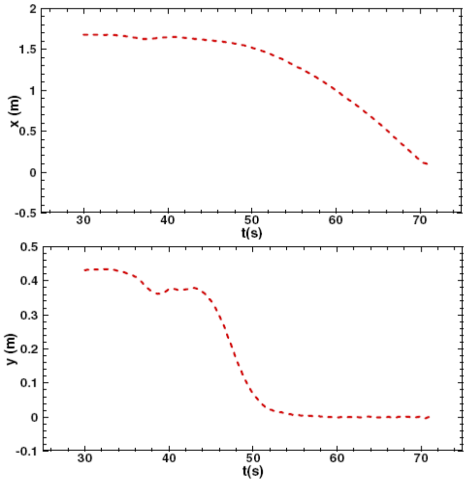

Figure 11. Curves of relative parameters in physical experiment

B. *Formation flying Exeriment*

The architecture of the formation flying experiment is shown in fig.12. There are three small satellite simulators in this experiment. They move according to the pre-designed orbit and cooperate with each other in the formation triangle. There is an earth simulator on the platform which demonstrates the focus of orbit of the formation flying ellipse orbit. The relative position and attitude data are real time collected and the control commands are generated by the algorithm run on the ground computer. And the control data are transmitted to all the simulators simultaneously to maintain the formation. Their configuration can also be changed according to specific requirement. The navigation and control system has been proved to be robust and reliable.

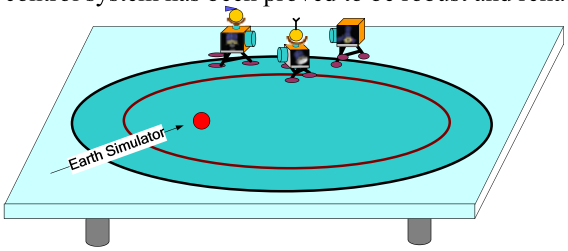

Figure 12. Formation flying Exeriment

C. *On-orbit refueling demonstration*

This experiment is based on the experiment rendezvous and docking Experiment. It can demonstrate one servicing satellite to one target satellite refueling and one servicing satellite to multi target satellites refueling.

In the one to one mode, the servicing simulator and the target simulator are both installed on air bearing systems. The procedure is as follows:

firstly, the servicing simulator rendezvous and docks with the target. Secondly, the servicing simulator checks the leak tightness of the pipes and valves. If all the conditions meet the requirement, step into the following step. Thirdly, the servicing and target simulator open the valves and begin to transfer fuel. When the transfer amount requirement is met, the on-board computer stops the transfer. When the refueling task ends, the two simulators separate.

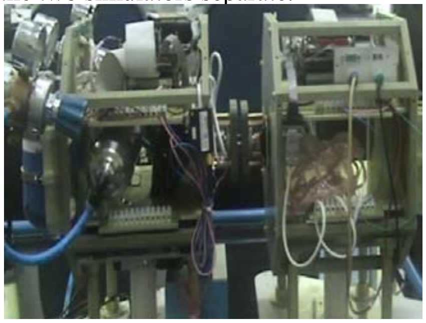

Figure 13. Docking and refueling

In the one to multi target mode, the servicing simulator will use path programming algorithm to get the optimum refueling scheme and then provide refueling to the targets one by one. To each target, the refueling procedure is the same as the above one to one mode.

IV. CONCLUSION

In this paper, a ground experiment testbed for synthetic mission demonstration of small satellites developed in NUDT is introduced. The testbed can provide two or three degree of freedom motion by means of smooth granite platform and air bearing system. The simulators can be controlled remotely by the ground computer through wireless communication. The data collecting system can get real time data for mission assessment and analysis, and support hardware-in-the-loop simulation. Now we have done several integrated demonstration on this testbed successfully, including the formation flying of three small satellites, the rendezvous and docking of two small satellites, the on-orbit refueling demonstration, etc. In the future, we plan to do the following experiments:

(1) Multi-sensor synthesis technology. Each module carries different payload. All the sensor data are transmitted to the ground computer for synthesis analysis. We may even use an on-board computer to run the algorithm.

(2) On-orbit assembly experiment, especially those with complex structure.

(3) Fractioned module satellite experiment. The cooperation of all the modules will be fully demonstrated.

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