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## **A Development of the Dynamic Motion Simulator of 3D Micro-Gravity with a Combined Passive/Active Suspension System**

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### **KEY WORDS**

Micro-Gravity Testbed, Hybrid Simulation, Pendulum System, Free Body Dynamics, Collision Dynamics

### **BACKGROUND AND GOAL OF THE PAPER**

The establishment of those in-orbit operations like “Rendez-Vous/Docking” and “Manipulator Berthing” with the assistance of robotics or autonomus control technology, is essential for the near future space programs. In order to study the control methods, to develop the flight models, and to verify how the system works, we need a tool or a testbed which enable us to mechanically simulate the micro-gravity environment; but it's not that easy.

There are a lot of attempts to develop the micro-gravity testbeds, but once the simulation goes into the docking and berthing operation that involves mechanical contacts among multi bodies, the requirement becomes suddenly critical. The testbed must move in 3D space with a very high frequency response to follow the impact or collision, which class of motion is very difficult to be modeled and numerically simulated by a computer, the hardware simulation or experiment by a testbed therefore is the only way to study.

A group of the Tokyo Institute of Technology has proposed a method that can simulate the 3D micro-gravity producing graceful, smooth repose to the impact phenomena with relatively simple apparatus. Recently the group has carried out basic experiments successfully using a prototype hardware model of the proposing testbed.

This paper will present our idea of the 3D micro-gravity simulator and report the results of our initial experiments.

### **MICRO-GRAVITY TESTBED OVERVIEW**

In order to study real mechanical dynamics and demonstrate the practical validity and effectiveness of a control system using actual sensors, computers and mechanical assemblies, we need experiments with a laboratory model. However, reproducing the micro-gravity environment is not an easy task because we cannot obtain natural 3D zero-gravity or perpetual free-falling environment on earth. In general, the following methods could be available for emulating psuedo-zero-gravity:

1. Do experiments either in an airplane flying along a parabolic trajectory or a free-falling capsule. In this case, we can observe the pure nature of micro-gravity, but the cost of such experiments are very

high. In addition, this environment is very inconvenient and accommodates only very short duration experiments.

2. Do experiments in a water pool with the support of neutral buoyancy. This is especially good for the training of astronauts' activities, but from a micro-gravity dynamics point of view, water current and drag forces disturb the dynamic motion.
3. Suspend an experimental model by tethers to cancel the vertical gravitational motion. In case active counter-balancing is employed, the design of a quick response, vibration free and simple suspension control must be a key issue.
4. Support an experimental model by air-cushions or air-bearings. This is the simplest method; however, the motion is restricted to a horizontal plane.
5. Calculate the motion which should appear in zero-gravity environment based on a mathematical model, then force the corresponding mechanical model to move according to the calculation. This method is called as a 'hybrid' simulation, a combination of mechanical and mathematical models. A testbed developed at the MIT comprising a 6DOF Stewart platform and a PUMA manipulator is classified into this category [1]. In the system, the platform provides base vehicle motion in a simulated micro-gravity dynamics based on the reaction torque sensing between the PUMA and the platform. This class of method is useful especially for 3D kinematic motion, but for the dynamic simulation, the computation and servo-control bandwidth becomes critical.

A group of the TIT has developed the air-bearing type of testbed named EFFORTS (Experimental Free-Floating RoboT Satellite simulator) and got excellent experimental results for many years [2][3]. The advantage of this testbed is that we can observe the nature

of mechanical system in a frictionless floating environment, but the drawback is the limitation to 2D motion.

For the 3D simulation, we decided the tethered hanging system, but paying attention that we should keep the advantage to observe the nature of pure dynamics; the solution to this requirement is to combine a passive mechanical system and an active control system. The detail shall be presented in the following section.

## OUR PROPOSING 3D MICRO-GRAVITY SIMULATOR

### Basic Principle

Imagine that a body is suspended by a spring, like Fig.1. If the spring is very long, we have a very small (close to zero) pendulum force for a small horizontal displacement.

$$F_x = mg \frac{\Delta x}{\ell} \cong 0 \quad : \text{if } \ell \text{ is large.}$$

And if the spring has a very low stiffness, the spring force is almost constant (just equals to the gravity force) for a small vertical displacement around the equilibrium point.

$$F_z = mg \cos \theta + k \Delta z \cong mg \quad : \text{if } \theta, k \text{ small.}$$

This simple mechanical system will accommodate a passive suspension to cancel the gravity with almost zero disturbance for small displacements to all directions.

If the displacement of the body reaches not a small amount, we should actively move the top of the spring to follow the body motion, however this active motion is not necessary so fast, just to follow and absorb vibration.

In conclusion, the proposing suspension system should be composed by a long and compliant spring and an active tracking mechanism to move the top of the spring. The passive spring will be transparent and give almost no disturbance to the high frequency force or impact dynamics of the body, and simultaneously, the low frequency gross motion is followed by the active tracker at the top.

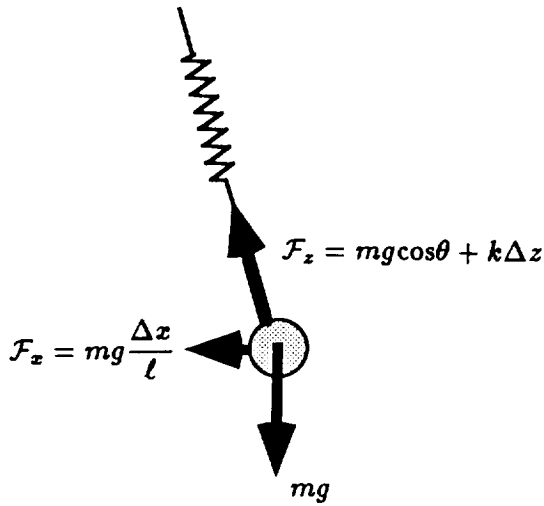


Fig.1 Basic principle of the suspension system

Combining a passive mechanism into the system, we can relieve the servo-controller from the requirement of high frequency response, which point is always a critical key for “hybrid” type of micro-gravity simulators. This is the advantage of the proposing Combined Passive/Active suspension system.

### Hardware Design and Control

The developed prototype system is shown in Fig.2.

To provide the 3D (x-y-z) active motion of the top of spring, though any types of tracker will be available, we employed a three-tether system for the convenient installation and lower cost per working area than a Cartesian-type linear motion table.

In the figure, points A, B, C, and P form a pyramid with a regular triangle base ABC on the horizontal ceiling. Controlling wire lengths AP, BP and CP with each reel over the ceiling, we can arbitrary position P in the Cartesian 3D space.

The micro-gravity simulated object (a plate in the figure) is supported by a passive gimbal system to allow the natural rotation, and hooked by a long and compliant spring with the driving system at the top.

The motion of the object (plate) is measured by a real-time 3D vision analysis system (named “Quick Mag” developed by

OKK Inc, Japan), and when it detects the displacement of point Q, the driving system translates the point P exactly above Q in the distance of the equilibrium spring length.

From a control system point of view, this is a non-collocate flexible system. However, our control goal is not fine positioning of the tip, but gross motion tracking and vibration absorption. Simply speaking, if the control system responses smoothly and quickly in higher frequency than the nature of the spring-pendulum system, the simulation system works. The long and low stiffness spring suspension contribute, again, to make the mechanical natural frequency lower, henceforth the control system implementation easier.

### EXPERIMENTS AND CONCLUSION

The developed system works very well to follow the natural micro-gravity motion of the supported body. We have carried out collision experiments that the body hits an fixed wall, or two supported bodies collide each others. We measured the whole sequence of the collision, then estimated the micro-gravity environment that the system can accommodate.

The mass below the spring is  $m = 0.3$  [kg] and the spring compliance about  $k = 0.3$  [kg/m], then the natural frequency of the spring-mass system for vertical vibration  $\omega_v$  is

$$\omega_v = \sqrt{\frac{k}{m}} \cong 1.0 \text{ [Hz]}.$$

The total length of the spring about  $\ell = 2.0$  [m], then the natural frequency as pendulum system for horizontal swing  $\omega_h$  is

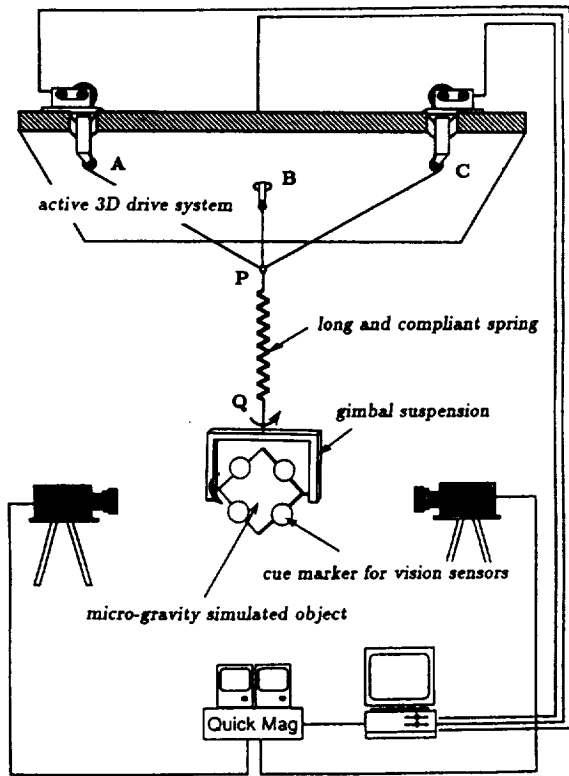
$$\omega_h = \sqrt{\frac{\ell}{g}} \cong 0.45 \text{ [Hz]}.$$

Comparing with these frequencies, the servo-controller frequency for the driving system is much faster (higher than 20 [Hz]), the system then follows the object motion smoothly with undesirable vibration or swing well damped.

As the result of the collision experiments (where a metal ball supported by the

developed combined active/passive system hits an aluminum plate supported by the passive hanging system with a gimbal. See Fig.3), we identified the disturbance acceleration of the developed mechanical simulator as about 0.01G when the object moves 0.1 [m/s] and 0.1G when the object moves 1.0 [m/s], the loss of momentum among the bodies through the collision is just 3.3% in average of more than ten times experiments.

In this paper, we proposed a new type of 3D micro-gravity testbed with a combined passive/active suspension system. The key was the introduction of a very compliant and low frequency mechanically passive part into the testbed. Such a passive suspension



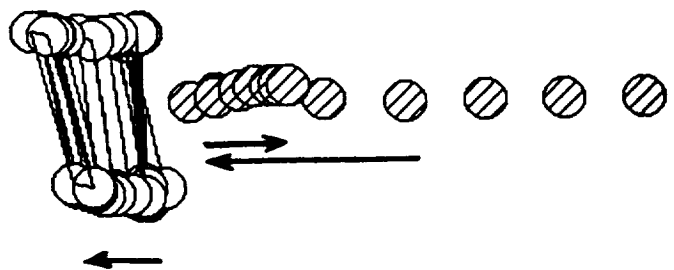
**Fig.2** The developed Dynamic 3D Motion Simulator with a Combined Passive and Active Suspension System

accommodates very small disturbance for the higher frequency impact dynamics, as well as relieves the active gross-motion tracking system from the high frequency response requirement.

Although the developed prototype testbed was very primitive, it worked relatively well showing good performance especially for the study of free body collision dynamics.

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**Fig.3** An experiment of collision between the suspended plate and ball