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Research paper

Preliminary design and development of an active suspension gravity compensation system for ground verification

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ABSTRACT

A new active suspension gravity compensation system (ASGCS) is developed to offload the gravity of spacecraft or satellites for ground verification. The ASGCS is of six degrees of freedom (6-DOF), including a compensation stage of 3-DOF translation and a gimbal of 3-DOF rotation. A buffer-assisted pinion-rack mechanism is developed to substitute the traditional cable suspension unit, which enables the proportion of gravity compensation is tunable. A new 3-DOF gimbal that is suitable for objects of various sizes and arbitrary shape is developed. Hence, the test object attached to the ASGCS can be free-floating as it is in the outer space. Furthermore, a prototype of the ASGCS is developed, and the dynamic model and kinematic model are derived. Experiments are conducted with the aid of a 6-DOF hybrid coordinate manipulator. The results demonstrate that the ASGCS successfully tracks 6-DOF trajectories of a typical docking task and compensates for 95% of the gravity.

1. Introduction

One of the key differences between the outer space environment and the ground environment is that the space is micro-gravity (micro-g). To reconstruct the spacecraft motion in the outer space on the ground and improve the fidelity of ground verification [1–5] of guidance and control system, the micro-g environment and full DOFs are required [6,7]. Various approaches have been proposed such as weight loss [8,9], air-bearing [10,11], neutral buoyancy [12] and suspension systems [13–16]. These methods may be beneficial in some aspects, however, they are limited in others. The suspension approach is relatively superior compared with other methods because of its economy, practicality and reliability.

There are two types of suspension method, namely, passive suspension [14] and active suspension [15,16]. The active one performs much better because of its controllability and less introduced mass. Many scholars and engineers have devoted themselves to studying the suspension gravity compensation mechanisms [17,18] and systems. Zero-rate mechanisms, typically as zero-spring-rate mechanism and air cylinder, are proposed. Various compensation platforms have been developed and applied to engineering practice. 3-DOF or 6-DOF passive platforms are proposed for testing space robots and small satellites. Active systems are more popular and platforms with various DOFs are developed.

A mechanical zero-spring-rate mechanism (ZSRM), proposed by Crawley et al. [14], has been applied to compensate the gravity of the test load. The ZSRM is mainly composed of a main spring and a side spring. However, it is difficult to tune the spring tolerances in manufacturing process, which are needed to precisely balance the position stiffness of the main spring against the negative stiffness of the side spring. Moreover, the main-and-side springs mechanism defines a limited

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Nomenclature

$o_w - x_w y_w z_w$,	world coordinate system, where x_w axis, y_w axis, z_w axis are parallel to the X linear unit, the Y linear unit and the Z linear unit, respectively, and o_w is in the same horizontal plane with the Z motor shaft;
o,	meshing point of the pinion and the rack of the Z linear unit;
o_1,	mass center of the pinion;
o_2,	mass center of the rack;
o_3,	mass center of the universal joint;
o_4,	mass center of the spacecraft simulator;
β,	swing angle between the spring buffer and the vertical direction;
β_x, β_y,	orthogonal decomposition of β;
$o - xyz$,	coordinate moving with o, where the axes are parallel to the corresponding axes of the word coordinate system;
$o_i - x_i y_i z_i, i = 3, 4$,	coordinates moving with o_3 and o_4, where their axes are parallel to the corresponding axes of the word coordinate system;
$o_3 - x_{31} y_{31} z_{31}$,	coordinate swinging with the spring buffer;
h_0,	length of the rack;
l_0,	initial length of the spring;
α,	rotational angle of the pinion;
R,	radius of the pinion;
g,	gravity acceleration;
M,	total mass of the spacecraft simulator and the 3-DOF gimbal;
k,	spring constant;
m_{0x}, m_{0y},	load of the X motor and the Y motor;
m_1, m_2,	mass of the gear and the rack of the Z linear unit;
F_x, F_y,	equivalent driven forces of the X motor and the Y motor on the X and Y linear units;
T_x,	output torque of the Z motor on the pinion;
F_{4x}, F_{4y}, F_{4z},	object driven forces;
T_{4x}, T_{4y}, T_{4z},	object driven torques.

translational range only along the vertical direction. In addition, there have been developed other springs based gravity balancing mechanisms (e.g., the passive gravity compensator implemented by three extension springs in [17]).

A passive 3-DOF test platform has been addressed in [19]. The passive mechanism, consisting of cables, pulleys and counterweights, was used to provide a constant vertical balance force. A controllable overhead carriage was developed to maintain the support point directly over the robot. However, when the joint of the test robot moves downwards without correctly adjusting the position of the counterweights, the passive test platform is ineffective. Furthermore, the rotational DOFs are absent.

Constant-force mechanisms have been researched in recent years [20]. A 6-DOF zero-g test platform has been presented in [21]. The platform adopts the passive spring suspension approach and can compensate any amount of the gravity (from 0% to 100%) in 3D space. The test object can experience a micro-g free floating state with a gyroscope-like gimbal [22]. However, it is difficult to satisfy the specific stiffness requirements of the springs to achieve the functions mentioned above. Furthermore, it is challenging to maintain the structural stability and the friction of the platform when the mass of the test object is large. In addition, as the main support components, the springs are exposed to fatigue failure.

A zero 6-DOF gravity simulator designed for experiment pointing mounts (EPMs) has been proposed in [23]. A cable was equivalently attached to the mass center of the test payload through a gimbal. A closed-loop force-control loop was designed to maintain a constant tension in the cable. The overhead translational structures tracked the suspension point horizontally to keep the cable vertical. This simulator is a typical active suspension gravity compensation system, and the other variants generally adopt part of the functions or improve part mechanisms. However, it is difficult to measure the small angle between the cable and the vertical direction.

A multiple DOFs micro-g emulation system has been developed in [24] to compensate the gravity of a space manipulator. The emulation system used two suspension arms to follow the horizontal trajectories of the space manipulator, and thus each wire attached to the space manipulator was maintained perpendicular to counterweigh the gravitational force. However, this system is too complicated to control all axes synchronously.

A suspended target emulation pendulum (STEP) [25] of 5-DOF has been developed to simulate the proximity operations involving contact dynamics. The STEP featured a pendulum motion simulator and was equipped with a rotating joint to simulate the pure spin of the attached mock target vehicle. The target vehicle was suspended by a universal joint through a cable at or very close to its gravity center that allowed a small range motion of the target in the other two rotational DOFs orthogonal to the pendulum. Hence, the target vehicle can swing as a pendulum. The swing ability allowed the in-