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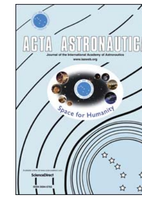

Divergence compensation for hardware-in-the-loop simulation of stiffness-varying discrete contact in space

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ABSTRACT

The hardware-in-the-loop (HIL) contact simulation for flying objects in space is challenging due to the divergence caused by the time delay. In this study, a divergence compensation approach is proposed for the stiffness-varying discrete contact. The dynamic response delay of the motion simulator and the force measurement delay are considered. For the force measurement delay, a phase lead based force compensation approach is used. For the dynamic response delay of the motion simulator, a response error based force compensation approach is used, where the compensation force is obtained from the real-time identified contact stiffness and real-time measured position response error. The dynamic response model of the motion simulator is not required. The simulations and experiments show that the simulation divergence can be compensated effectively and satisfactorily by using the proposed approach.

1. Introduction

The simulation of contact process on the ground is very important for many space missions [1,2], e.g., spacecraft docking and space robot manipulation. The active spacecraft docks with the target spacecraft (e.g., space station) through the docking mechanisms (DM) for subsequent missions. The contact force will be produced after two spacecrafts contact through the DM. The relative motion of two spacecrafts will be changed according to the dynamics law. Then the new contact force will be produced and further change the motion of two spacecrafts. This contact process will continue until the completion of the space task. To design and verify the docking system, the contact dynamics process should be simulated on the ground. The main difficulty is that the simulator in the one-gravity (1-g) environment should reproduce the contact process in the zero-gravity (0-g) environment [1,2].

To simulate the contact process of flying objects in space, three classes of approaches have been developed. The full numerical simulation [3–6] only uses software, therefore it is low-cost and flexible on the changes of simulated objects. In general, the relative motion of the spacecrafts with respect the force is accurate enough, while the accurate contact model of the real DM is difficult to be obtained. Therefore, the contact experiments on the real DM are still necessary. The full physical simulation can test the real contact process of the real DM on the spacecrafts physical model in a 0-g emulation environment. The 0-g emulation methods include the air-bearing supported floating [7–10], suspension system [11,12] and so on. The full physical simulation has a high fidelity, however it is inconvenient to change flying objects. For the hardware-in-the-loop (HIL) or hybrid simulation, the relative motion of spacecrafts with respect to the force in the 0-g environment is calculated by a numerical model and implemented by a motion simulator. The real DM is installed on the motion simulator to generate the real contact force. Therefore, the HIL simulation can achieve both high fidelity and high flexibility.

Many HIL simulators have been developed to simulate the contact process in space, e.g., the European proximity operations simulator (EPOS) [13–15], the special purpose dexterous manipulator (SPDM) task verification facility (STVF) [16–19], the space capturing ground experiment system [20,21], the six-degree-of-freedom (6-DOF) test system (SDTS) [22], the rendezvous and docking operation testing system (RDOTS) [23], the shuttle on-orbit berthing ground experiment system [24], the 6-DOF docking simulator [25,26], and the dual-arm space robot ground experiment system [27–29].

One challenging problem for the HIL contact simulator is the simulation divergence. The coefficient of restitution (CoR) (i.e., the ratio of the approach velocity before the contact and the rebound velocity after the contact) will be larger than the real value.

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Therefore, the contact velocity will be larger and larger as the contact number increases. In the worst case, the DM could be damaged. The simulation divergence is caused by the time delay, i.e., the delay between the measured force and desired position. Because the force delay cannot be avoided, the delay compensation algorithm has to be developed for the HIL contact simulator. Currently, there are several delay compensation approaches with successful applications in HIL contact simulators.

- The first approach is the phase lead position compensation, where the desired position is phase leaded. For example, in [24] a second-order compensation model is trained offline by minimizing the error between the known on-orbit velocity and the ground system rebound velocity. However, the on-orbit data could be unknown in advance. In [26], a second-order filter model is designed by the quantitative feedback theory (QFT) or tuned by experience. However, the proper parameters are not easy to be obtained.
- The second approach is the phase lead force compensation, where the measured force is phase leaded. For example, in [30] a first-order and one-parameter compensation model is used to compensate the pure or first-order time delay. In [28,29] the first-order and multi-parameter compensation model is designed to compensate the pure time delay and achieve the expected CoR. The methods in [28,29] require that the undamped elastic contact model, contact frequency and time delay are known. In [15,31], a virtual force computed from a virtual stiffness and damping contact model is added onto the measured force to compensate the pure time delay and obtain the expected contact behavior. The compensator parameters are tuned based on the experimental results.

The existing delay compensation approaches depend on the experimental data and engineer experiences, or require that the contact stiffness is known and constant. In this study, a divergence compensation approach is proposed for the stiffness-varying discrete contact. The dynamic response delay of the motion simulator and the force measurement delay are considered. For the force measurement delay, it is identifiable and time-invariant, thus the model-based phase lead force compensation can be used. For the dynamic response delay of the motion simulator, it is difficult to be known and modeled due to the complicated dynamics, therefore a model-free based force compensation is expected. In particular, a response error based force compensation approach is used, where the compensation force is obtained from the real-time identified contact stiffness and real-time measured position response error. The dynamic response model of the motion simulator is not required. The simulations and experiments show that the simulation divergence can be compensated effectively and satisfactory by using the proposed approach.

The rest of the paper is organized as follows. The HIL contact simulation system is introduced in section II. The HIL contact simulation system modeling is described in section III. The HIL contact simulation divergence compensation is proposed in section IV. Section V includes simulations and experiments. Finally, some conclusions are given in section VI.

2. HIL contact simulation system

In the following, the HIL contact simulation system is introduced.

2.1. HIL contact simulation system

A HIL contact simulation system is developed as shown in Fig. 1. It includes the upper platform, the motion simulator, the force sensor, the passive DM and active DM (i.e., the physical model), the control system (including the numerical simulation model). The force sensor is installed between the upper platform and the passive DM, and the active DM is located upon the motion simulator. The system structure is shown in Fig. 2.

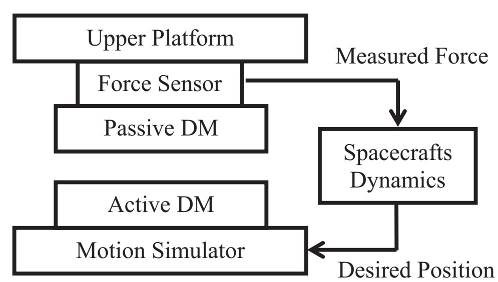

Fig. 2. HIL contact simulation system structure.

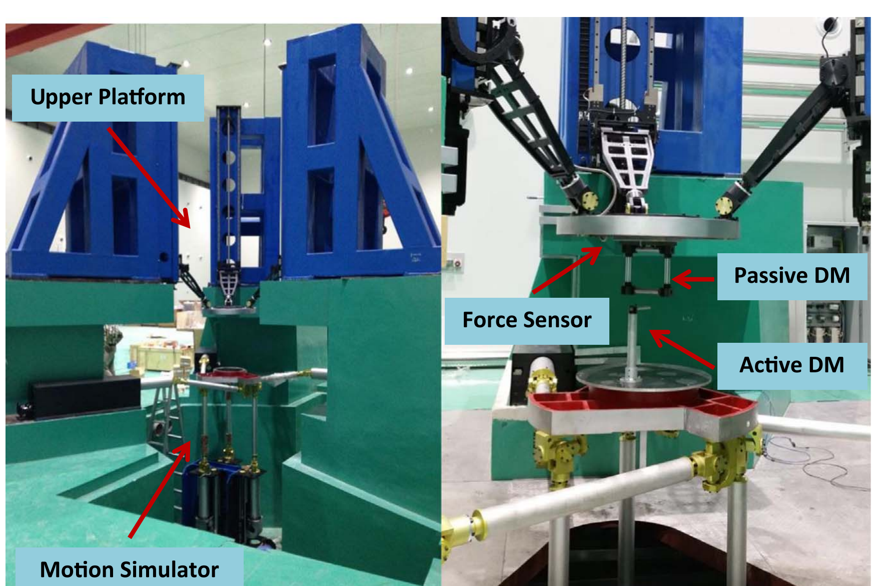

Fig. 1. HIL contact simulation system.