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Shared control on lunar spacecraft teleoperation rendezvous operations with large time delay

Zhang Ya-kun[a], Li Hai-yang[a,*], Huang Rui-xue[b], Liu Jiang-hui[a]

[a] College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, China
[b] College of Xiangya Public Health, Central South University, Changsha 410073, China

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ABSTRACT

Teleoperation could be used in space on-orbit serving missions, such as object deorbits, spacecraft approaches, and automatic rendezvous and docking back-up systems. Teleoperation rendezvous and docking in lunar orbit may encounter bottlenecks for the inherent time delay in the communication link and the limited measurement accuracy of sensors. Moreover, human intervention is unsuitable in view of the partial communication coverage problem. To solve these problems, a shared control strategy for teleoperation rendezvous and docking is detailed. The control authority in lunar orbital maneuvers that involves two spacecraft as rendezvous and docking in the final phase was discussed in this paper. The predictive display model based on the relative dynamic equations is established to overcome the influence of the large time delay in communication link. We discuss and attempt to prove via consistent, ground-based simulations the relative merits of fully autonomous control mode (i.e., onboard computer-based), fully manual control (i.e., human-driven at the ground station) and shared control mode. The simulation experiments were conducted on the nine-degrees-of-freedom teleoperation rendezvous and docking simulation platform. Simulation results indicated that the shared control methods can overcome the influence of time delay effects. In addition, the docking success probability of shared control method was enhanced compared with automatic and manual modes.

1. Introduction

The focus on debris deorbiting and on-orbit servicing push research techniques forward toward automatic rendezvous and docking (RVD) control technology with uncooperative targets [1] as well as real-time teleoperation (RTTO) technology for active debris removal [2]. Teleoperation technology could be applied to the field of robotic on-orbit servicing [3]. ROTEX was first used to telecontrol the space robot RVD with the ISS on board the Space Shuttle Columbia [4]. The ROKVISS mounted on the Russian Service Module of the International Space Station (ISS) was then realized by DLR and their partnerships in 2002 [5]. The manipulator could be teleoperated in the ground center with a force feedback system. In addition, the ETS-VII, which was established to verify the advanced teleoperation technology, was used to develop the rendezvous operations and space robotics by NASDA [6].

Unmanned and manned lunar exploration plans were proposed early in this century and have been projected to be carried out [7,8]. However, space operations in lunar orbit such as cargo ferrying and staging assembly are usually limited to the measurement accuracy of relative navigation sensors and control accuracy [9]. The accuracy of automatic RVD control system may be decreased, which could result in the failure of the whole space mission. In the frame, teleoperation RVD technology could be used as the prime option as well as a backup means for lunar orbit close proximity operation to avoid undesired collisions and mission failure [10].

In teleoperation RVD mode, the operator may be confronted with large communication time delays which may lead to the misjudgment of the relative state of the chaser and target [11]. In addition, measurement errors may result in considerable challenge to the automatic control of RVD missions [12]. Thus, the idea of shared control should be considered to improve RVD accuracy. Sheridan first proposed the concept of shared control in Ref. [13] and put the shared control theory into the field of robot control in Ref. [14]. Different degrees of freedom (DOF) were controlled in automatic and manual mean to complete the entire controlling task [15]. Shared control strategy can be used as an effective mean in the field of teleoperation in Ref. [16]. The bilateral teleoperation with time delay in the constrained environments problem was solved by adapting the shared adaptive control scheme in Ref. [17]. The space exploration minimalistic model

* Corresponding author.
E-mail address: lihaiyang@nudt.edu.cn (L. Hai-yang).

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was conducted with linear and PID-fuzzy control scheme to support future teleoperational missions in Ref. [18]. Human supervisory control is crucial to achieve future space exploration in a limited resource environment, as indicated in Ref. [19]. Filtering data process was studied for rendezvous monitoring in the practical application of the rendezvous between the Automatic Transfer Vehicle (ATV) and the International Space Station (ISS) in Ref. [20]. The shared control scheme can be more efficient than manual control teleoperation, as proven in Ref. [21].

Autonomous RVD navigation scenarios and experiments were designed to conduct numerical simulation on an air bearing table with single camera [22]. Hardware-in-the-loop (HIL) experiments for guidance navigation and control were conducted to test the on-orbit servicing in Ref. [1]. A teleoperation RVD system was designed to investigate the effect of teleoperation mode with large time delay in Ref [23]. Teleoperation RVD accuracy was enhanced using a shared control method in Ref. [24,25].

Although numerical simulations concerning teleoperation RVD missions in lunar orbit are necessary, the credibility and performance are often unsatisfactory. The sensors measurement accuracy, real time onboard data downlink rate and varying initial docking conditions required for processing can pose a great effect on the final approaching task. In this paper, we discuss and attempt to prove via consistent, ground-based simulations the relative merits of fully autonomous (i.e., onboard computer-based), fully manual (i.e., human-driven at the ground station) and shared control command techniques. Furthermore, the control authority in lunar orbit that involves spacecraft RVD mission was discussed.

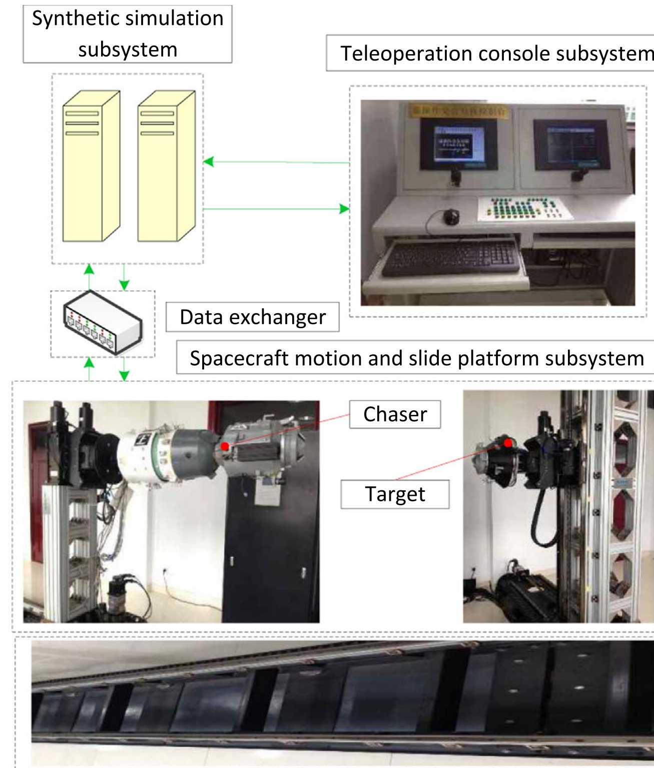

Fig. 1. Schematic diagram of teleoperation RVD system.

2. Characteristics of teleoperation RVD

RVD operations have been performed by automatic systems; alternatively, rendezvous operations have been controlled and executed by crews to telecontrol the chaser that approaches the target. The teleoperation RVD system, in the broad sense, comprises of the space station-based mode (i.e., crews command and monitor in the space station) and the ground station-based mode (i.e., crews command and monitor in ground station) [11]. Given that the automatic RVD system was thus far unable to handle the uncooperative target conditions, teleoperation rendezvous technology can be used to perform these missions as an option. In this paper, the ground-based teleoperation is considered the research subject. As shown in Fig. 1, the teleoperation RVD system was comprised teleoperation console subsystem the synthesize simulation subsystem and the motion platform subsystem. It was scaled down to 7:1 with respect to the original spacecraft RVD device and built based on the dynamic similarity principle.

2.1. Teleoperation console subsystem

The pilot seat was installed in front of the teleoperation console platform. As shown in Fig. 2, two image screens that were respectively used to display the relative position and attitude between the chaser and target were installed on the right and left sides. A three-axis translational joystick was installed on the left side of the platform, and a three-axis rotational joystick was installed on the right sides. The command panel, which was used to send emergency and stop commands, was installed in front the joysticks. The left screen (Fig. 2.(a)) shows the simulated view, which is the same as the camera installed on the nose of chaser, with a large reticle in the chaser view and a small reticle in the target docking mechanism. The right screen (Fig. 2(b)) shows the relative attitude information, i.e., the angle of yaw, roll and pitch.

2.2. Synthesize simulation subsystem

The principal function of the synthesized simulation subsystem was to describe the spacecraft dynamics model and the time delay model used in the simulator, as well as to simulate the function of sensors, such as ladar. The teleoperation simulation system scheme is depicted in Fig. 3.

The teleoperation RVD mission primarily focuses on the final phase of approaching, during which the chaser approaches the target vehicle in the last 30 m. The chaser approaches the target along the V-bar, i.e., in the direction of the target's orbital velocity vector. The control system designs were representative of a range of possible implementations, from those used since the Tiangong-1 and Shenzhou-9 spacecraft to several adapted from advanced rotorcraft systems. The teleoperation RVD approach uses the automatic attitude system and the longitudinal velocity hold system is engaged; the only task for the pilot is to supervise and control the errors in the lateral motion directions. The pilot needs only focus on the two translational DOF control task. The side view of the subsystem information linkage is shown in Fig. 4. Commands were sent via joysticks and command panel. The relative state was calculated based on the target dynamics simulation and the chaser dynamics simulation with the time delay model. In addition, all simulations were under the simulation time model. The translational maneuvers were developed with the manual teleoperation mode only. Meanwhile the attitude maneuvers were developed with the automatic and manual modes.

2.3. Spacecraft motion platform and slide platform subsystem

The nine-DOF motion, real camera, and target simulator model were each developed in the spacecraft motion platform and slide platform. The spacecraft system motion platform mimics the motion based on the kinematic principle. As shown in Fig. 5, a double rail guide was installed in the front side of the simulator along the x-axis direction. The chaser simulator could simulate the attitude and translation motion in the x-axis. Furthermore, the target could simulate the attitude change in yaw, pitch, and row angel, as well as simulate translational motion in the y-axis and z axis.