Stability Analysis of a Hardware-in-the-loop Satellite Docking Simulator

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Space proximity maneuvers and autonomous satellite docking and capture are complex high-risk operations that require thorough ground testing and validation of the docking and capture mechanisms. The European Proximity Operation Simulator (EPOS) is a hardware-in-the-loop (HIL) simulator especially conceived for verification and validation of satellites docking phases. The simulator essentially consists of two robots, with very accurate pose controllers, holding, respectively, a docking interface and a probe element. In a real scenario, the probe belongs to the "client" satellite while the "servicer" satellite hosts the docking interface. Installed on the docking interface, a device measures the forces and torques applied to it when contact with the probe takes place. These forces and torques are fed back via a real-time controller interface and used as inputs to a computer numerical simulation of free-floating body dynamics. The software outputs are then used as reference commands to the robots in order to vary the poses of the probe and of the docking interface. This force-torque feedback is a key feature of the EPOS HIL facility, which is is, thus, a physics-driven demonstrator. This is an obvious advantage with respect to pure software simulators. Yet, this approach has its limitations. The closed-loop control system must ensure a very high bandwidth, which is due to the high stiffness of the robots and of the interface materials, while overcoming the time delays that are inherent to the robots dynamical response. In other words, the contact duration being shorter than the robots controller settling times, the closed-loop HIL system shows an instable behavior that can damage the system.

This work presents a novel two-fold solution to the above challenge. First, the high-stiffness compliance issue is mitigated by combining virtual and real compliances in the software and hardware, respectively. Second, the time-delay issue is tackled by implementing an energy-based active control. Furthermore, a stability analysis of the time-delay HIL closed-loop control system is proposed. The analysis is based on an extension of pole location methods to time-delay systems. The case of co-planar motions with planar rotations of the docking interface and of the probe is considered in this work. The results will be experimentally validated with the EPOS facility.