FREND: Pushing the Envelope of Space Robotics

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Introduction: The Front-end Robotics Enabling Near-term Demonstration (FREND) project is a DARPA-sponsored effort that is developing the state of the art in autonomous rendezvous and docking with satellites not pre-designed for servicing. This capability allows nearly any satellite to be repositioned on-orbit and provides a number of national benefits including better ground coverage in time of crisis, satellite life extension by eliminating the requirement imposed on fully functional satellites to expend their fuel to move to a safe disposal orbit, and disposal of derelict spacecraft which present navigation hazards to active satellites. FREND has successfully demonstrated autonomous rendezvous and docking in a ground test environment using research grade robotics and spaceflight traceable control software under simulated orbital conditions. NRL will soon perform these same demonstrations with the prototype and flight robotic arms to prove that this capability is ready for spaceflight operations.

Demonstrations: The FREND mission concept uses robotic arms to position a grappling tool at a customer spacecraft structural hardpoint, and docks the two spacecraft together by first rigidizing this tool, then rigidizing the positioning robotics. NRL performed two demonstrations of this technology in FY2007. In both, FREND docked with a geosynchronous satellite mock-up using only the pre-existing satellite-to-launch-vehicle interfaces that are common to most satellites. The first demonstration used hardware from an FY2005 proof-of-concept demonstration with improved, more flight-like software. Five times out of five, FREND successfully rendezvoused with the satellite mock-up and docked with a bolt hole interface. The second demonstration consisted of an upgraded satellite mock-up with flight-like blanketing, a Marman band interface, and a navigation sensor simulator. A new end effector tool was designed by NRL to dock with the Marman band interface. Furthermore, orbital lighting conditions were simulated to demonstrate the increased robustness of the NRL system. FREND again performed successfully, this time ten out of ten times. FREND has consistently shown the ability to dock with both of the hardpoint launch vehicle interfaces commonly found on existing satellites.

Simulation Facilities: NRL's Proximity Operations Testbed (Fig. 1) was used for both demonstrations. This unique facility allows the full-scale simulation of two satellites operating with six degrees of freedom in close proximity to each other and accurately simulates orbital dynamics and thruster effects during rendezvous and docking. A commercial robot arm was used for both demonstrations, in advance of the prototype spaceflight robot arm (Fig. 2). This prototype arm was designed and built by Alliance Spacesystems during FY2007 for future FREND testing. An optical testbed is used to test machine vision algorithms against a variety of simulated on-orbit lighting conditions, satellite thermal blanket configurations, and camera placements. The Gravity Offset Table is a granite table supporting a test frame fitted with air bearings that allow the test frame to hover above the table surface. Different weight configurations on the test frame simulate different classes of satellites, and an optical measurement system precisely tracks the positions of the robot arm and the test frame. This testbed allows simulation of zero gravity contact dynamics between the robot arm and the customer satellite and investigates issues such as angle of approach, end effector finger configuration, and time needed to dock.

Algorithms Development: FREND is fully autonomous from test start to stop, demonstrating the robustness that will be needed for spaceflight operations. A simulated satellite bus thruster system controls the approach and position hold near the customer satellite. A novel trajectory planner develops the commands that will move the robot arm from its stored position to the docking interface feature, using laser-based time-of-flight and triangulation data to estimate the customer's location and orientation, and machine vision data to home in on the docking interface. The machine vision algorithms locate the docking feature out of the images provided by cameras mounted at the end of the robot arms. They must be robust to the extreme lighting conditions found in space and to the reflective nature of many blanketing materials. A compliance controller moderates the robot arm's contact with the docking feature, emulating a soft spring-mass-damper system rather than a rigid contact that pushes the customer away. Fault detection routines monitor sensor inputs to ensure safe operations. A mission sequencer organizes the interactions between these algorithms and the hardware and controls progress through the test. Engineers monitor telemetry and issue emergency commands if necessary using the NRL-developed Comet ground system. Mathematical simulations and visualization software (Fig. 3) are used for planning, verification, and test planning, allowing us to safely test trajectories and parameter tunings in simulation before applying them to full hardware test environment.

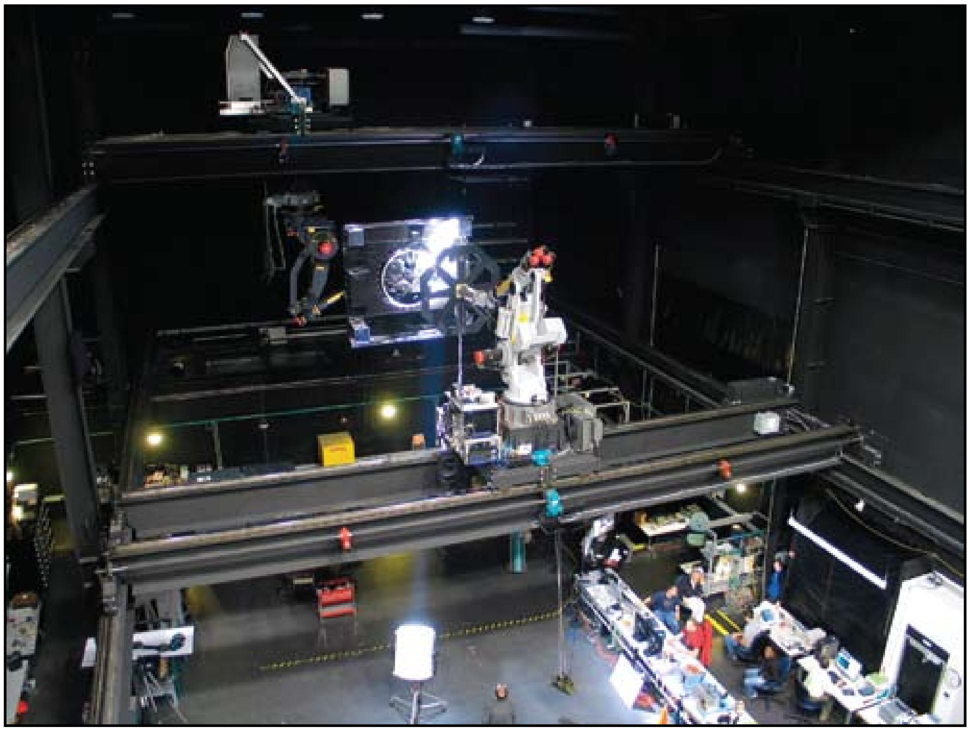

FIGURE 1
Proximity Operations Testbed. Full-scale rendezvous and docking testing for FREND includes a servicing satellite simulator, shown here as an octagon in the center of the image, and a mock-up of a customer satellite, shown here as one face of a rectangular satellite in the distant center. Unique track and trolley system provides two degrees of positional freedom, while industrial robot arms on the upper and lower trolleys provide a third degree of positional freedom and all three degrees of rotational freedom for a simulated spacecraft.

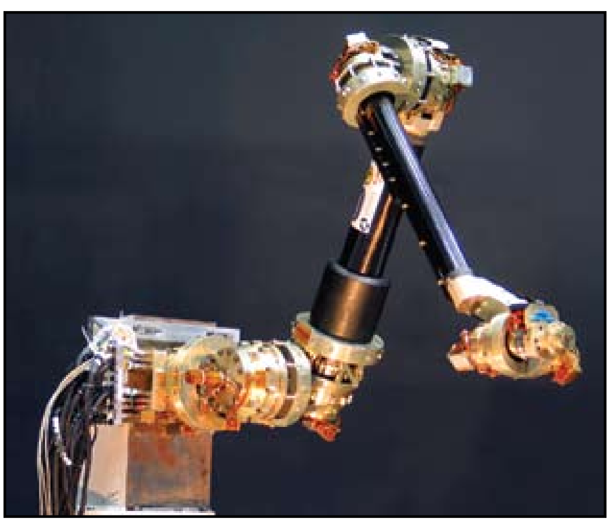

FIGURE 2
FREND flight prototype robotic arm. The engineering development unit (EDU) arm is the ground test unit to the spaceflight arm under development. The EDU has the full form, fit, and function of the flight arm, but has cost-saving material substitutions that are not qualified for the space environment.

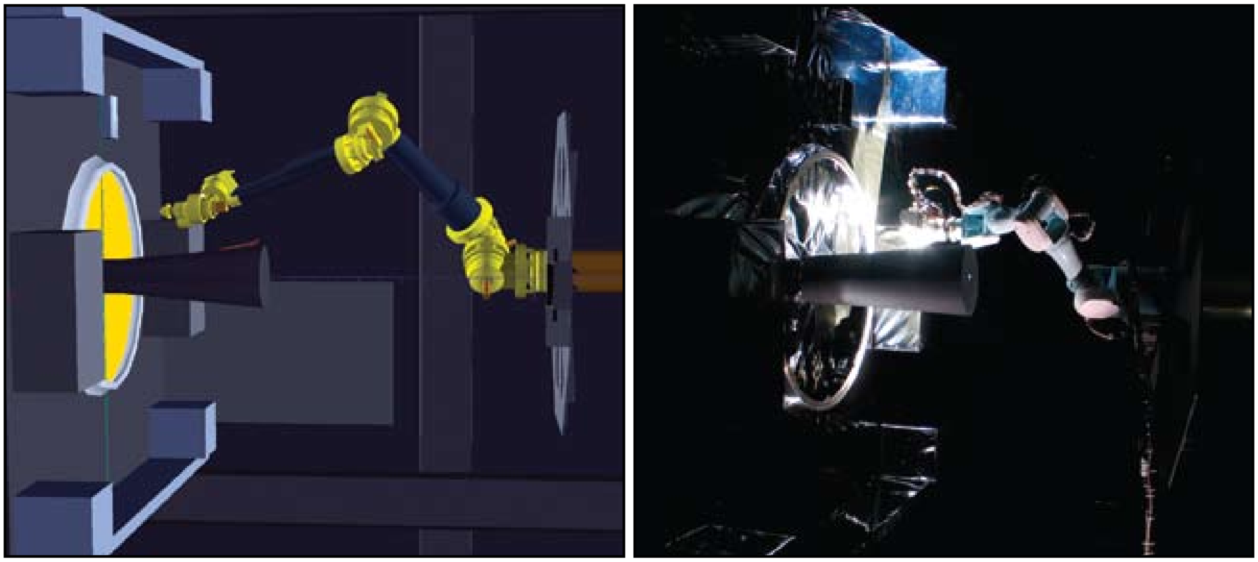

FIGURE 3
FREND simulation environment. FREND's software test environment allows algorithm development and testing to simulate all hardware components virtually before proceeding to full system testing with hardware-in-the-loop demonstrations. Images depict the grapple of a satellite Marman band interface, the structural "hardpoint" which attached the satellite to its rocket booster during launch.

Summary: The DARPA/NRL team working on FREND is currently leading the world in research and development necessary to autonomously rendezvous and dock with satellites not pre-designed for servicing. NRL continues to advance the technology readiness to be spaceflight ready in terms of both hardware and software. Once ground development and testing are complete, DARPA and NRL will be ready to perform an on-orbit demonstration of revolutionary new spacecraft operations.

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