A Robotic Simulator for Satellite Operations

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Keywords  robotics, satellite operation, simulator, virtual reality.

Abstract

Developing new applications for space can not only be difficult, but very expensive for test and verification. Conditions on Earth are simply not the same as those in orbit, and until the application has been tested in a representative environment, its performance cannot be accurately estimated. Testing in orbit is expensive, and the amount of experimentation that can be done is limited. This paper describes a robotic facility built by MDRobotics that mimics as closely as possible conditions in low earth orbit for satellite operations. The facility consists of two industrial robots, a simulated sun, Earth albedo reflection, and a virtual reality control station. This facility is used as a testbed for current and future space products developed at MD Robotics. It provides an environment in which new vision based robotic rendezvous and docking techniques can be tested to establish performance metrics.

1 Introduction

Over the past year, MD Robotics has developed a robotic facility called RPHS, a Reusable Space Vehicle Payload Handling System (Figure 1). The purpose of this facility is to provide an environment where emerging technologies can be tested. These technologies include stereo vision for space, and next generation docking interfaces. The goal of the facility is to create a testbed that simulates as closely as possible lighting conditions and satellite motions in low earth orbit for satellite capture and rendezvous. This was accomplished using a variety of off the shelf components and a real-time control system developed at MD Robotics. Two Fanuc 710iW industrial robots serve as generic 6 DOF positioning units for a variety of scale model satellites or end effector tools. Each robot is equipped with a force moment sensor that serves as a collision indicator, and can be expanded to incorporate force moment accommodation or virtual mass simulation for the satellites. A computer controlled re-locatable high-intensity broad-spectrum light represents the sun and gives 1/100th of the sun intensity in low earth orbit. Projection screens simulating earth albedo reflection are also integrated into the system. A control station where an operator can program trajectories for the robots controls the entire facility. With this setup, interactions of two satellites including all lighting conditions encountered throughout a low earth orbit can be realistically simulated.

Figure 1: RPHS Satellite Simulator with Satellite

2 System Overview

Using the RPHS system an operator is able to realistically simulate a variety of on orbit operations. For instance the system can simulate the scenario of a maintenance satellite performing an approach to dock with a second on orbit target satellite. From a camera perspective on the approach satellite, the simulator provides an exact recreation of the motions and lighting conditions that would be experienced by a real approach satellite. Lighting can be adjusted to simulate the approach for any portion of the low earth orbit; from the
low light conditions seen in umbral and penumbral regions of the Earth’s shadow, to the harsh glare of full sun. Shadows cast by the approach satellite on the target satellite as well as procession of shadows across the face of the target satellite as both satellites orbit the Earth can also be simulated.

In addition to simulation of a wide variety of lighting conditions, motions of two satellites can also be simulated with a high degree of realism. A variety of docking approaches and separations can be performed between the two satellites, from simple approaches to rolling and tumbling target satellite capture scenarios. Teach interfaces as well as external computer control allow an operator to expand the motion profiles beyond what was originally programmed.

Interfaces exist for adding greater realism to the existing system. For example, by adding a real-time dynamics module, the force sensor on each satellite can be utilized to create a virtual mass system. This would allow the operators to test docking interfaces with greater confidence as the target satellite’s position changes due to forces on the docking interface during docking could be simulated.

There are two main pieces to the RPHS simulator system, the simulator room itself and the operator console which is physically located outside of the simulator room for safety reasons. Each main component is described in the following sections.

2.1 Operator Console

The operator console (Figure 2) is where the operator defines and executes motions for either or both of the robots and associated payloads. From the console, the operator can also enable and disable the system, choose physical camera views into the facility, and control the facility lighting. Except for exchanging tools and satellites on the robots and powering up and down the robot controllers, every operation of the RPHS facility can be performed from here.

The operator console also contains the three operator screens, and the operator panel where the power on and off, e-stop and mode selection buttons and keyswitches are located. Two handcontrollers are located on the desktop, while underneath are both operator computers and a CD burner for archiving database tests.

2.1.1 2D operator Interface

The 2D Operator interface (Figure 3) occupies the centre monitor on the operator console. It provides a display for robot and tool status, as well as providing screens for control of the closed circuit video cameras, robot motion definition and execution, and system configuration and calibration.

![Figure 3: 2D Operator Interface](image-url)
Each of the different screens for operation can be displayed by using the right mouse button to click on the tab group, then clicking on the ‘+’ and ‘-‘ page flipping icons until the desired page is displayed. All of the pages in the system can be displayed using the page flipping icons; when one tries to flip past the first or last page in a group, the last page of the preceding group or the first page of the next group is displayed. An alternate method of page selection is to right click either on the tabs or the title area directly beneath the tabs. A popup menu will be displayed where the operator can choose the tab group desired and the page within that group directly.

2.1.2 3D Operator Interface

The 3D operator interface (Figure 4), located as the right-hand monitor, gives 3D visual feedback of what is happening in the robotic facility. As the operator may not have direct line of sight to the robot through the viewer, the virtual display was designed to augment the physical camera views available. This virtual display provides much better situational awareness for the operator to aid in operations such as path planning. Robot status, current position, planned position and endpoint force readings are all displayed graphically on this screen to give the operator a quick, one-glance method of seeing the current state of the RPHS system.

Similar to the tab views of the 2D interface, multiple page views are also available on the 3D page. These pages allow the operator to customize the display by choosing to display or not display certain objects, or to display a different viewpoint. These multiple viewpoints and camera positions are all designed to aid the operator in their test execution.

2.1.3 Closed Circuit Cameras

As it is not always possible for the operator to have a physical view of the satellite simulator room, cameras have been strategically placed to give the operator live video feeds of what is happening. This was done as a safety measure as well as an enhanced awareness feature for the operator. The video feeds are presented to the operator on the closed circuit video monitor.

The closed circuit video monitor is located as the left monitor on the operator console. It is a programmable display capable of showing up to eight different live video feeds from the simulation room. The different video feeds can be displayed in individual overlapping windows, configurable from the 2D user interface menu bar. Each window can be individually turned on and off, positioned, sized, and can optionally have a text message overlaid onto the live video.

2.1.4 Operator Panel

The operator panel sits on the operator station directly underneath the bank of monitors. This panel provides hardware enable and disable buttons for each robot, along with a system e-stop and mode selection keyswitch.

Two signals are required to enable a robot for operation; one is a software signal generated by the RPHS application, the other is a hardware signal generated by the enable button on the operator panel. This was done so that the operator could not accidentally enable the robot for movement, and likewise a failure in the software could not enable the robots on its own. A single signal can enable either or both of the robots; the software can send a software disable or the operator can press the hardware disable button. Once a robot has been enabled, the hardware enable light becomes lit, and the virtual robot on the 3D operator interface also lights up to indicate an active system. These visual cues help the operator be aware of how the system is configured and what operational mode it is currently in.

The system e-stop removes the enable signals to both robots and asserts an external signal to the robot controllers. No movement is possible from the robots – even through an attempted override using the robot teach-pendant.. Before the robots can be re-enabled, the e-stop signal has to be removed and the errors cleared.
2.1.5 Handcontrollers

The hand controllers are for manual positioning of either robot by the operator. This could be for initial positioning of the satellites in preparation for an operation, or it could be for an operation itself where a non-predetermined satellite motion is desired. The hand controllers are mounted into the workstation directly in front of the operator on either side of the main keyboard. Each hand controller has three axis of motion: the left hand controller provides positional X, Y and Z (forward and back, left and right, up and down), while the right hand controller provides rotational roll, pitch, and yaw (forward and back, left and right, rotate clockwise and counterclockwise). The exact mapping between direction of deflection and axis of movement depends upon the frame of reference that the system is in at the time, however it is designed to be always intuitive from the operators’ physical or virtual point of view.

Each hand controller has a thumb switch located near the top of the grip. These switches are mapped to provide quick mode changes between the different frames of reference and different speed scales. A trigger located on the front of the hand controller acts as a deadman switch: motion will not start until both deadmans are depressed, and motion stops when both are released. If a single deadman is released, then the deflection information from that hand controller is not used until the deadman is again depressed.

2.1.6 Database

In addition to providing accurate motions of both satellites, the RPHS system is responsible for logging and archiving all activity as it occurs. The programmed trajectory, the executed trajectory, the forces sustained on the end effector, and the position and intensities of the artificial sun and earth albedo are recorded in real-time throughout each test. A tester is also able to associate any kind of non RPHS specific data to a test. This could be external data related to the test such as images taken by an attached vision system.

By recording this information it is possible to replay any previous test either live or virtually. In this manner, the system being tested can be compared against historical performance to monitor any changes in performance. The tester can also execute ‘what-if’ scenarios. For example, a vision system test can be modified such that the sun is in a slightly different position casting different shadows, the intensity can be increased or decreased, and different target satellites can be used. The results obtained using these changes can be compared against the original test to see how the system performs against these changing operational parameters. Any weaknesses can be identified and corrected while the system is still in the development phase resulting in a higher confidence of its ability to perform once in orbit.

An archived test and its associated data can be retrieved by the operator and replayed either virtually on the 3D display, or live using the robot manipulators. Data from archived tests can then be compared to current test results to determine any changes in performance of the device under test. For instance, the performance of a vision system under full intensity lighting conditions can be compared to its performance when in partial shadow.

2.2 Simulation Room

The simulation room is where the satellite simulation actually occurs. It contains the robot manipulators and the lighting equipment, and is physically separated from the operator control station. This is done for practical reasons, as when lighting simulations are occurring, light sources not generated or controlled by RPHS, such as those from computer screens, must be blocked out. Also safety requirements for use of the Sun Simulator dictate that either no one be in the room or they wear protective eyewear and skin protection. The Sun Simulator light source can provide an exact 1:1 intensity of exoatmosphere light intensity across the visible and UV spectrum and is useful for certain types of camera and materials testing. Normal vision testing however uses the 1/100th intensity lights. Windows allow the operator to look from the control station into the simulation room, however a curtain can block these windows out when lighting tests are occurring.

To enhance the realism of the simulation, the room itself is painted matte black to give the appearance of space operations when viewed through the vision cameras. The robots are covered in a black cloth that is difficult for cameras and laser sensors to pick up. Other reflective surfaces are covered to prevent sensors from detecting any object other than the satellites.

2.2.1 Manipulators

The payload positioning units are standard Fanuc 710iW industrial robots (Figure 5). The robot controllers have been upgraded to support high rate external communication and control, as well as high accuracy local calibration. This robot is capable of moving a 75kg payload at a maximum rate of just under 9 m/s, however this speed is limited in the controller to a more manageable 2 m/s.
Each robot has attached to the endpoint a high accuracy force moment sensor to measure payload forces and moments during motion. This data is used to detect a collision with an unknown object (an object not modeled in the 3D workspace) and the system will instigate a shutdown if such a collision occurs.

On the endpoint of each robot is a pneumatic quick tool exchange system. This tool exchange plate mates with rings attached to each of the payloads (Figure 6), and provides a convenient means of attaching and removing payloads from the robot. To each payload the tool exchange can provide power, digital and analog input and output, and e-stop signals. Some of the digital I/O signals available are dedicated to a tool identification scheme. Using these signals, the RPHS knows what model is attached to the endpoint, and if defined, can load up a VRML model of the payload for the operator and infer a collision boundary.

This automatic identification eliminates the possibility of operator error if the system had to rely upon the operator to input the type of payload that was attached. This positive identification is important, as collision boundaries have to be calculated correctly in order to prevent self-collision or payload – payload collision.

### 2.2.2 Lighting

The simulated sun sits on an overhead gantry and can be positioned manually, or be told to automatically track the target satellite. This positioning combined with the motions capable by the robots means RPHS can simulate the entire lit portion of a low earth orbit. The operator also has intensity control over the light, but 70% intensity gives a calibrated 1:100 scale intensity of actual low earth orbit intensity.

The simulated Earth albedo is a bank of six floor lights that reflect from a diffuse screen to illuminate the satellites. Each light can be independently controlled for intensity or can be turned off completely. This intensity control allows simulation of some of the widely ranging intensity reflections from the Earth expected to be encountered in low Earth orbit.

As previously mentioned, there is also a 1:1 intensity Sun Simulator for specific lighting tests to give a true on orbit lighting simulation.

### 3 Satellite Operations

The RPHS facility was developed as a testbed for MDRobotics’ stereo vision system (ORPE) [4]. Although this facility was designed to easily expand beyond that role, the initial performance and operational requirements stem from the ORPE program. The end goal of the stereo vision system is to autonomously locate a target satellite, track its motion and fly into a docking situation without human intervention. The facility will be able to take trajectory data generated by the vision system and execute it as if the vision cameras were actually on a capture satellite, without requiring the vision system to have knowledge of the kinematics or the dynamics of the robots.

The RPHS control station allows an operator to select one of several pre-programmed trajectories representing the most common motions expected to be encountered in low earth orbit satellite operations. In addition, the user can create new trajectories using positional keyframes, combinations of existing trajectories, and relative motions. Trajectories can also be generated in real-time by an external computer using the supervisory interface. This method would be used when an external
device such as a vision system wishes to control the position of the robot directly. The operator can also choose to manually position either robot using the handcontrollers.

Once a trajectory is created, it is sent to the virtual 3D display where it is checked for kinematic resolvability and potential collisions (Figure 7). The collision detection and avoidance algorithms are based on V-Collide, a freely available package from the Department of Computer Science at University of North Carolina, Chapel Hill [2,3]. A software wrapper around this package was created to enhance it to prevent unintended collisions, but allow controlled collisions such as would occur in a docking situation. Figure 8 shows a programmed motion that is rejected because it would cause a self-collision. In this instance, the collision boundary around the satellite payload and the boundary around the manipulator elbow have turned red to indicate to the operator the location of the potential collision. If the system rejects a trajectory either due to a potential collision or kinematic limits, the operator is notified and can then reprogram the trajectory, or make small parameter changes to it to make it collision free.

When the trajectory is verified as viable, it is animated in 3D where the operator can review the motions before they are executed by the robots. From the 3D display, the operator can view the trajectory from a variety or real or virtual viewpoints (Figure 9), providing a much better sense of the resulting motion than a single fixed viewpoint. Once the operator accepts the planned trajectory, the robots can be commanded to execute it.

The 3D display now switches from an animation of the trajectory to the actual positions of the robots. As the trajectories are executed, the computers controlling the motions are constantly checking for static collisions of the robots or satellite payload with itself and the surrounding lab, and dynamic collisions of robots and payloads against each other. Using the supervisory interface, an external computer can also define a number of ‘no-go’ collision volumes where RPHS will prevent the robots or payloads from entering. These areas are also checked when programming a trajectory and in real-time during robot operations.

Since both manipulators are working cooperatively in the same workspace, there is a high possibility of damage to systems and even personnel should something go wrong. If one of the computers loses control, expensive flight hardware could be irreparably destroyed. For this reason, all four computers work cooperatively to maintain system safety. Keep-alive heartbeats are constantly being monitored between the computers and the Fanuc controllers. Both programmed virtual positions and
actual positions from telemetry are checked for accuracy and compared against each other to capture runaway conditions. If an anomalous situation is detected, RPHS uses a combination of hardware and software safety systems to halt motion and prevent, or at the very least, minimize any damage that may occur.

4 Calibration

One crucial aspect of the facility is positional accuracy. Since the RPHS facility is being used to verify accuracy of a stereo vision system, it was determined that the satellite to satellite position accuracy and repeatability had to be known within 1 mm of the true position. A variety of calibration techniques were used to determine overall average and maximum positional error of one satellite with respect to the other. Calibration involved determining each tool coordinate system with respect to the robot tool plate coordinate system, the robot positioning accuracy of the endpoint with respect to its own fixed base, and the position and orientation of one robot base with respect to the other robot base. Endpoint to robot base calibration was performed using Fanuc’s Accucal calibration system [1]. This system involves attaching the endpoint of the robot to a instrumented cable. The cable sensors are passed to the digital inputs on the Fanuc controller I/O board. After telling the application the bounding planes of the workspace and specifying the number of points to use along with the weight of the payload to use, the Accucal calibration program begins the calibration process. The application exercises the robot through various combinations of positions and orientations such that the greatest range of movements for each of the joints is utilized within the defined workspace. The Fanuc controller then compensates internally for deviations found in joint motions and calculates link length deviations from nominal.

After calibrating each robot, we then calculated the distance and orientation to from one robot base to another. This was accomplished by commanding one robot to align its endpoint to an exact fixture position and orientation. After recording the joint values obtained, the second robot was now commanded to the exact same position and orientation. Knowing both kinematic chains back from the endpoint to the base allowed us to mathematically determine one base position relative to the other. After calibration, the average error for the system throughout the workspace was determined to be 0.32 mm while the maximum error is 0.93 mm which was within the system goal of 1 mm.

5 Conclusion

The goal of the RPHS satellite docking simulation facility was to make an accurate satellite motion simulator for ground testing of on-orbit systems. In addition, the system had to be expandable and easy to use while keeping system and operator safety in the forefront of the design.

All of the initial design goals for RPHS have either been met or exceeded. The online configuration screens allows new tools to be added and trajectories created without having to perform and software coding changes. Employees unfamiliar with robotic systems have been able to operate the facility within a half an hour of being introduced to it.

The system was completed late in 2000 and was used to successfully test ORPE, MDRobotics’ Object Recognition and Pose Estimation toolkit for space stereo vision [4]. It has also been committed for use in the MDRobotics’ Remote Operations with Supervised Autonomy (ROSA) project and is being considered to demonstrate SARAH a Self-Adapting Robotic Auxiliary Hand [5,6]. The RPHS facility adds an important tool for MDRobotics in both current and future space based initiatives.

References


