RACOON - A HARDWARE-IN-THE-LOOP SIMULATION ENVIRONMENT FOR TELEOPERATED PROXIMITY OPERATIONS
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Andreas Fleischner [(1)], Markus Wilde [(1)], Ulrich Walter [(1)]

[(1)] Institute of Astronautics, TUM, Boltzmannstr. 15 85748 Garching, Germany, Email: office@lrt.mw.tum.de

ABSTRACT

The RACOON (Real-time Attitude Control and On-Orbit Navigation) laboratory was set up at our laboratory to provide an end-to-end simulation environment for teleoperated orbital activities. These activities cover aspects of on-orbit servicing missions with uncooperative client satellites as well as space debris removal missions. The current focus of the investigations is on teleoperation of proximity operations, and rendezvous & docking.
In order to provide a realistic simulation environment, RACOON consists of a mission control center and a simulated space segment which can also integrate hardware-in-the-loop components to test actuator and sensor hardware under realistic motion and lighting conditions. Both simulator parts are connected by a space communication link segment which closes the communication chain either via simulated or real satellite links.

1. INTRODUCTION

In today's space business, satellites are treated as disposable articles. After rigorous testing and qualifications on ground, today's spacecraft are typically launched and operated without the option of inspecting, replenishing, repairing or upgrading the hardware on orbit. Any deployment malfunction or component failure that cannot be addressed by software workarounds or redundant hardware systems results in degraded spacecraft capability and thus degraded mission performance, reduced revenue potential or, in extreme cases, the loss of the spacecraft. But even if the spacecraft functions properly, changes in payload technologies or customer demands could mean technological or commercial obsolescence before the end of the current design lifetime of approx. 15 years for most telecommunication satellites [1, 2].
After planned or unplanned end-of-life (EOL), spacecraft remain in orbit and thus either interfere with satellite operations in geostationary Earth orbit (GEO) or pose collision hazards in crowded low Earth orbits (LEO). Over time, collisions [3] among these space debris objects lead to the creation of small, hard to detect and very dangerous space debris. The current countermeasure for GEO is to move the spacecraft into a so-called "graveyard orbit" 200 km above the GEO belt before they reach their planned EOL [3]. The available solutions for LEO are to de-orbit the spacecraft or move them into higher orbits [3]. These maneuvers are propellant-intensive and many LEO satellites are not equipped for such orbit change maneuvers. Optimism by program managers and spacecraft operators also lead to spacecraft being operated beyond their planned EOL, until equipment failures finally render them useless and often uncontrollable. Self-propelled orbit-changing maneuvers are then no longer an option in these cases. A noteworthy recent example is ESA's Envisat [4, 5].
The spacecraft serviceability issue and the associated space debris problem can be addressed by activities summarized in the terms On-Orbit Servicing (OOS) and Space Debris Removal (SDR). OOS was a prime design driver for the U.S. *Space Shuttle* and was also accomplished successfully on a number of occasions, most noteworthy the servicing missions to the *Hubble Space Telescope* [6–8]. However, *Space Shuttle* experience also showed the high cost and risks associated with launching human crews, and many question if human lives should be risked on missions such as satellite servicing. For future operational OOS missions a robotic system should therefore be considered. In the past decades, a number of robotic OOS systems have been developed and tested to verify the feasibility of some core OOS activities [9–13].
One of the major enabling capabilities required for operational on-orbit servicing and especially space debris removal is a safe, reliable and flexible rendezvous & docking capability for uncooperative target objects. Such uncooperative targets are not equipped with docking/capture interfaces or dedicated sensor targets required for auto-mated relative navigation. Under worst case conditions, on-orbit servicing and space debris removal targets will also feature substantial rotation or tumbling rates. The flexibility and adaptability required for rendezvous & docking under such circumstances are currently beyond the reach of autonomous systems. They therefore require the use of teleoperated robotic systems, which combine the capabilities of robots – e.g. robustness, endurance, precision and patience – with the

spatial planning capability and ingenuity of humans [14, 15] and thus achieve a substantially higher capability with complex tasks and complex environments. The need for active involvement of human operators, either in a monitoring/supervisory role or actually as active controller, was experienced during the contingency operations occurring in the Orbital Express mission [16].

Future real-time teleoperation of spacecraft during proximity operations and rendezvous & docking would strongly benefit from the development and refinement of methods and technologies in the fields of human-machine interaction, near real-time communications, supervised spacecraft autonomy, and mission and trajectory planning. In order to close some of these research gaps, the Institute of Astronautics (LRT) at the Technical University Munich is investigating the use of teleoperated spacecraft in on-orbit servicing and space debris removal applications. The focus lies on enabling real-time teleoperation via space communication links and their associated signal travel delays, as well as on teleoperation of spacecraft during final approach and capture of uncooperative, rotating or tumbling targets.

For the purpose of verifying technologies and methods in a representative end-to-end environment, the LRT established the Real-time Attitude Control and On-Orbit Navigation (RACOON) laboratory, which allows the realistic simulation of proximity operations, rendezvous & capture, in operating conditions representative of operational missions with uncooperative target objects.

2. STATE OF THE ART

Telepresent robotic operations, while being straightforward in the fields of ground, air and underwater robotics, are hampered by the unfamiliar characteristics of the orbital operation environment and form a challenge to the sensory, modeling and control capabilities of computers and humans. Therefore in addition to the standard set of spacecraft component testing, auxiliary simulations on ground are extensively used for verification and evaluation of operational and robotic aspects linked with the servicing scenario. Three main issues must be faced, being essential for any realtime teleoperated OOS applications, and thus need to be covered for a realistic simulation and mission preparation on ground: 1) the effects of the communication link 2) the reproduction of the proximity operations between spacecraft, and 3) the simulation of orbital lighting conditions.

2.1. Communication Link

Real-time teleoperation requires the availability of a high performance communication link. For teleoperated proximity operations or complex manipulation tasks the critical parameters are (1) long continuous contact time, (2) low round-trip delays, (3) low bit error rates, packet loss and jitter, and (4) high data rate for high-fidelity video and telemetry.

Long contact times are essential for teleoperation tasks that take longer than the 8-10 minutes available in direct ground-to-space links (single ground station). Longer contact times can be accomplished by communication chains via data relay satellites (DRS) in GEO. The problem with such relay links is that they introduce substantial signal travel delays into the system. Using multiple data relay satellites like the U.S. Tracking and Data Relay Satellite System (TDRSS), roundtrip delays of between 3 and 12 seconds are a reality [17]. At roundtrip delays larger than 700 ms, humans lose their feeling of telepresence [18] and thus the effectiveness and efficiency of teleoperation is substantially reduced. It was shown, however, that using a single DRS in S band (data rate 1 Mbps) roundtrip delays below 700 ms can be accomplished and that uninterrupted contact times of an average of 42 minutes can be realized [19]. Telepresence and real-time teleoperation of OOS tasks is therefore feasible.

During mission phases like inspection, RVD and telemanipulation, the operator has a demand for high-fidelity and high-quality video and sensor data. In such cases, the required data rates can be as much as 4 Mbps and above [20].

2.2. Proximity Maneuvering Simulation

The current state of the art in proximity operation simulation systems includes hardware-in-the-loop (HIL) systems. Software-only simulations are seldom used. In general, four types of HIL systems can be distinguished [21]:

Air-bearing table systems [22] use air flotation to eliminate friction and are very powerful for the simulation of dynamic effects. They are limited to planar simulation and are also limited in their practical size since they require high-precision leveled surfaces. Their use furthermore increases the complexity of the simulation environment since the satellite models must be self-contained units incorporating a pressurized air system, a power system, on-board computers and wireless communications in order to attain their full potential. Air-bearing tables are nonetheless used successfully for dynamics and control simulation purposes, e.g. at the Naval Postgraduate School [23], the Marshall Space Flight Center Flight Robotics Laboratory (FLR) [24], the Georgia Institute of Technology [25] and the SPHERES laboratory [26].

Micro Gravity Platform systems are able to reproduce a free fall environment but the experiment has limitations on size and weight. Drop towers are used extensively for that purpose but are limited to a few seconds of reduced gravity. Parabolic flights in special airplanes provide up to 25 seconds of micro gravity [27], but access time, cost and manpower requirements for their

use are too high for use on an everyday academic basis.
The SPHERES (Synchronized Position Hold Engage and Reorient Experimental Satellites) experiment setup aboard the International Space Station (ISS) [28] is unique in providing theoretically unlimited micro gravity conditions for proximity operations simulations. In practice, however, SPHERES experiments aboard ISS require astronaut monitoring which comes with the associated complex coordination and scheduling overhead.

Neutral buoyancy systems place the target in a suspension medium, usually water. This allows full simulation in 3D space for an essentially unlimited time. Active countermeasures are however required to eliminate damping of spacecraft kinematics and dynamics due to the surrounding fluid. The spacecraft simulation models must furthermore be designed to work in water, which increases the overall complexity of the simulation system. The upkeep of the water tank is also associated with substantial time and manpower needs and the installation and exchange of simulation system components may require the presence of qualified divers. Nonetheless, neutral buoyancy facilities like those used at the Space Systems Laboratory at the University of Maryland [29] provide valuable research data for space robotics projects.

Mechanical systems use robotic components to represent the relative motion computed in a numerical simulation. Measured position, velocity, orientation, force and torque data from the hardware setup can then serve as feedback input to the numerical simulation. This approach allows a detailed simulation of the proximity operations scenario if the underlying physical laws and the interrelations between the system components are fully understood.
A number of simulators use two industrial robotic arms for simulation of relative position and orientation of chaser and target spacecraft [30]. These systems have the advantage that the forces and torque sensors of the robots can be used to feed contact forces and disturbance torques to a dynamics simulation model. The range of the arms, however, limits the motion envelope of the system. Sometimes Stewart platforms, also referred to as hexapods [31, 32] are used. These systems have smaller motion and positioning envelopes than industrial robots, but outperform most robots in torque, force, accuracy and speed, thus making them useful during contact dynamics simulation of docking subsystems.
The motion envelope can be extended by the introduction of simulators based on ground-mounted or ceiling-mounted rail systems or cable suspension systems, as for example, the Gemini/Apollo RVD simulator [33], the FLR [24], or Lockheed Martin’s Space Operations Simulations Center (SOSC) [34], thus providing high-fidelity, relative kinematics simulations with motion envelopes only limited by the size of the facility.
In many cases, robotic components and rail systems are combined to provide dynamics simulation capabilities with an enhanced motion envelope. Examples for these facilities are the DLR EPOS (European Proximity Operations Simulator) [35], the motion simulator at DFKI (German Research Center for Artificial Intelligence) [36], as well as the Naval Research Laboratory (NRL) Proximity Operations Testbed [37].

2.3. Lighting Simulation

Sun lighting conditions in orbit are mostly simulated by high power arc lamps. They are essentially point sources that can reproduce the nearly parallel beam path of sunlight if they are placed at sufficient distance, leading to realistic hard shadows and extreme contrasts on the illumination target. In addition these devices are commercially available and easy to use. Most simulation environments install the light as a stationary source, e.g. in the DFKI simulator [36], the NRL Proximity Operations Testbed [37], or EPOS [35]. Some simulators are also able to move the light source along programmed trajectories [38, 39]. Due to the large distance between light source and illumination target required for achieving parallel beam paths, high motion velocity as well as large motion envelopes would however be required for such mobile-light sources. This can especially become important in proximity maneuver simulators that focus only on relative motion of the involved spacecraft by abstracting the real positions in global space to alternate solutions that retain the relative position configuration and stay within the mechanical limitations of the simulation environment. In such cases, due to the transformation of global space, the light direction and therefore also position and orientation of the light source have to be changed if correct lighting conditions shall be retained. Distant light sources are subjected to higher velocities and motion envelopes in such cases.
Albedo light is seldom included in the simulation. Also cases where Earth is visible in the background are normally neglected as the simulation of this condition is very difficult. The standard solution is to prevent these states in mission operations as most current autonomous systems would be overstrained with such situations. For a real OOS mission, this goal might not be achievable in all cases, especially during off-nominal situations.

Light intensity of the simulation can vary between levels of full sun down to 1/100 of the intensity [39]. Using current technology, full sun intensity simulation requires very high power input and the resulting heat dissipation and high infrared fraction could damage equipment under test. If a reduced light intensity is used, adapted camera setups can be employed, e.g. tuning shutter speeds or sensor sensitivity, to maintain realistic camera images.

Most OOS simulation environments today combine more than one of the above methods into one single end-to-end simulation as well as incorporating real sensor subsystems and algorithms in the loop as the complexity of OOS missions result especially from the interaction between the coupled subsystems and their interaction with the orbital environment.

3. SPECIAL CONSIDERATIONS FOR HUMAN IN THE LOOP SIMULATION

Since the human operator is an essential part of the control loop of any real-time teleoperation scenario, the operator must be included in the simulated teleoperation system too. As with any technical system, the human operator has a set of unique requirements that must be addressed in the hard- and software architecture of the simulation environment.

First, the simulation must be operated in real time, as the human operator cannot participate in the simulation with realistic performance if it is run with a time scale other than 1. Real-time response of the simulation is a demanding requirement and can be limited by the performance of today's computer hardware for complex simulation scenarios. To address this problem, the simulation can be supplemented by hardware-in-the-loop components, such as e.g. cameras, laser rangefinders, lidars, or other sensors. This approach eliminates the need to build fast and accurate mathematical simulation models for such system components. However, if a component is extracted from the software and placed within the simulation as real hardware, all its interfaces with the simulated environment must still be retained. A synchronized hardware simulation of the environment is therefore required and must recreate all relevant stimuli and operating parameters for the individual hardware components.

Second, a human operator cannot be paused or interrupted without affecting the realism of his performance. A simulation environment for real-time teleoperation must therefore be capable of simulating the whole task, e.g. final approach and docking, in one continuous session. For the generation of a continuous simulation, a software solution has clear benefits since the orbital environment is hard to reproduce on ground and hardware-based simulation environments have stronger limitations on reproducible states. For example, during simulation of relative kinematics numerous keep-out areas exist for the suspension systems as a consequence of the mechanical limits of its actuators, intersections of suspension elements, or mechanical load limits. Hardware based simulators must therefore use intelligent heuristics to shift between redundant degrees of freedom to keep the simulation system inside its valid ranges. In return, hardware-in-the-loop simulations have the benefit of flexibility, especially where the effects are not clearly understood or are too complex to model. An example of this point is the usage of real-time rendered camera images compared to real camera pictures from a hardware simulator, where the rendered images might, for example, not be able to produce correct reflection and blinding effects without immense computing power. This flexibility can become important when the human operator serves as the primary mission and maneuver planning unit, making the decisions and action of the operator to a certain degree unpredictable.

Third, the performance of the human operator will only be realistic manner if the operator is feeling immersed in a real mission scenario. Operator stress level is always an important factor when simulating proximity operations scenarios such as in final approach and docking. These stress effects are reduced substantially if the operator has the feeling of "just operating a simulation". Our own observations during experiments show that if real hardware is involved, and thus a risk of damaging equipment in collisions exists, operator attention and excitement are increased generating more realistic test results. In contrast to a computer algorithm, the attention of a human operator can furthermore not be limited to special areas of interest. Therefore, even minor distracting (mostly visual) elements in the environment are able to ruin the immersion of a real situation. The simulation environment must therefore cover all aspects of the environment including lighting, lack of references in the environment, relative motion, response to control inputs, etc., in order to allow realistic simulations of teleoperated missions.

4. OVERVIEW OF THE RACOON LAB

The RACOON laboratory at the LRT focuses on a realistic simulation of teleoperated on-orbit servicing missions by incorporating the relevant key aspects of those missions into an end-to-end simulation, particularly focusing on the human operator and his/her special simulation requirements. The common element of all on-orbit servicing and space debris removal missions is rendezvous & docking as well as proximity operations around the target object. This mission phase is therefore currently the primary objective of the RACOON simulation scenarios.

In the underlying reference scenario a chaser spacecraft equipped with a representative sensor suite and a docking or capture tool, is teleoperated within close proximity of a target object. Fly around, collision avoidance, or final approach and docking/capture maneuvers are then conducted based on individual scenario goals. During these maneuvers, the chaser spacecraft can be controlled by direct link from a ground station, by relay link via one or multiple data relay satellites, or by a combination of both. The ground operator is provided with video and telemetry from the remote worksite by means of an

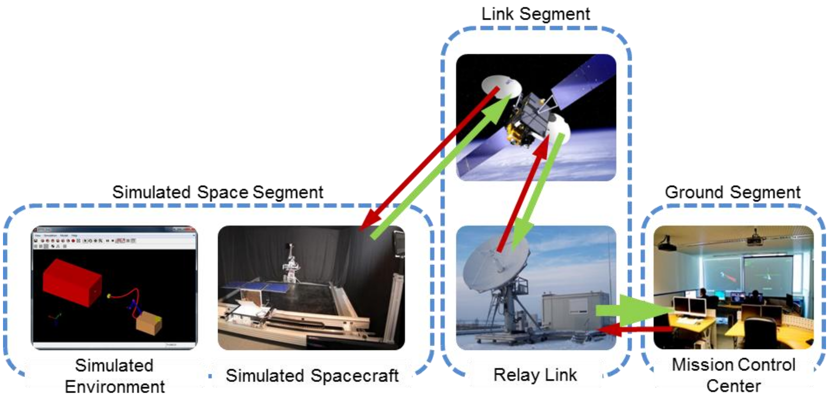

Figure 1. The components of the RACOON simulation environment.

operator interface and can issue real-time commands to the satellite with a number of input devices.
For the realistic representation of such a scenario, the RACOON laboratory is split into four major parts (Fig. 1) simulating the system components in space, the relevant characteristics of the operating environment, as well as their interconnection.

In the **Ground Segment,** different setups of relevant ground based mission control systems can be integrated. The system architecture differs from common satellite ground stations (e.g. store and forward architecture) due to its special real-time data handling and real-time mission control capabilities. With the environment, kinematics and dynamics in Earth orbit being highly unfamiliar and unintuitive for human operators on the ground, special focus is set on human-machine interfaces that can improve the situational awareness of the human operator [40, 41] and thus the performance of the operator during mission operation.

The **Simulation Control Segment** is incorporated in the Ground Segment and is the central configuration and control station of the simulator. The terminals are somewhat separated and are not interfering with normal mission operation yet enable the supervisors to monitor the behavior of the operator crew. Different mission configurations can be set up and possible spacecraft failures can be activated during a simulated servicing mission. All parameters, system states, and operator inputs can be monitored by the simulation advisors and are logged in real time for later analysis.

The main characteristics of the space communication link are covered by the **Space Link Segment**, being the only path for data between mission control and the simulated spacecraft. The available options for the link architecture are a simulated roundtrip delay within the local network, data transmission via internet mirrors, and incorporation of an actual GEO data relay satellite. ESA Artemis and a number of Eutelsat and Astra satellites are available for this purpose. Using the data relay satellite option, realistic data rate limitations, packet loss rates, bit error rates and jitter are part of the simulation setup.

Orbital dynamics, lighting conditions and environment interactions are simulated by the **Simulated Space Segment**. It further consists of a simulated spacecraft and the simulated space environment. Both the simulated spacecraft and environment consist partially of software components and partially of real and prototype space hardware in the loop. The simulation involves the relevant spacecraft subsystems and environmental influence factors for a given scenario. Thermal, vacuum, and radiation environments, while generally being a challenge for space system components, are ignored in RACOON because they do not create particular requirements for teleoperated space systems.

MATLAB/Simulink as well as native code are used to model the multi-body orbit dynamics and control systems of the space segment. The main elements of the model are (1) a kinematics module to simulate the relative and absolute motion of the spacecraft and actuators, (2) a control module comprising the control algorithms, and (3) a multi-body orbit propagator for the simulation of relative motion between space robot, target and relay satellite.

The hardware-based simulation supplements the software simulation with realistic lighting effects, camera pictures, and sensor measurements. A detailed description of the hardware and its current configuration and future extensions currently in development are presented in the following chapters.

5. CURRENT SETUP OF THE ENVIRONMENT SIMULATION HARDWARE

The current phase A setup of the RACOON simulation environment was used to simulate close range in-plane relative motion between chaser and target. The target was required to be able to rotate about the orbit normal axis, while the chaser was required to be able to rotate about its yaw and pitch axes. The setup was designed to allow the simulation of final approaches from a range of ten meters at a scale no smaller than ¼.

5.1. Mechanical Setup

The required five degrees of freedom (DOF) for in-plane maneuvers were realized in two independent mechanisms (Fig. 2). The mechanisms include a 2D motion table (planar Cartesian manipulator) on which a vertical rotation axis is mounted, and a stationary 2 DOF slewing mechanism. The motion table with a size of 4 m x 5 m, is designed to carry a 50 kg, 1.8 m diameter mockup of an uncooperative target satellite. The target mockup is a passive box primarily made of a lightweight wood structure covered with realistic surfaces to represent multi-layer insulation (MLI) or external components of the structure. The chaser spacecraft model is mounted on the slewing mechanism. This installation of target and chaser was selected since the chaser is equipped with multiple computers, sensors and cameras. A stationary chaser is therefore easier to handle. This setup however requires the inversion of the relative motion computed by the simulation software since it is not the chaser but the target that is actually moving, in contrast to reality. Tab. 1 provides an overview of the axes assignment and the motion envelope of the setup.
The motion hardware is enclosed in a frame supporting black theater curtains to simulate the black background of space for the cameras. Sunlight is simulated by a single, fixed 50 W lamp. While this does not reproduce the intensity and spectrum of real sunlight in orbit, it nonetheless suffices to generate strong image contrasts and surface glare. These are the major visual features required for teleoperation studies.

The setup as a whole is designed for robustness and rapid implementation of simulation scenarios, allowing quick adaption to new test cases. In addition, all hardware parts are lightweight allowing handling by a two-person team and enabling a smooth work flow.

Table 1. Axis assignment and motion envelope of the RACOON current phase A setup. The chaser rotation axes are limited to the values shown in order to prevent damage to the current chaser mockup. The maximum accelerations are only reached during off-nominal stops. Nominal accelerations are substantially lower.

Axis no.	Axis use	Motion range	Velocity limit	Acceleration limit
1	Target x translation	4 m	0.3 m/s	1 m/s²
2	Target y translation	3 m	0.3 m/s	1 m/s²
3	Target z rotation	unlimited	45°/s	100°/s²
4	Chaser z rotation	± 90°	45°/s	100°/s²
5	Chaser y rotation	± 20°	45°/s	100°/s²

5.2. Electrical and Software Setup

Software used in the simulation environment is purpose-built in C++ and C#, or in Matlab/Simulink. Different logical parts, as for example user consoles or hardware drivers, are coded as independent components. All components inside the Ground Segment and inside the Simulated Space Segment intercommunicate over streams by publishing or listening to data on the network using the Data Distribution System (DDS) provided by Realtime Innovations (RTI) [42]. DDS allows easy and flexible language independent data exchange with the possibility to define various quality of service levels such as communication reliability. Each system component must be able to operate even if data on its

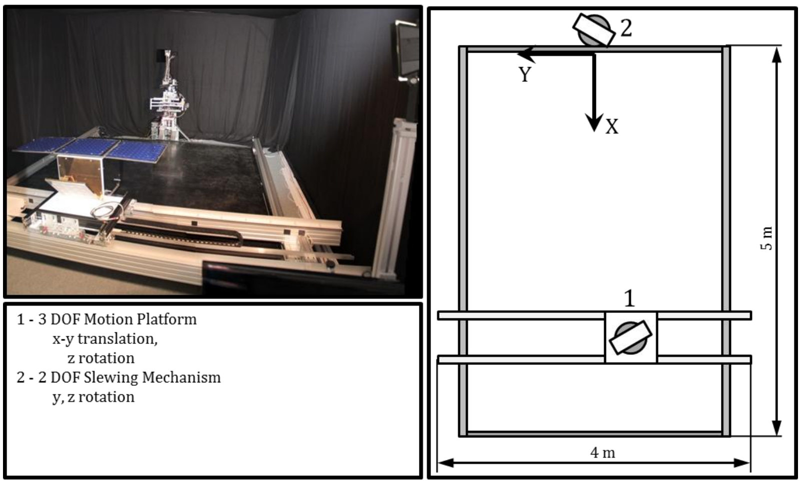

Figure 2: Phase A Motion platform of the RACOON-Lab for simulation of OOS missions. The 2D platform has a motion envelope of 4 m x 5 m, allowing scaled simulations of close proximity operations.

input stream is missing. For example a control algorithm could listen for data of a user input device. If no device, and thus no data, input streams are present, the component could be designed to assume standard values or switch to alternate modes. Such a design decouples the whole system, prevents deadlocks, and makes it quickly adaptable for different mission scenarios as new components can be integrated on the fly. Furthermore, components can be executed on different processors or computers easing up performance requirements. However, component composition has to be chosen wisely as the approach introduces dead times into feedback loops across multiple components and thus works only if signal frequencies in the transmitted data and the underlying simulation are low compared to the frame rate of the stream. With communication frame rates greater than 100Hz, as used in the RACOON, this holds true for most cases in the OOS scenario when using a composition with controller set points, relative positions, or values of sensor measurements as interfaces between streams. Nevertheless, strong couplings – e.g. inside the dynamics simulation core – are better kept inside a single component.

All components of the simulation environment run either in soft, virtual or hard real-time. Soft real-time components, such as user displays, have no special requirements on timing. Virtual real-time components, running on standard operating systems, use a fixed step size, for e.g. 10ms, in their internal virtual clock for the calculation of simulation values, but the timing of the calculation is not bound to hard real time. Therefore some jitter exists between the internal virtual clock and the real-time clock, limited only by the timing accuracy of the non-real-time operating system. Virtual real-time components keep their virtual clocks on track with real time by adjusting calculation breaks. Hard real-time components interact directly with (motion or sensor) hardware and use special hardware devices that synchronize with a real-time clock managing execution at fixed times with high accuracy. Hard real-time components also de-jitter data from the virtual real-time domain by shifting execution from virtual simulation time to the real time. In case of a timing miss of the virtual component, data is interpolated for critical tasks. Due to the fixed time delay between the virtual and the real clock, offsets can be nearly eliminated with forecasting of data. Experience with our setup, using Windows with high priority processes for the virtual real time domain, showed that this approach offers great flexibility and is very stable and potent.

Motion control of the simulation hardware is controlled by a National Instrument *CompactRIO* device incorporating a real-time operating system (RTOS) and a field-programmable gate array (FPGA) in order to minimize the number of hardware levels and interfaces. A special soft motion controller, optimized for FPGA size, was implemented in the hardware and is capable of driving 32 axes simultaneously. The controller implements a spline algorithm based on position and velocity set points and generates a smooth path through the de-jittered points calculated by the multi-body orbit dynamic simulation. Step generation is handled by the FPGA.

All mechanical axes are driven in open loop by stepper motors. Step loss is prevented by operating the system inside the maximum allowable acceleration limits for the motors.

5.3. Current Results

Using the phase A configuration of the RACOON testbed, a number of as yet unpublished studies were conducted, investigating human-machine interaction factors of teleoperated final approach and docking with uncooperative target objects. These studies covered issues such as benefits of multiple vantage points on operator performance, learning curves of different operator interface configurations, and the impact of video frame rate reduction on docking performance with rotating targets. Experience gained during operation of the system setup revealed several points for future optimization as follows.

6. PLANNED SYSTEM EXTENSIONS

The first system extension will be to expand the mechanical setup from a planar-only operation to a configuration that allows continuous full degree of freedom relative maneuvering, enabling the simulation of complex off-plane maneuvers. This upgrade will also make the hardware fully compatible with the current state of the software simulation, already featuring full degree of freedom flight maneuvers.

Second, the darkroom shall be extended to increase the operator immersion of the simulation by upgrading the quality of the background materials and integrating new covers for moveable parts and rails. Finally, a dynamic lighting simulation shall be integrated, capable of simulating a continuous sun and albedo illumination. Fig. 3 shows the architecture of the planned upgrade.

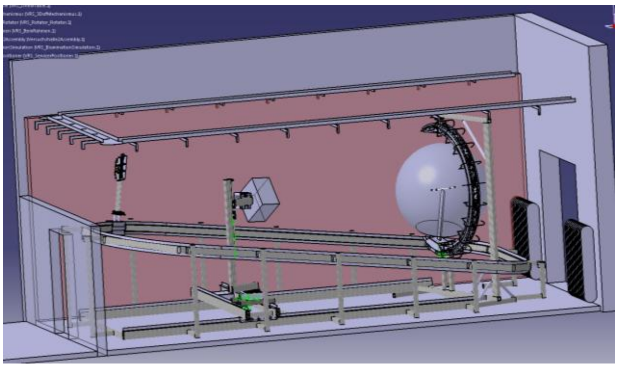

Figure 3: Future RACOON-Lab simulator full degree of freedom extension including also a dynamic lighting simulation.

The new mechanical setup is currently under development and uses, similar to the current setup, specially designed stepper motor / pulley drive units that can move along straight or bent guide rails fitted with adhered timing belts. The target will be installed on a new panning mechanism (sphere in right of Fig. 3) using three rotation axes: (1) (unlimited) azimuth, (2) elevation, and (3) (unlimited) polarization for positioning in any attitude. The elevation axis is constructed by applying a drive unit on an external, bent C-shaped profile to allow the panning of the target around its center of gravity. This setup minimizes mechanical stresses in the mechanisms as well its space requirements. Deadlocks, caused by the alignment of azimuth and polarization axes, will be prevented by two additional ±30° tilt degrees of freedom placed behind the polarization axis. The target mockup characteristics are retained, allowing a lightweight structure up to 50kg with a maximum diameter of 1.8 m. The whole surface, except a 60° cone (full angle) around the suspension beam, can be covered with realistic materials and device models as required for the simulation. This mechanical setup allows an unobstructed view from the servicer to the target from any orientation except a position inside a 90° cone (full angle) around the suspension. In those cases the C-shaped profile has to cross through the camera area in order to allow continuity of the simulation.
The servicer is located on a second mechanical setup and can be positioned in all six degrees of freedom. It uses the 2D motion table from the current version, upgraded to a positioning envelope of 6.5 m x 4 m and expanded by a new rotatable azimuth axis, a 2m long linear z-axis, an elevation rotation axis and a continuously rotatable polarization axis. The servicer has a maximum allowed weight of 25 kg and offers an internal volume of 0.6 m x 0.6 m x 0.25 m for integration of sensors. In addition the system is designed to permit external actuators on the servicer in the future.

The dynamic lighting simulation is implemented on a closed rail around the two mechanisms. Sleds on the rail are limited by the room dimensions to a footprint of 0.6 m x 0.6 m and a height of 1.8 m. Power and data may possibly be fed from the top via a rotary feed-through allowing unlimited motion around the rail.

To generate the parallel light conditions of sunlight in earth orbit, either a point source placed at a large distance away, or a large surface-emitting radiator with suitable optics for parallel light emission can be used. For financial reasons and for verification of requirements, a point source shall be installed first. Light intensity is planned up to 1/10 of sun intensity. A large parallel surface-emitting radiator would greatly enhance simulation capabilities as it could also be placed closer to the target. However, the required optical elements are complex and can result in a bulky and heavy setup. Segmented arrays can reduce the overall size, but handling visual artifacts between the elements would be difficult due to unwanted superposition of light. There have been un-published investigations at the institute dealing with flat segmented arrays using high power light emitting diodes (LEDs) in combination with optics. However, visual artifacts were significant due to the light emitting surface not being an ideal point source, the fabrication tolerances of the primary LED dome lens, and optical aberrations of the secondary Fresnel lenses. Progress in freeform lens design could perhaps remove these limitations in the future.

Albedo simulation is planned to be performed by stationary dimmable light sources around the target, which could possibly be supplemented by an additional sled on the rail.

The RACOON extension shall be finished at approximately the end of the year, offering enhanced simulation capabilities that can be used in future studies addressing complex mission operation scenarios in nominal and off-nominal situations.

7. CONCLUSION

The RACOON laboratory is a hardware-in-the-loop simulation environment for real-time teleoperation of spacecraft proximity operations and rendezvous & docking. It allows high-fidelity, end-to-end experimentation of this critical mission phase for on-orbit servicing and space debris removal missions.
In its initial capabilities phase, it was utilized for a number of studies investigating human-machine interface and data transmission issues. After its enhanced capabilities upgrade, it will allow simulations of tumbling targets and realistic sun and albedo lighting. It will then be used in research of approach trajectory planning, mission sequence planning and human-machine interaction.

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