Chapter 1
Multimodal Human Spacecraft Interaction in Remote Environments

A New Concept for Free Flyer Control

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Abstract Most malfunctioning spacecraft require only a minor maintenance operation, but have to be retired due to the lack of so-called On-Orbit Servicing (OOS) opportunities. There is no maintenance and repair infrastructure for space systems. Occasionally, space shuttle based servicing missions are launched, but there are no routine procedures foreseen for the individual spacecraft.

The unmanned approach is to utilize the explorative possibilities of robots to dock a servicer spacecraft onto a malfunctioning target spacecraft and execute complex OOS operations, controlled from ground. Most OOS demonstration missions aim at equipping the servicing spacecraft with a high degree of autonomy. However, not all spacecraft can be serviced autonomously. Equipping the human operator on ground with the possibility of instantaneous interaction with the servicer satellite is a very beneficial capability that complements autonomous operations.

This work focuses on such teleoperated space systems with a strong emphasis on multimodal feedback, i.e. human spacecraft interaction is considered, which utilizes multiple human senses through which the operator can receive output from a technical device. This work proposes a new concept for free flyer control and shows the development of an according test environment.

1 Introduction

On-Orbit Servicing (OOS) has been an active research area in recent times. Two approaches have been studied: teleoperation by humans and autonomous systems. Autonomous systems use machine pattern recognition, object tracking, and

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acquisition algorithms, as for example DART [1] or Orbital Express [2]. The research is still in early stages and the algorithms have to be realized in complex systems.

In contrast, the human eye-brain combination is already very evolved and trainable. Procedures can be executed by the trained user from the ground. Unforeseen incidents can be solved with greater flexibility and robustness. Arbitrary spacecraft could be approached, i.e. spacecraft which were not explicitly designed for rendezvous and docking maneuvers. Analogously, inspections and fly-arounds can be controlled by the human operator. Based on the acquired information the human operator on ground can decide how to proceed and which servicing measures to take. Another element in the decision queue is the path planning approach for the target satellite to the capture object.

Multimodal telepresence, which combines autonomous operations with human oversight of the mission (with the ability to control the satellites), provides the benefits of autonomous free-flyers with the evolved human experience. In case autonomous operations cause the work area to exhibit an unknown and unforeseen state (e.g. when robotically exchanging or upgrading instruments) the human operator on ground can support the operations by either finishing the procedure or returning the system into a state which can be processed by autonomous procedures. The advantage of multimodal telepresence in this connection is the fact that the operator will not only see the remote site, but also feel it due to haptic displays. A haptic interface presents feedback to the human operator via the sense of touch by applying forces, vibrations or motion.

The applicability of the telepresence approach, with a human operator located in a ground station, controlling a spacecraft, is mostly limited to the Earth orbit. This is because the round trip delay increases with increasing distance from operator to the teleoperator. A decrease of the telepresence feeling is the consequence, which has a large impact on the task performance. Therefore, as the distance increases, the role of the autonomy must increase to maintain effective operations.

For an overall and significant evaluation of the benefits of multimodal telepresence a representative test environment is being developed at the MIT Space Systems Laboratory using the SPHERES satellites on ground and aboard the International Space Station (ISS).

2 The MIT SPHERES Program

The SPHERES laboratory for Distributed Satellite Systems [3] consists of a set of tools and hardware developed for use aboard the ISS and in ground based tests. Three micro-satellites, a custom metrology system (based on ultrasound time-of-flight measurements), communications hardware, consumables (tanks and batteries), and an astronaut interface are aboard the ISS. Figure 1 shows the three SPHERES satellites being operated aboard the ISS during the summer of 2008.

Fig. 1 SPHERES operations aboard the International Space Station (Picture: NASA)

The satellites operate autonomously, after the crew starts the test, within the US Destiny Laboratory.

The ground-based setup consists of an analog set of hardware: three micro-satellites, a metrology system with the same geometry as that on the ISS, a research oriented GUI, and replenishable consumables. A “guest scientist program” [4] provides documentation and programming interfaces which allow multiple researchers to use the facility.

2.1 General Information

The SPHERES satellites were designed to provide the best traceability to future formation flight missions by implementing all the features of a standard thruster-based *satellite bus*. The satellites have fully functional propulsion, guidance, communications, and power sub-systems. These enable the satellites to: maneuver in 6-DoF, communicate with each other and with the laptop control station, and identify their position with respect to each other and to the experiment reference frame. The computer architecture allows scientists to re-program the satellite with new algorithms. The laptop control station (an ISS supplied standard laptop) is used to collect and store data and to upload new algorithms. It uses the ISS network for all ground data communications (downlink and uplink). Figure 2 shows a picture of an assembled SPHERES satellite and identifies its main features. Physical properties of the satellites are listed in Table 1.

Fig. 2 SPHERES satellite

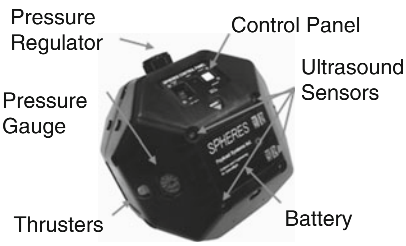

Table 1 SPHERES satellite properties

Property	Value
Diameter	0.22 m
Mass (with tank and batteries)	4.3 kg
Max linear acceleration	0.17 m/s^2
Max angular acceleration	3.5 rad/s^2
Power consumption	13 W
Battery lifetime	2 h

SPHERES has been in operation aboard the ISS since May 2006. To date, 21 test sessions have taken place. The test sessions have included research on Formation Flight, Docking and Rendezvous, Fluid Slosh, Fault Detection, Isolation, and Recover (FDIR), and general distributed satellite systems autonomy.

2.2 Human-SPHERES Interaction

Most of the previous test sessions matured autonomous algorithms. However, future servicing missions and the assembly of complex space structures will not only depend on increased autonomy, but the ability of humans to provide high-level oversight and task scheduling will always be critical. SPHERES tests were conducted to develop and advance algorithms for adjustable autonomy and human system interaction. This research began with basic tests during Test Session 11, where the crew was asked to move a satellite to multiple corners in a pre-defined volume. The satellite autonomously prevented collisions with the walls of the ISS. The test demonstrated the ability of the crew to use the ISS laptop to control SPHERES. It provided baseline results for future tests. An ongoing sequence of ISS tests is being conducted in the framework of a program called “SPHERES Interact”. The goal of the program is to conceive new algorithms that utilize both human interaction and machine autonomy to complete complex tasks in 6 degrees of freedom (DoF) environments. Tests during Test Session 19 and 20 included several scenarios where human interaction helps schedule tasks of a complex mission (e.g. servicing or assembly). The research area comprises human orientation, navigation, and recognition of motion patterns. Further, high level human abort commands and collision avoidance techniques for part of this ongoing research aboard the International Space Station.

2.3 SPHERES Goggles

The SPHERES Goggles is a hardware upgrade to the SPHERES satellites that adds cameras, lights, additional processing power and a high speed wireless communications system. Even though it was designed for autonomous operations, it can be used to support the operator with a visual feedback. The main objective of the SPHERES Goggles is to provide a flight-traceable platform for the development, testing and maturation of computer vision-based navigation algorithms for spacecraft proximity operations. Although this hardware was not intended to be launched to orbit, it was designed to be easily extensible to versions that can operate both inside and ultimately outside the ISS or any other spacecraft.

The Goggles, which are shown in Fig. 3, were designed to be able to image objects that are within few meters range and to possess the computational capability to process the captured images. They further provide a flexible software development environment and the ability to reconfigure the optics hardware.

The SPHERES Goggles were used in several parts of the telepresence environment setup at the MIT SSL ground facilities to support the human operator with a realistic video feedback which is representative for a camera system used on orbit. Apart from virtual reality animations of the remote environment it serves as the only source of visual data in the experiments.

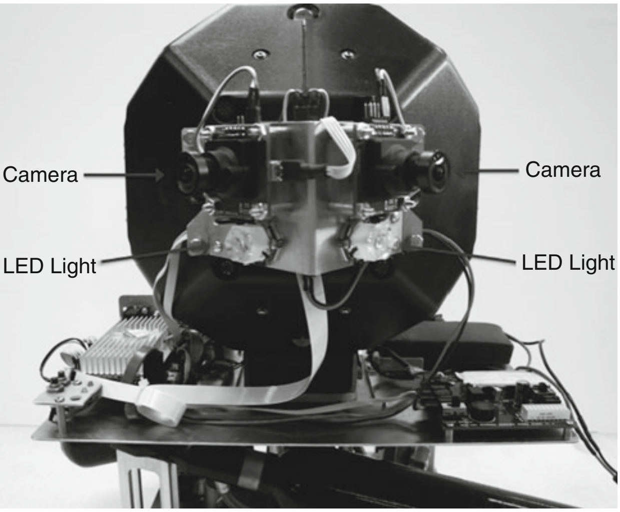

Fig. 3 Front view of Goggles mounted on SPHERES satellite

3 Multimodal Telepresence

Servicing missions can be differentiated by whether or not a robotic manipulator is connected to a free flying base (the actual satellite). Different levels of autonomy can be applied to the control of either and the human operator receives the according feedback.

3.1 Areas of Application

Unlike robotic manipulators, where haptic feedback plays an important role for control as e.g. ETS-VII [5] or Rokviss [6], free flyers are commonly only steered using visual feedback. That means that even though free flying experiments can be steered with hand controllers, as for example Scamp [7] or the Mini AERCam [8], usually no haptic information is fed back to the human operator.

The implementation of haptic feedback into the control of free flyers enriches the telepresence feeling of the operator and helps the operator on ground to navigate. It paves the way for new concepts of telepresent spacecraft control. Collision avoidance maneuvers for example can be made perceptible for the human operator, by placing virtual walls around other spacecraft. Equipping these virtual walls with sufficient high stiffness means that the operator is not able to penetrate them by means of the haptic device, since it exerts to the operator a high resistance force.

Areas of fuel optimal paths can be displayed to the operator by implementing an ambient damping force, featuring a magnitude which is proportional to the deviation of the actual path from the fuel optimal trajectory and area, respectively. Docking maneuvers can be supported by virtual boundaries as a haptic guiding cone and damping forces which are increasing with decreasing distance to the target.

Summarizing the benefits it can be seen that the application of telepresence control will extend the amount of serviceable spacecraft failures by involving a well trained human operator. In this connection it is proposed that the task performance of the operator can be enhanced by feeding back high-fidelity information from the remote work environment. Here the haptic feedback plays an important role in human perception and will be tested in a representative test environment.

3.2 The Development of a Test Environment

The key element of the test environment is the Novint Falcon [9], which is a 3-DoF force feedback joystick. All degrees of freedom are of translational nature and servo motors are used to feed forces in 3-DoF back to the user. This system has high utility for space applications since it allows the human operator to control the space application in 3D dimensional space. The Falcon is implemented in a Matlab/SIMULINK environment via the HaptikLibrary [10], which is a component based architecture for uniform access to haptic devices. It is used as the interface to Matlab and reads the positions and button states of the haptic device as well as feeds calculated forces back to it. By displacing the joystick handle, the human operator is able to interact with two instances of the remote environment - the virtual instance in SIMULINK and the hardware (SPHERES) instance on the SSL air table.

The joystick displacement is interpreted by the system, as either position, velocity or force commands. The received commands are communicated to a SIMULINK block, containing the satellite dynamics and a state estimator. The simulation returns the estimated state of the satellite in the virtual entity of the remote environment. This remote workspace is created using SIMULINK's Virtual Reality (VR) toolbox (cp. Fig. 4), allowing for satellite states and environmental properties to be displayed.

In addition to the Matlab environment, algorithms in C are used as the interface to the actual SPHERES hardware via the "SPHERES Core" API. Commands are transmitted via wireless communications to the SPHERES satellites. Torques and forces are calculated and directly commanded to the thrusters, which will cause a motion of the SPHERES satellite. The satellites measure their position and attitude and transmit the information in real-time to the laptop.

By transmitting the actual states to the VR, the operator obtains information of the estimated and the actual motion of the free flyer, which should be identical if the communication channel is not delayed and the virtual instance is a good

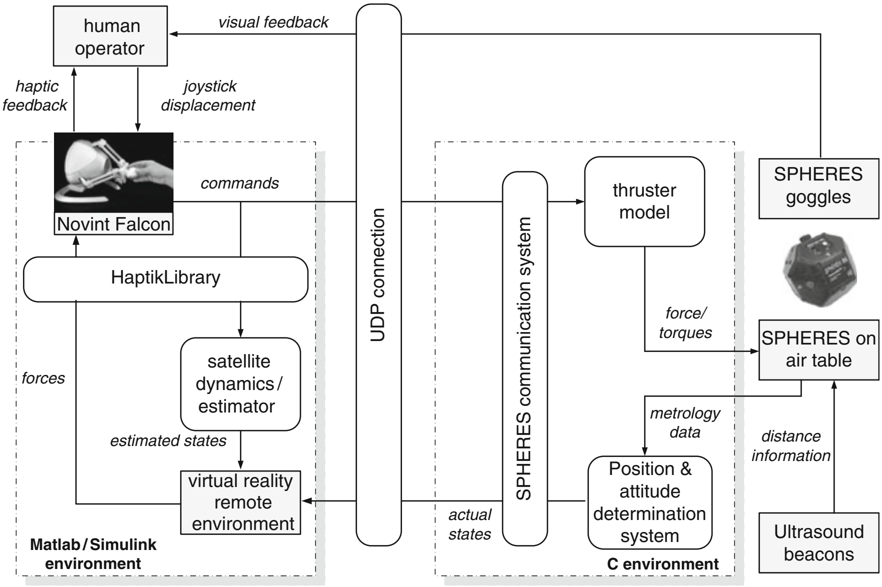

Fig. 4 General block diagram of the test environment

approximation of reality. In the presence of time delay the predictions should give the user a feeling for the behaviour of the system (cp. ETS-VII) and enhance the task performance. This is an important point if a human operator on ground will steer an application in space. That way the interactions between the autonomous space operations and a telepresence controlled free flyer can be tested.

4 Experimental Setup

If OOS missions are executed in low Earth orbit (LEO) only limited time windows are available for telecommands. The common approach for increasing those acquisition times is the usage of geostationary relay satellites. While those satellites do not have a profound impact on autonomous missions, they will influence the task performance of an operator on ground directly interacting with a satellite. Thus, this human spacecraft interaction was tested using a representative test scenario at SSL, which involved a geostationary relay satellite.

4.1 Control via ARTEMIS

Due to the orbit height of geostationary satellites, the relay of the signal increases the round trip delay between operator action and feedback to the operator to up to 7 s as in the case of ETS-VII. The delay between telecommand and telemetry is usually not very intuitively manageable for the human operator and thus a special area of interest if human spacecraft interaction is considered.

The effect on the human has already been shown for OOS missions in which the operator on ground steers robotic manipulators via geostationary relay satellites [11]. It has not been tested, yet, for multimodal human free flyer interaction. Accordingly, for initial tests a geostationary satellite was introduced in the commanding chain. The UDP connection (cp. Fig. 4) was utilized to send the commands of the Novint Falcon at SSL via a terrestrial internet connection to a ground station at the Institute of Astronautics of Technische Universitaet Muenchen in Germany. The telecommands were forwarded via the geostationary relay satellite ARTEMIS (Advanced Relay Technology Mission) of the European Space Agency (ESA) to a ground station of ESA in Redu, Belgium. The signal was mirrored in Redu and retransmitted analogously back to MIT, where again the UDP connection was used to feed the telecommand into the hardware on the air table and change the position of SPHERES in the test environment. That way the SPHERES satellites were controlled by the Novint Falcon via a geostationary satellite. The round trip delay characteristics were logged and subsequently implemented into the scenario as a SIMULINK block. That way the test scenarios could be evaluated in the absence of a satellite link but with round trip delays representative for commanding a spacecraft in orbit.

4.2 The Servicing Scenarios

To show the benefit of multimodal feedback to the operator, two scenarios were developed and tested. Both are based on a servicing operation, in which three satellites are involved. The *target satellite* is the satellite to be serviced. Therefore, the *servicer satellite* has to execute proximity operations, approach the target, and eventually dock with it. The *inspector satellite* is supporting the operator on ground with additional data of the remote environment. It carries a camera system and can yield information on the distance between the two other satellites.

4.2.1 The Human-Controlled Inspector Satellite

In this first scenario the control of the inspector satellite is handed over to the human operator, while the servicer and the target dock autonomously. The task of the operator is to ensure that the initial states of the other two satellites are appropriate for the docking maneuver. Thus, the operator commands the inspector satellite as depicted in Fig. 5 from its position in front of the other two satellites to a position behind the two satellites, which is indicated by a virtual checkered marker.

For efficiently accomplishing this circumnavigation, virtual obstacles were created to avoid collisions with the servicer, the target, and the borders of the experimental volume. As to be seen in Fig. 5 both of the satellites to dock feature a virtual collision avoidance sphere. Further, on the left and the right side of the volume, there are virtual (brick) walls introduced. The Novint Falcon generates forces in case the operator penetrates those objects. These resistance forces are fed back to the operator and thus prevent from colliding with the actual hardware on the SSL air table.

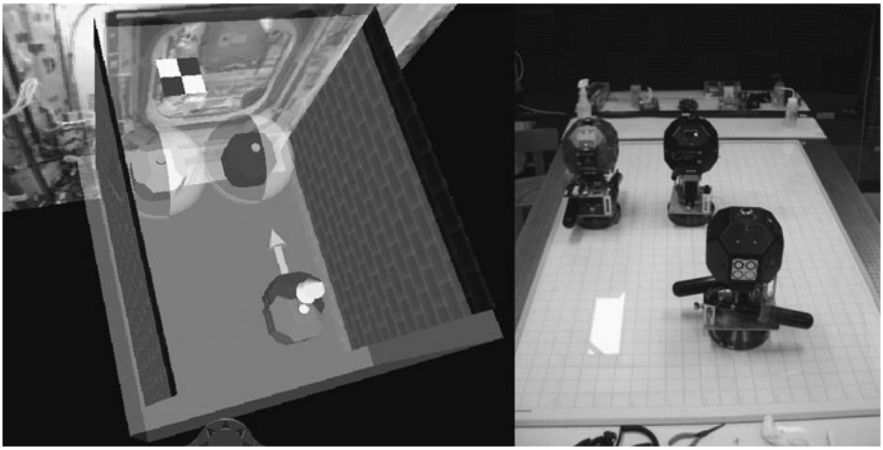

Fig. 5 Virtual and hardware instance of the inspection scenario

A further benefit of using the virtual reality techniques is that the environment can be augmented with additional data of the remote environment. For example, arrows can be used for indicating the current velocity and rotation rate (double arrow) of the inspector. Furthermore, there are two entities of the inspector satellite to be seen in the VR environment. The dark entity shows the commanded state, whereas the pale entity shows the actual state of the hardware in the remote environment. This is of great benefit for the human operator in the presence of time delays as they occur due to the use of relay satellites.

4.2.2 The Human-Controlled Servicer Satellite

Similar to the first scenario, the inspector, target, and servicer satellite are again involved in the second scenario. The servicer is supposed to dock with the target, whereas the inspector is transmitting additional data from the remote scene. In this scenario the target and the inspector (right upper corner in Fig. 6) are operating autonomously and the servicer satellite (lower right corner) is controlled by the human operator via the relay satellite.

Again, the virtual environment is enriched by collision avoidance objects (at the inspector and the borders of the volume). The task of the operator is to accomplish a successful docking maneuver. Therefore, the human operator is supposed to command the servicer at first to a position roughly aligned with centre of the docking cone, which can be seen in Fig. 6 and approx. 50 cm away from the target. In a second step the operator is commanding the servicer along the virtual cone until the berthing takes place.

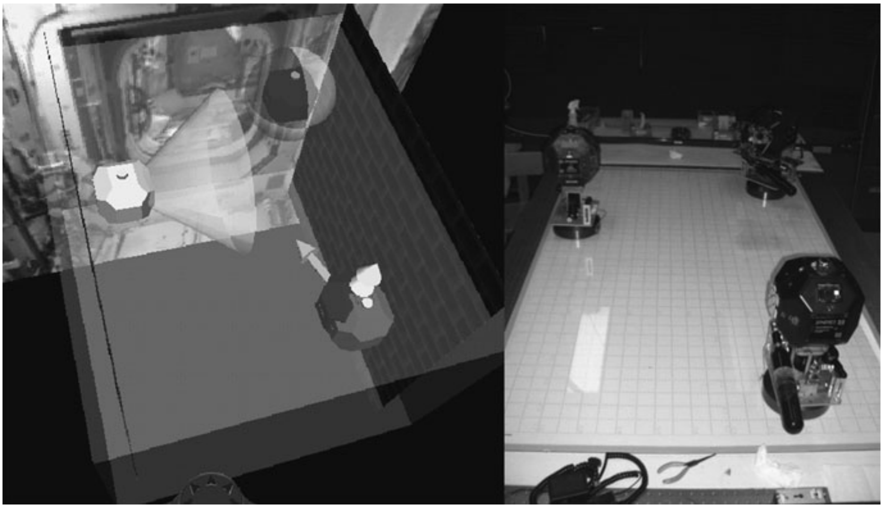

Fig. 6 Virtual and hardware instance of the docking scenario

The docking cone is a mean to simplify the proximity operations for the operator. Once the servicer has crossed the assistance horizon of the cone, a force field is applied to the Falcon, which drives the servicer into the docking cone. Inside the docking cone another force field drives the servicer towards the target. Here, the forces are proportional to the distance to the target. This helps the operator to concentrate on the precision of the docking point rather than to worry about relative velocities and collisions.

5 Results of the Experiments

The two scenarios were controlled via the German ground station [12] at the Institute of Astronautics and the ESA relay satellite. The human operator at MIT in Cambridge received instantaneous feedback from the haptic-visual workspace. To have a representative test conditions the operator had only visual feedback from the SPHERES Goggles and the Matlab Simulink virtual instance of the remote environment. Further, the haptic device yielded additional forces for an advanced human spacecraft interaction in the 3D environment.

5.1 Round Trip Delays due to the Relay Satellite

The occurring round trip delays were logged since they are a first indicator for the quality of the human task performance. Figure 7 shows an example graph of the delay characteristics over time. The round trip delays are plotted depending on the respective UDP packet number. They indicate that the delay in a real OOS mission can be, except for a couple of outliers, well below 1 s. The outliers occurred due to the use of a terrestrial internet connection and the lack of synchronization between

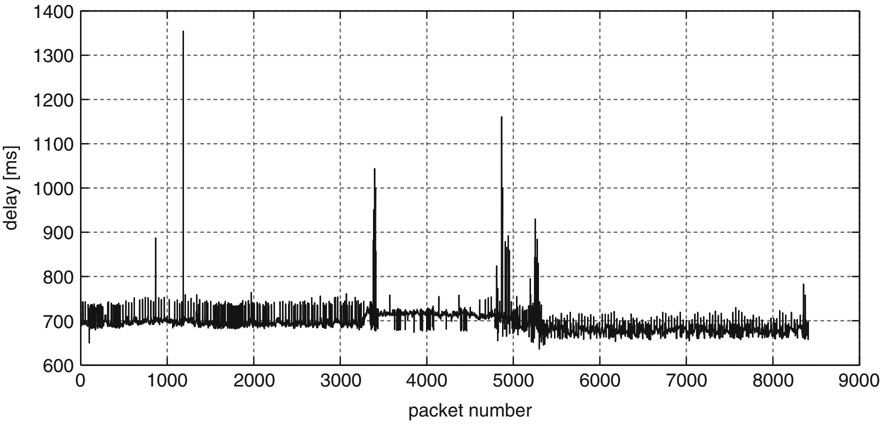

Fig. 7 Round trip delay characteristic of the free flyer control via ARTEMIS

the sampling rate of the hardware at MIT and the sampling rate of the satellite modem at LRT. Nonetheless, a mean of 695.5 ms with a sample standard deviation of 24.1 ms indicate an acceptable round trip delay [13] for telepresence operations.

5.2 Operator Force Feedback

Navigation in a 3D environment with a sparse number of reference points can be very complicated for a human operator. The motion with 6-DoF is not only very unintuitive since the motion in free space is no longer superimposed by gravity as it is on Earth the case. The equations of motions are further coupled in a way that an introduced torque about a main axis of inertia of the spacecraft will not necessarily cause the spacecraft to rotate about the respective axis but about all three axes.

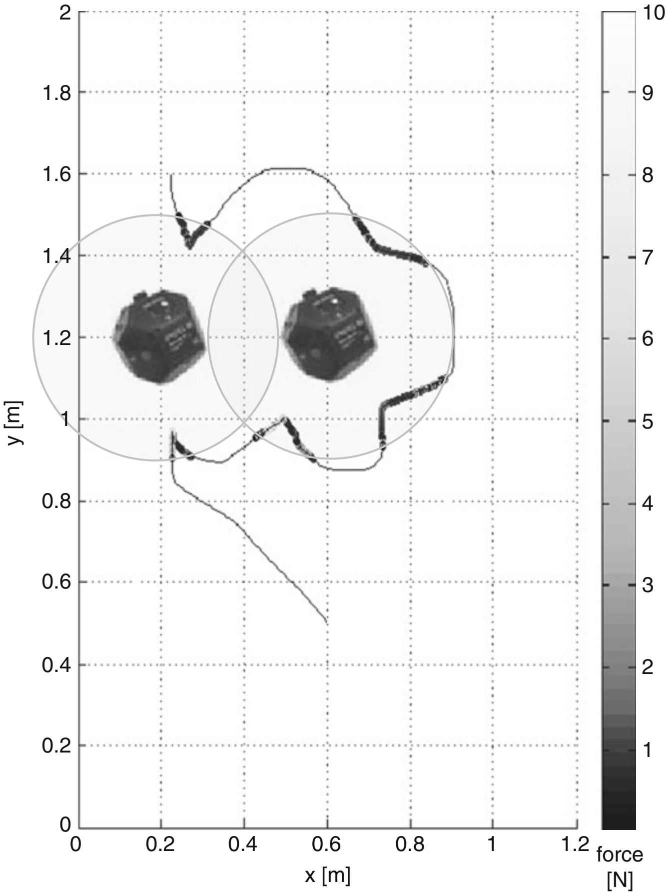

Fig. 8 Force feedback of the inspection scenario

Thus, the human operator has to be supported by technical means in order to solve complex problems in the remote environment. One of those means is, as shown in this work, to augment the feedback to the operator. Virtual reality can be used to show commanded/planned states versus actual states of spacecraft and can additionally visualize potential dangerous areas.

Since the 3D remote environment is usually projected onto 2D screens, it can be difficult for the operator to realize where exactly such an area, in which collisions could take place, is located. Consequently, a haptic device was used which utilizes another human sense and enriches the perception. Forces are fed back to the operator site, permitting the operator to enter the respective areas.

Figures 8 and 9 show example forces that were fed back to the operator depending on the position of the spacecraft in the remote environment. The path

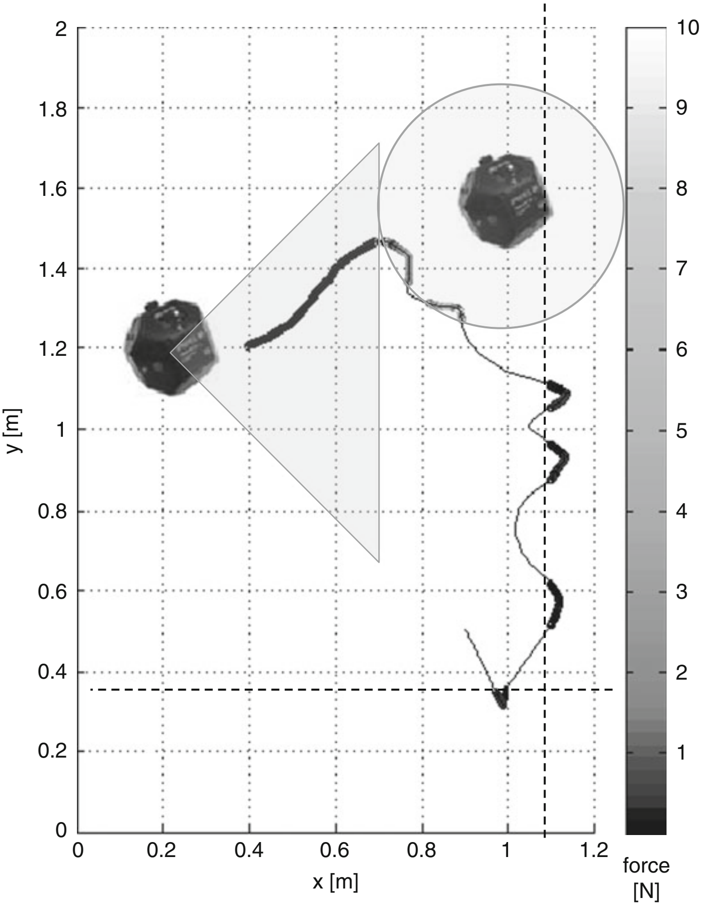

Fig. 9 Force feedback of the docking scenario

of the spacecraft is indicated by a solid line, whereas the force feedback is labeled by small circles in gray scale. If a collision avoidance sphere was penetrated as e.g. in Fig. 8 a restraining force was created proportional to the penetration depth and the velocity (spring-damper system) of the spacecraft. The same held true for virtual walls as can be seen in Fig. 9. This figure further shows the force feedback inside the docking cone. As can be seen, the haptic feedback prevented the human operator form colliding with the other spacecraft or the experimental boundaries. It gave the operator a feeling for critical areas and helped the operator to accomplish a very smooth docking/berthing approach.

6 Summary

This work presented the first tests on haptic feedback for free flyer systems. It proposes that multimodal feedback from servicer satellites enhances the human task performance. This feedback supports the operator with an intuitive concept for collision avoidance and relative navigation. That way, complex tasks in microgravity can be safely operated from ground.

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