ROBOTIC TECHNOLOGICAL OPERATIONS FOR RE-FUELLING SATELLITE SERVICING MISSION

Maediger, B., Doermer, M., Regele, R., Luebke, V., Wilde, D. [(1)]

[(1)] {bernd.maediger;manfred.doermer;ralf.regele;verena.luebke;detlef.wilde}@airbus.com

ABSTRACT

In this paper, a novel approach for robotic refuelling operations in space is described. The approach is based on robust, simple operations instead of complex motions that require a high degree of precision. Based on the impedance control mode of modern robots, which enables the autonomous control 'by touch' instead of precalculated or tele-operated actions, the typical applications like positioning, cutting and screwing have been tested and verified with a sophisticated laboratory testbed, using space-qualified target structures. The necessary tasks for refuelling were successfully demonstrated with a simple, robust motion control and provisional tools, showing the viability of a low-requirement approach for space servicing.

The paper describes the status of the project as well as the developed concept and the main technical features. Furthermore, the paper introduces the implementation of a mock-up of the proposed system in the Space Robotics and Automation Lab at Airbus DS in Bremen. Results of first experiments conducted in this facility are shown in detail as well.

Figure 1. The Fill and Drain Valve (FDV)

1. INTRODUCTION

Recent developments in the market of telecommunication satellites and their specific needs on the one hand and the idea of the extension of the remaining life-time of satellites in orbit on the other hand increase the need for an on-orbit refuelling service of existing satellites. Up to now no commercial satellites in orbit are prepared or equipped for refuelling. Therefore, satellite components and procedures used for the fuelling on-ground must be considered also for in-flight services. This includes especially the Fill and Drain Valve (FDV)(Figure 1) and the corresponding tanks, piping and valves on the satellite's side. Additionally, it must be taken into account that dedicated means are implemented on the satellite to handle special space environment issues, which are e.g. the coverage with MLI or the securing of the FDV-cap with a wire lock.

Recent developments in robotics technologies [1][2] provide excellent force-torque handling capabilities for more complex robotic operations like refuelling operations, which can be solved without using sophisticated tools now. Based upon these robotic capabilities, robotic tasks for the complete refuelling operations sequence (with the exception of the liquid transfer itself) have been developed and tested in the Space Robotics & Automation Lab at Airbus. Nowadays, industrial robots are available which provide comparable impedance control features as the planned space robots. So the described operations could be conducted with an unmodified, commercially available robot, the KUKA iiwa.

2. MISSION AND CORRESPONDING ROBOTIC TASKS

In a typical refuelling mission, a servicer will approach a potential client satellite before performing a rendezvous manoeuvre followed by the capture of the client satellite (Figure 2). After the capture a rigid connection between servicer and client satellite will be established.

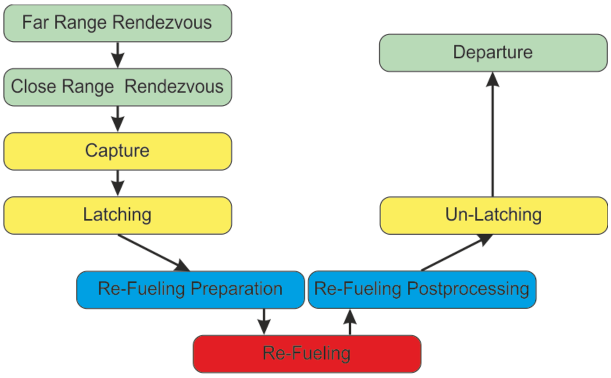

Figure 2. Stages of a refuelling mission
(green: satellite ops, yellow: potential robotic ops, blue: robotic refuelling ops,
red: pump refuelling ops)

In all these operations robotic components or subsystems (e.g. a robot arm) can be involved, e.g. for the capture of the client. For this paper though, the focus is on the next phase, the refuelling activities. Here, besides the real pump operation, several preparation and post-processing activities are needed, which shall be conducted by a robotic arm, equipped with dedicated tools.

The preparation activities include following operations:

- Inspection of the surrounding of the valves and of the valve box itself, verification and/or refinement of the target position.
- Removal and stowage of the MLI covering the FDV.
- Cutting of the wire-lock without generation of debris.
- Unscrewing and stowage of the cap of the FDV.
- Connecting the refuelling tool to the FDV.

Now the actual pump operation can be conducted including all needed monitoring and supervision activities. In this phase the robot is not involved, dedicated pumps including tanks and pipes will execute this pump over operation. After the successful completion of this activity the robot takes the next actions for the finalization of the refuelling mission. For the post-processing, the following operations must be performed:

- Detach the refuelling tool
- Screw a cap onto the FDV
- Place a MLI patch to cover the FDV again

According to the latched condition all target object positions are roughly known, but, nevertheless, object positions deviations e.g. due to thermal issues must be observed.

3. OBJECTIVES

The operation of tools by robotic manipulators is a new concept in space missions. Therefore, as a first step, the feasibility of such operations needs to be shown and demonstrated to potential customers. This includes investigations on the functional allocation between robot and tools as well as corresponding requirements on the tool design. The objectives of the project can be summarized as follows:

- Development of an implementation concept for robotic refuelling operations based upon advanced space robots.
- Functional allocation between robot and tools taking into account the advanced force-torque control capabilities of the robot.
- Demonstrate the feasibility of the selected concept.
- Gain experience in the implementation of robotic technological operations for refuelling as well as for other on-orbit missions like e.g. payload exchange or in-space manufacturing as precondition for the definition of further development steps.

4. IMPLEMENTATION CONCEPT

At Airbus Bremen a concept for robotic conducted technology operations like refuelling was developed which can be characterized by the following features:

- All main control and handling functionalities are implemented in the robot. This means that an impedance-controlled robotic manipulator performs all servicing operations. As a consequence, the functionality of the tools used is relatively simple. This is comparable with a human approach, where the flexible universal human arm grasps specialized tool for dedicated tasks.
- In addition to the smart robot, for each class of servicing operations a dedicated tool is used. In the refuelling demonstration three different tools were implemented: A MLI-removal tool, a wire cutting tool and a cap removal tool. In some other application cases it could be demonstrated that this concept can be easily extended by exchanging only the tools.
- The connection between the robot and the various tools is established by a universal gripper. Such a gripper, which shall be as simple as possible, can be a two- or three finger gripper or a kind of tool exchange mechanism. Both concepts were implemented in the introduced concept. Obviously, the tools must be equipped with a complementary handle.

To perform the feasibility tests as realistic as possible, two pre-conditions should be observed:

- The used robotic manipulator shall be comparable in kinematic and dynamic behaviour with the design of advanced space robots. This can be realized by using the last generation of industrial robots, designed on the basis of space robotics developments and providing well advanced force-torque and impedance control modes.
- All used components shall be similar or equivalent to real space equipment. In the refuelling demonstration this includes especially the FDV and its surrounding.

5. TESTBED

The core of the testbed persists of a KUKA iiwa 7 R800 robot, which will handle all tools and perform all operations. This type of robot is equipped with full impedance control, enabling it to react directly on external forces and to act 'on touch'. This is a major difference to most industrial robots, and also to the robotic manipulators currently used for space applications. Based on these capabilities, the robot is expected to perform its operations with a high degree of robustness and flexibility. It does not rely on high-

precision movement controls (precalculated, or fine-tuned by manual tele-operation), which would be problematic anyways. The pose-estimation for the target structures (using the on-board sensors) will only work with a certain precision, especially since the fine structures are most likely hidden behind a MLI cover. Within the testbed, the robot is able to compensate for a pose error of up to 10mm by using its impedance mode for touch control.
To test the capabilities, the robot is mounted on a 3m linear motion module in front of a satellite mock-up. The robot is equipped with a standard two-finger gripper to handle the different tools. A dedicated tool-changing system would be more precise - but as we want to test the robustness of the system, precision is generally not a high priority. Racks for the different tools are placed around the robot base, simulating the servicing satellite.

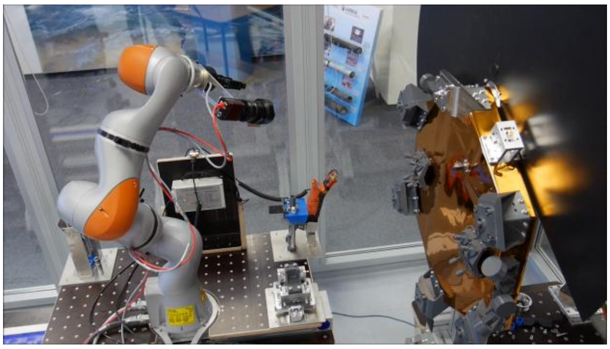

Figure 3. Testbed overview

This testbed, although relatively simple, can be used for a wide variety of docking and servicing tasks. For the refuelling operations, it is assumed that the serving satellite is docked and in a stable position in front of the target satellite, facing the FDV. It is assumed that the rough position and orientation of the target structure is determined by the sensors of the servicer (although the sensor processing will not be discussed within this paper). The target satellite is assumed to be uncooperative, with no supporting movement and no special guiding structures or markers. As a matter of fact, all satellites so far were never designed to be refuelled, and it was never assumed that the FDV structures are accessed after launch. The servicer (represented by the robot here) will have full control over all operations, acting as a single control instance. There is no planned human interference or tele-operation besides a general safety supervision. All operations should be done autonomously by the robotic system.

6. TOOLS

All the described tools are prototypes developed for the testbed, using low-cost materials not intended for usage in space. For the creation of the tools, consumer power tools were modified and combined with 3D-printed holding structures. This made easy adjustment and fast test cycles possible. It is expected that these tools have a much lower performance than the final space products. The feasibility of these tools further emphasizes the robustness of the system, in which low-precision components were used for the satellite model, the mechanical structures, tool gripping, tool structures, sensor processing and motion control.

6.1. MLI removal tool

The first task of the refuelling operation is to get rid of the MLI covering the actual valve. A specialized tool for this task was developed which can be gripped and operated by the robot. For the cutting process itself, different methods were evaluated like mechanical cutting, stabbing or laser burning. Major decision criteria were the safety, low precision needs, robustness and reliability, as well as the avoidance of additional debris objects which could fly away. In the end, a heating wire was chosen for the tip of the MLI removal tool, which works by placing a blunt metal tip heated up to 450°C on the intended cutting seam. The main advantage of this method is that the MLI is melted, but not burned, and that the different layers of the MLI are melted together at the cutting seam, avoiding the problem that the MLI patch could split up in different layers which might separate from each other and fly away. To avoid any further interferences of the cut-out MLI patch, it was decided to completely remove a circular patch of MLI around the valve. This generates two problems: The removed patch must be safely grabbed and secured, and the resulting hole in the MLI must be covered up after the refuelling operation is finished. For both tasks, a safe method to grab or attach a piece of MLI must be provided. The solution here was to use adhesive tape strips which are based not on a chemical glue, but work with mechanical structures using van der waals forces to achieve the adhesive property (and therefore work in space). These are the same forces that the gecko foot uses to walk on walls, leading to the name gecko-tape for the adhesive strips.
The general operation process for the MLI removal looks like follows:
- A gecko-tape covered stamp is placed on the MLI to secure the patch.
- The robot moves the heated cutting wire in a circular path around the stamp to generate a clear seam.
- The stamp with the attached MLI patch is removed and stored away, creating a circular hole for further work.

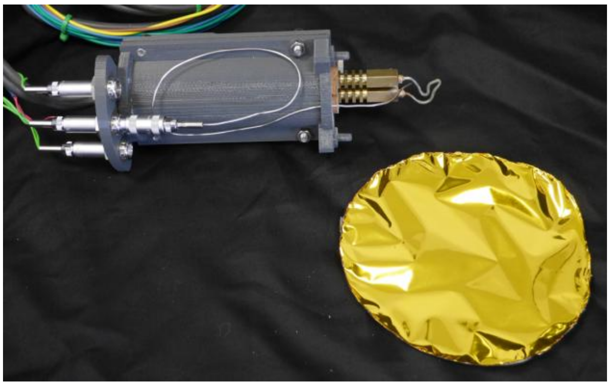

Figure 4. The MLI removal tool (top) and a cut out MLI patch.

Figure 5. The MLI cutting in operation. Note the stamp structure in the middle that is attached to the MLI, while the hot wire cutter moves around it.

6.2. Wire cutting tool

The FDV is secured with a lock wire that connects the valve cap with the valve base. To unfasten the cap, the lock wire must be cut. Again, different methods of cutting were evaluated, with safety, debris avoidance and efficiency as major criteria. Approaches in the past have used a scissor-like clipper[3], however, this requires a high precision for positioning and a fine-tuning of the motion control to correctly catch the movable and not well-defined wire. Instead, we use a vibrating saw blade, which is able to cut the wire at any point and at any angle. A circular saw was excluded to avoid unwanted torque forces on the system.
For a correct positioning of the saw blade, the tool is supplied with a guiding frame that can be used to both detect the correct distance to the target satellite's surface (by moving towards it and detecting the touch force when it contacts the target), and the correct side alignment of the tool (by using generous centring cones for fitting the valve body). Remaining positional errors and alignment errors are compensated by using the tool together with a soft robot impedance mode, in which the robot adjusts to external forces applied by the contact.

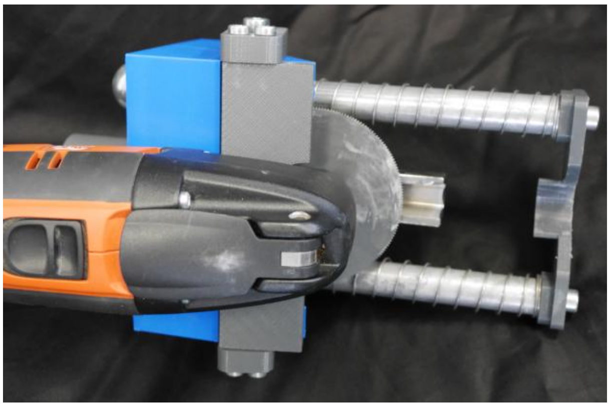

Figure 6. The wire cutting tool

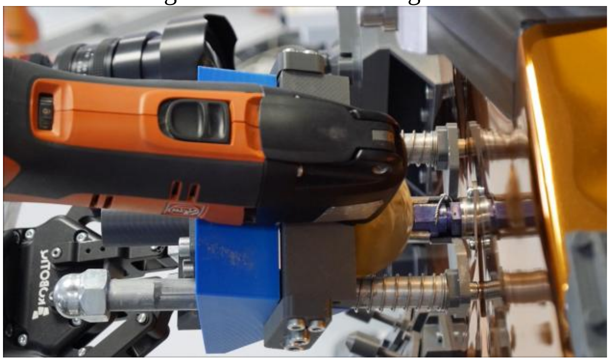

Figure 7. The wire cutting in operation. The guiding frame has been put around the valve, and the saw blade is closing in towards the wire.

6.3. Cap removal tool

On top of the FDV, there is a screw cap that needs to be removed before the valve opening itself can be accessed. The cap removal tool is powered by a standard electrical screwdriver motor. It is equipped with a guiding frame similar to the one used for the wire cutting tool, allowing a robust positioning of the tool in front of the valve cap. By pressing the tool against the valve, the screwdriver nut will then fasten itself over the valve cap. The cap can then be unscrewed, or screwed back on. Inside the nut of the screwdriver are magnets which hold the cap in place when it is unscrewed, so that it does not float away. As the cap remains within the tool, it is possible to use the cap removal tool also for fastening the cap back onto the valve after the refuelling is done. The process for this is almost the same as for the unscrewing - only the turning direction needs to be reversed.
Screwing can be a tricky task for robots if high-precision positioning is used. The position of the cap changes depending on the turns of the screw, and it is necessary to precisely monitor the process to detect the moment when the screw has attached to the thread. By taking advantage of the impedance mode, the process is much simpler: Just like a human, the robot will apply a certain force to the screwdriver, but will not enforce a direct motion. It is not necessary to calculate the motion

of the cap during the screwing process. The cap removal tool is therefore relatively simple to use.

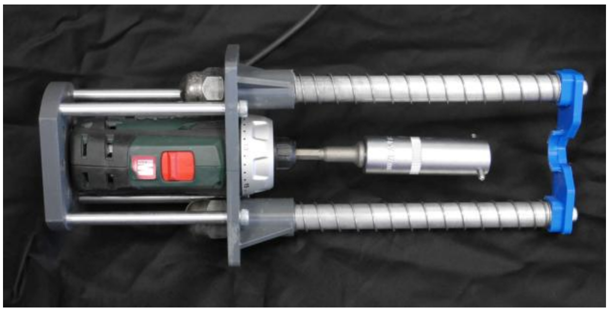

Figure 8. The cap removal tool

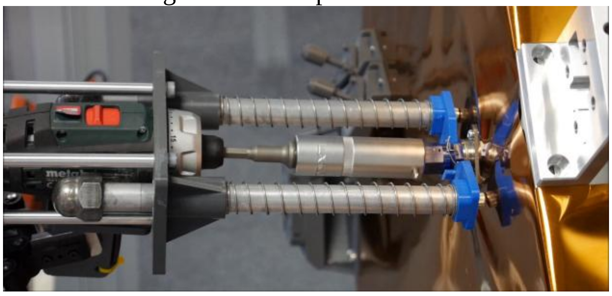

Figure 9. The cap removal in operation. The guiding frame has contact with the valve, and the nut of the screwdriver is about to glide over the cap.

7. TEST CONDUCTION

All tests were conducted in the Space Robotics&Automation Lab in Bremen. Generally, the tests started with a known (rough) position and orientation of the target valve, but did not use further input from the camera sensors, relying completely on the touch capabilities of the root. Because of safety concerns, the MLI burning tests were executed in separate tests than the mechanical manipulations. Wire cutting, cap removal and cap re-installation were executed as a combined test, including all tool changes. The actual refuelling operation was not simulated - the positioning of the fuel nozzle would be very similar to the existing tools. The fuel transfer itself is tricky, but was already examined in the past [3].

The control software for the system is relatively simple: No high-precision motions are needed, so only the basic movement must be programmed. The fine-adjustment of the robot motions will be done by the robot itself, when running in impedance mode. Because of the simplicity of the control software, all of it can be stored and executed from the robot control computer.

8. TEST RESULTS

All discussed tool operations could be successfully demonstrated on the testbed. A high number of test runs were executed, with consistently high success rates. No further human assistance or control was needed. In isolated cases, in which a task was not fully successful (e.g. the wire not completely cut, the cap screw not fully closed), the problem could be solved by simply repeating the process. Based on the rough movement/self-adjustment approach, the task operation is not fully deterministic. Small position changes, together with various error margins can lead to a slightly different behaviour of the robot. It is therefore quite difficult to give fixed precision criteria for the success of the operations, which can be regarded as a disadvantage. It is expected that the success rate is further improved when high-quality tools and calibration methods are used.

9. CONCLUSION

The successful tests have shown that the approach of relying on the impedance of the robot and not on high-precision motion control is a viable one. Operating by touch and not by vision is fully possible, if the base scenario is known. A clear advantage of the approach is the fact that the refuelling operation can be done without relying on human tele-operation, making the expected operation much faster and cheaper. The rough-but-sensitive approach is also very promising for the handling of not fully known structures, including damaged or distorted components. The necessary tools for the operations could all be developed in a straight-forward and cost-effective way, with human behaviour giving a good indication about the needed motion actions. In the end, the robot handles the tools quite similar to the way a human would handle similar tools, including actions like move-till-contact, pressure push or shaking the tool for a better fit.

With the viability of all major tasks shown, the overall task of refuelling an unprepared satellite seems to be fully achievable. The needed technical effort for the different tasks is not as high as sometimes assumed - with the usage of general-purpose tools like the sensitive robot arm the need to develop specialized tools and operations is greatly reduced.

10. REFERENCES

1. Dittmann, R. et al., Robotic Components Verification on ISS (ROKVISS), Proc. 55th IAC, Vancouver, 2004

2. Astrium wins DEOS contract to demonstrate in-orbit servicing, https://www.airbusgroup.com/int/en/news-media/press-releases/20120913_astrium_deos.html, Sept 13, 2012

3. Cepollina, F. Robotic Refueling Mission (RRM). https://www.nasa.gov/mission_pages/station/research/experiments/778.html#publications, 2016