RTES: Robotic Technologies for Space Debris Removal

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Abstract

The removal of large parts of space debris is an upcoming task for next space missions. Such missions are characterized by new challenges, e.g. the close range rendezvous with an un-cooperative target and the capture and de-orbiting of a large tumbling satellite. Although basic technologies are available these technologies must be improved for an efficient implementation, especially concerning costs and reliability.

Therefore Airbus Defence and Space conducted a technology development program called RTES to assess available technologies and potential improvements considering a robotic arm as basic capture element. The focus was on close range activities, like:

- Inspection
- Close approach rendezvous
- Capture
- De-tumbling

A consistent development requires an investigation of all involved technologies, especially

- Multi-system GNC
- Distributed visual navigation
- Capture- and holding mechanisms
- Control systems
- Operations

For all these technologies dedicated requirements were derived, a trade-off of potential methods was performed and a feasibility analysis of promising solutions was performed.

1 Introduction

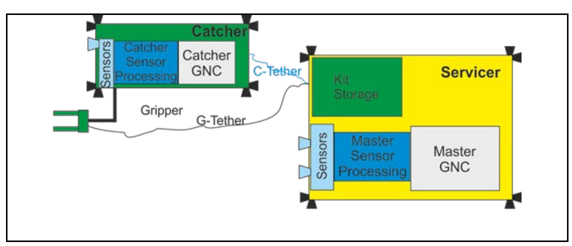
For the new emerging missions types like space debris removal and on-orbit servicing many new technologies are required or existing technologies must be modified taking into account the new mission constraints. Relevant core technologies for these new applications are developed already in some demonstration missions like Orbital Express [20] or DEOS [19]. But for commercial missions these technologies must be improved especially concerning the reliability and the costs. This includes also the investigation of modified mission concepts, e.g. the consideration of multi-target removal missions. The objective of the project RTES was to develop and to demonstrate first solutions in the direction, using a robotic arm as core handling component.

In chapter 2 the basic system concepts for such an approach will be described, followed by the more detailed description of the relevant technologies for this application. This includes the multi-system GNC, where the main results are shown in chapter 3 and the distributed visual navigation (chapter 4), which delivers the necessary relative navigation input data for the GNC. The next chapters give an overview of the related frame technologies like control system and operations and the needed mechatronic components. Thus all technologies relevant for close range rendezvous and robotic capture operations can be shown in their system context.

2 System Concepts and Related Technologies

Besides the removal of large satellites also the disposal of small debris parts should be considered in the frame of commercial missions. Due to the different constraints for the two application areas the considered system concepts are quite different too. Especially for the removal of a large satellite in most cases a dedicated mission is foreseen, whereas in the small debris case within one mission several debris parts must be removed. This leads to a kind of kit-design for the servicer spacecraft. Here each kit can remove one debris part.

This kit-concept is applicable also with a robotic arm as key capture element. Considered system concepts are shown below.



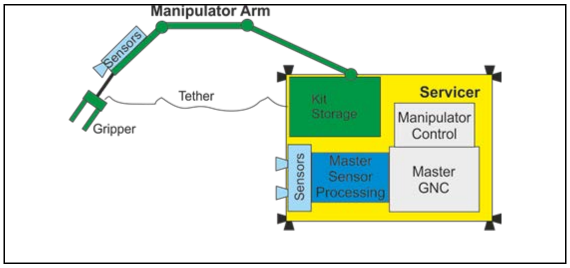


Figure 1: Considered kit-based system concepts

The first concept can be characterized as a "free-flying gripper". In this case the catcher must be equipped with components of the navigation and of the GNC system, allowing an autonomous approach to the target. In the second case the gripper is must simpler, most of the handling operations are conducted by the robotic arm. Therefore this concept was selected for further investigations.

In the following chapters the resulting consequences on the necessary technologies and proposed solutions shall be described.

3 Multi-System GNC

From the chapter above it is clear that the GNC system requirements are quite different depending on the selected concept. This holds in particular for the tethered concept, where both, de-tumbling of the target spacecraft and de-orbiting of the linked tethered system needs to be performed by the servicing spacecraft via the tether. On the other hand there are a large number of functions needed independently of the envisaged concept. This concerns in particular the approach up to grappling. Since focus of this study was given to robotic systems, the tether control was not further investigated.

3.1 Approach to Grappling Point

The far range approach to an uncooperative target is largely independent of the target and the potential tumbling motion. Optical cameras provide the capability of target detection at 10km or even beyond. Though these measurements are only available outside the eclipse, it can be shown that the navigation performance is sufficiently accurate (see [3]) to perform an autonomous approach to mid-range distances of <1km, where precise and eclipse independent measurements, e.g. of a Lidar become available. With these measurements navigation performance becomes more than an order of magnitude better and the approach to an inspection flight is safely possible. Like the inspection flight itself the approach up to this point is based on relative orbital elements control ensuring e-i-separated trajectories (see [4]). During the inspection flight the servicer is surrounding the target while keeping a target pointing attitude. This allows to check the client satellite's structural integrity, derive a first estimation of the tumbling motion and determine the strategy for the close range approach up to grappling. Depending on the attitude motion and whether or not the client satellite is equipped with large appendices (antennae, solar arrays) the further approach need or not motion synchronization with the tumbling motion of the client. For small, compact bodies or slowly moving target satellites the rotational energy can be absorbed by the manipulator arm so that a synchronous motion is not needed. For a tumbling satellite with large appendices like Envisat, synchronization is needed. In this case, a target body fixed approach axis is defined (see figure 1 as 2D example), a hold point on this axis acquired and then a straight line approach to the grappling point performed.

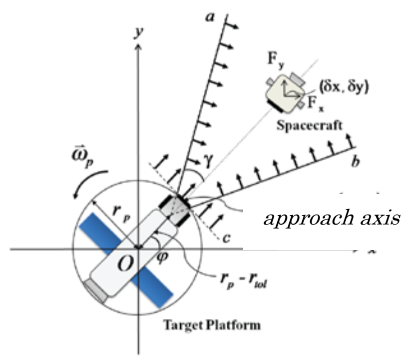


Figure 2: Target body fixed approach axis ([6])

The selection of the hold point on the approach axis is determined by safety constraints and the attitude rate of the client spacecraft, which in turn drives the requirements for the actuators (necessary thrust level to counteract centrifugal forces when following the target motions). The acquisition of the approach axis as well as the approach along this client fixed axis can be performed by applying segmented onboard path calculation based on the pose estimation provided by the navigation function (see para 4) with an underlying closed loop control for position and attitude to keep the servicer target pointing.

Alternatively to this classical approach the model predictive control (MPC) technique as assessed in [6] has been applied. The controller is based on predicting the future behavior of the system under a certain control sequence at each time step, while optimizing the control input with a QP-solver (see [7]). The dynamics of the system are the Euler rotation (tumbling) of the target platform and Clohessy-Wiltshire-Hill equations in three dimensions. The result is shown in the figure below

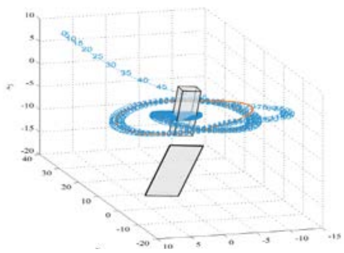


Figure 3: Approach to a tumbling target in LVLH frame

It can be seen that the trajectory clearly take into account the wobbling rotation of the platform.

The big advantage of this approach over the use of pre-computed trajectory segment parameter is the possibility to define constraints such as actuator saturation and approach corridors and the algorithm will find the optimal trajectory w.r.t. fuel consumption and performance index from an arbitrary initial position and velocity. This however for the cost of very high processing performance needs.

3.2 Detumbling

Once the client satellite is grappled and the relative motion is tranquillized the angular momentum of the client satellite is transferred to the composite system. At the end of this manipulator operation a rate damping (typical rate is about 3deg/s) and a subsequent LVLH realignment of the composite satellite system is performed. Two controller concepts have been compared for this, a quaternion based feedback controller with fixed gain and a phase plane controller allowing the direct consideration of the rather moderate accuracy requirements and thus keeping the thruster duty cycle low.

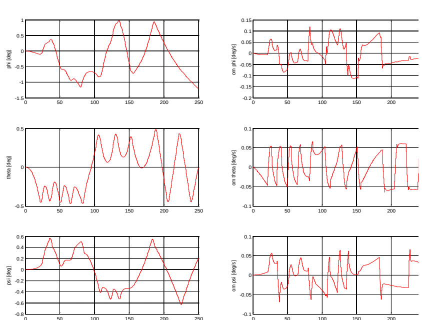


Figure 4: Attitude control error during a 70 deg slew

As a result of this preliminary analysis the phase plane approach was found advantageous because the linear feedback controller design required about twice the control energy and twice the number of thruster pulses. The ratio became even worse, when large uncertainties in the MCI characteristics were assumed.

3.3 De-orbiting

A controlled de-orbiting requires an entry angle of around -0.7deg, which can only be achieved by appropriately high acceleration (around 3cm/s2) level. For a debris removal mission the centre of mass of the composite spacecraft generally is not adjustable so that either a gimbaled main engine or a combination of pulse commandable thruster is needed. For a composite mass of typically 2t a total thrust of 60N would be needed which can be achieved with a set of 20N thrusters. Arranging them similar to the sketch in the figure below, allows the application of Off modulation to cover a centre of mass region as indicated by the green square

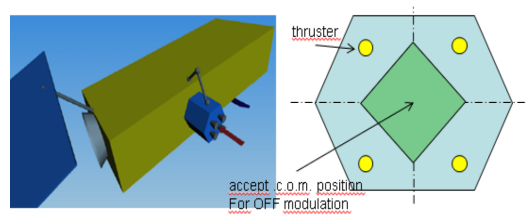


Figure 5: Thruster configuration for de-orbiting

To avoid high frequency bumping of the servicer satellite on the client satellite due structure elasticity and thruster ON/OFF firing the off modulation should respect thrust level decrease to max 50% at a time. This can be achieved by placing the OFF interval of the individual thrusters within the control cycle such, that only one thruster is switch off at a time. The figure below shows a typical force profile for an OFF modulated boost.

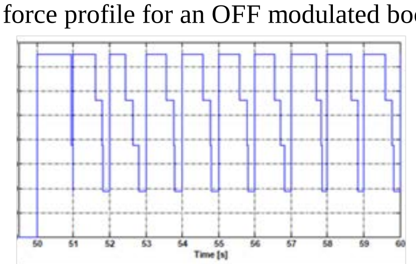


Figure 6: Boost with OFF modulation

The effect of the off modulation on the realized total delta-v needs to be counteracted by appropriate prolongation of the burn duration. Since off time is known onboard, this can be done by the boost control function.

4 Distributed Visual Navigation

Vision-based navigation (VBN) has long been identified as one of the core-technologies for enabling future debris-removal missions. Many different sensors and sensor data processing techniques have been proposed. In the frame of the RTES technology assessment, existing and also proposed techniques have been reviewed and assessed. The following sections present the results of this technology assessment and the results of the trade-off analyses. Several techniques have been selected and are currently in their test and implementation phase. First results on this work will be shown at the end of this section. It has been revealed, that in many cases one single VBN system might not be sufficient and a distributed system consisting of more than one sensor might be appropriate.

4.1 Scenarios from the VBN Viewpoint

As required within the RTES project the technology developments should be focused on the close-range rendezvous phase, where all scenarios have the following main tasks in common:

a. Navigation for close distances,
b. Motion estimation of the target
c. Motion planning of the arm or free-flyer, respectively, in order to perform the capturing.
d. Determination and tracking of capture point.

4.2 Sensors

Potential sensors for these tasks were discussed and included monocular cameras in the visible range (monochrome) and stereoscopic cameras, infrared cameras (bolometers) and ranging sensors like scanning LIDARs, flash-LIDARs or photonic mixing devices (PMD). The following figure depicts the summary of the trade-off analysis of the different sensors for the main tasks relevant for the scenarios described in the paragraph before.

Sensor / Missionphase/ Task	Far-Range-Nav.	Medium-Range-Nav.	Close-Range-Nav.	Cooperative Tracking of Free-Flyer	Grasping
Monocular monochrome camera	+	--	-	+	+
Binocular monochrom stereo camera system	--	O	O	-	+
monokulare IR camera	(++)	-	-	-	-
3D-LIDAR	--	++	+	+	-
(Imaging) RADAR	--	++	-	-	-
Flash-LIDAR	--	O	+	O	-
PMD-camera	--	--	-	O	+

Figure 7: Synthesis of sensor trade-off analysis

It has been demonstrated in the PRISMA -ARGON-experiment, that monocular line-of-sight measurements are sufficient for far-range position estimation [8]. For the medium range where range measurements become feasible, a 3D-LIDAR was chosen. In this range it is sufficient to measure the centroid of all available range measurements, which delivers a rough estimate of the position of the target object. The close the object gets, the higher are the accuracy requirements. Here full 6D pose and attitude information is regarded necessary for robotic capture tasks. Again, the scanning LIDAR has been selected as the best sensor choice. It is mainly preferred to camera based systems because the sensor is inherently independent from illumination conditions and proved to be very robust even in blinding situations by the sun. Furthermore it directly provides 3D information which helps in using the object geometry for recognition and pose estimation purposes and also gives the best available information for assessing the distances to the object. The biggest drawback is the scanning character of the sensor which needs time and which makes it difficult to use the sensor for very fast moving scenes. However, in most of the cases, relative motions and tumbling rates are considered to be moderate such that scanning frequencies in the order of 3-5Hz are sufficient. Additionally, controlling the field of view of the scanning LIDAR is one of its big advantages since the density of the point cloud can be optimally adapted to the size of the target and the distance to the target.

For the final grasping tasks, the situation dramatically changes and large sensors like RADAR, scanning or flashing LIDARs are not a good choice since it is expected that a grasping sensor should better be accommodated at the end of the end-effector of a potential capture tool, e.g. a robotic manipulator. Therefore, smaller devices which only have to measure in very close-ranges up to 1-2m have been selected. A PMD-camera based on pulsed LED illumination and a phase-shift ranging principle could be advantageous. However, no such device is expected to be space-qualified in the near future.

4.3 Sensor-Data-Processing

Beside the sensors, the sensor-data-processing is another very important and crucial task. In order to assess potential techniques we had to distinguish between the different data categories provided by the sensors. We mainly distinguished camera-based and range-image based approaches.

4.3.1 Camera-Based Approaches

The well-known stereo-camera based methods that apply feature extraction and tracking are able to estimate the center of mass of the target object [14]. However, we were not able to obtain very accurate results in many simulations based on our own implementation of [14]. Especially the precession angle of a tumbling target has a big impact to the accuracy of the center of mass. Another method like visual odometry [15] was also applied to a simulated scene of a tumbling satellite. Based on feature tracking only it was not possible to get rid of an accumulation of errors. This effect is shown in the next figure.

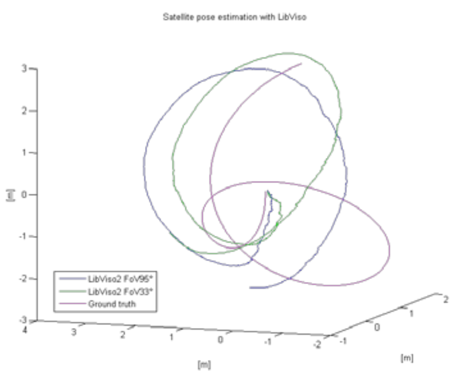


Figure 8: Results of visual odometry [10] applied to a video sequence of a tumbling satellite.

An alternative solution to model-free camera-based approaches are model-based approaches. We looked at methods based on key-points as basic features e.g. [11,12] as proposed in ESA's HARVD study.

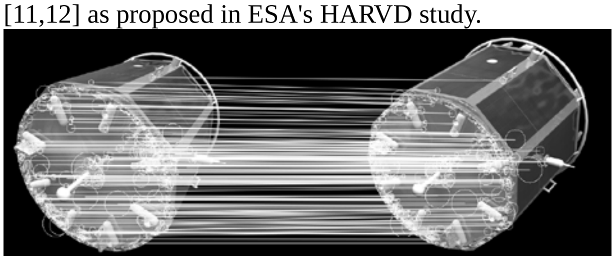


Figure 9: Results of matching of keypoints between a real object (left) and a virtual image (right).

Especially the method based on matching of keypoints between real and virtual images was tested and assessed. Although the similarity of the virtual and real scenes was quite high, the keypoint matching suffered from differences in small details, such as reflections of the environment in the object's surface and details of illumination.

In contrast to that the most promising results have been obtained on edge-based methods that applied a canny edge detector [13] followed by a distance transform and a optimization algorithm like Levenberg-Marquardt that keeps the projected lines of a model in the valleys of the distance transform. Lowe's method [14] inspired us to the proposed method and differs in that respect that the optimization is not carried out in Cartesian space but in image space. However, in order to get sufficient results with Lowe's method it is necessary to extract corresponding feature points such as corners. As this is not always easy to achieve, we found the method based on the distance transform to be more robust.

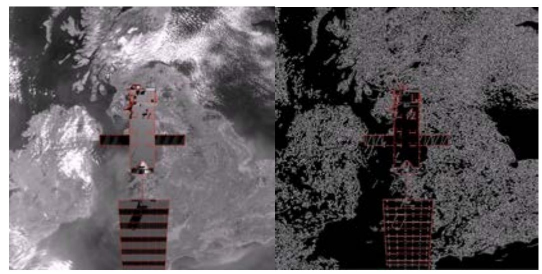


Figure 10: Results of matching of keypoints between

4.3.2 Range-Image-Based Approaches

Beside the camera-based methods range-image method approaches have been assessed and tested. Motivated by Neptec's TriDAR system [15] most of the work has been spent on methods adapted for 3d-point clouds provided by scanning LIDARs. As explained in detail in [16], the methods are based for a technique called 3D-Template-Matching that performs model-based initial pose estimation. This initial pose-estimation enables further tracking based on a variant of the iterative closest point algorithm (ICP) [17]. Further techniques that have been investigated in the technology assessment were based on particle filters and voxel representations [18] of the 3D-point cloud. However, these techniques were not as robust and accurate as the 3D-Template-Matching and needed much more computational time. The template matching was also outperforming our re-implementation of the polygonal aspect hashing as proposed in [15].

5 Capture- and Holding Mechanisms

To regain complete control of a space debris object it is necessary to establish a physical contact between the servicer satellite and the space debris. For this task Airbus Defense and Space developed a dedicated robotic tool which establishes the physical contact between the servicer and the target satellites, break up a physical connection and provides a turning axis to reconfigure the configuration of the combined flight segment. See figure 11, which shows the main elements of the Airbus Defense and Space capture and cutting tool. The main subassemblies are:

- Gripper 1: attach and hold function
  at the end of the blue lever arm
- Gripper 2: attach, hold and cut function
  at the end of the black lever arm
- Joint: turning axis
  at the intersection of the two lever arms
- Camera: for visual navigation
  on the blue lever arm
- Lever arms: main structure
  blue and black lever- -
- Robotic flange: interface to manipulator
  rear side of the joint

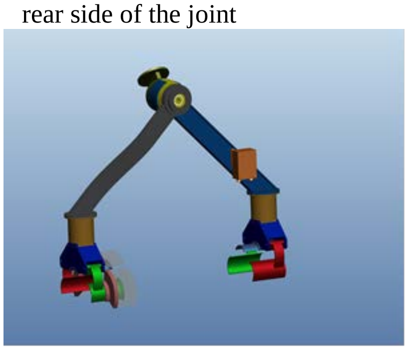


Figure 11: Airbus Defense and Space capture and cutting tool (concept)

This version of the tool is equipped with pyro cutting loads as part of gripper 2. This is used to cut the structure grappled by gripper 2. The area around the cutting loads is protected by caves build up with metallic meshes. The caves also catches debris generated during the cutting process. There is an alternative option to fulfill the cutting function - mechanical cutting - under consideration .Here we only consider nonoperational satellites which constitute a threat to future spaceflight. We cannot presume that these satellites provide dedicated interfaces for robotic interaction. Therefore the structure of the satellite has to be analyzed to identify structural/contact elements which are mechanically reliable. This means that the handling and deorbit loads has to be tolerated with sufficient margin. Additionally their position on the satellite must be appropriate to the desired orbit maneuver and configuration changes. The tool itself must support the robotic operation. The tool shall tolerate small deviations in position and orientation while it is placed on the target structural element. The approach of a free flying satellite in order to perform a contact operation with a robotic manipulator requires support of the path planning by visual-sensor based navigation. The mounted camera delivers the required sensor data. Grappling /cutting / reconfiguring process:

1. The cutting tool is placed on the satellite structure by the manipulator with both grippers in open position. The positioning is supported by visual tracking.
2. Both gripper closed as the grapple position is reached, see figure 12
3. Check whether the desired position of the tool is achieved. If "yes" - proceed with operations if not reposition the cutting tool.
4. Cutting of the structural element
5. Activating the joint and reconfigure the satellite see figure 13

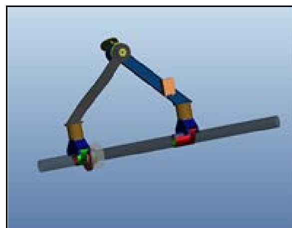


Figure 12: Cutting tool placed on structural element

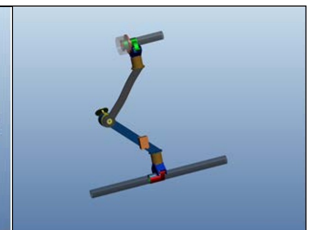


Figure 13: Activating of the joint after cutting

6 Control Systems

Within the RTES-project, the requirements of a control system for the proposed mission scenarios have been analyzed. With respect to the results and related work of DEOS project [19], the following requirements for the architecture of the control system have been derived:

- Providing computational power for:
  - GNC algorithms
  - Control of the sensors
  - Processing sensor data
  - Control of the robotic subsystem
- Communication Framework (incl. space standard communication services)
- Real-time Operating System supporting
  - Time Partitioning
  - Space Partitioning
- Hot and Cold Redundancy Definition for required Components
- Integration of Software from different parties with varying levels of maturity

These requirements have driven the development of a layered architecture, whereof each layer has been analyzed in detail with respect to the technologies and mechanism applicable (Figure 14).

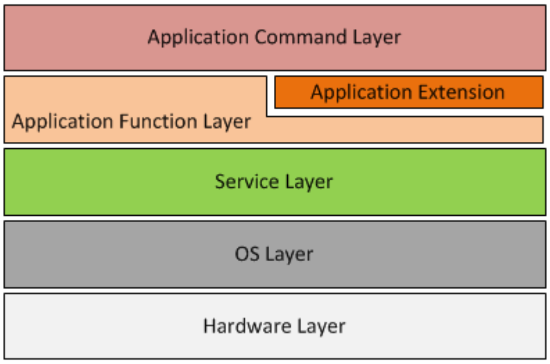


Figure 24: Layered Architecture of the Control System

Having concluded the trade-offs (Development Effort, Performance, Costs, etc.) for each layer, resulted in a layout of the control system. The implementation of the mission specific applications will be realized in the Application Function and the Application Command Layer, which have not been investigated further.

In addition to that, the different avionic concepts, i.e. a single, powerful computer vs. a multiple, dedicated, and different system concepts, i.e. manipulator vs. flying gripper have been assessed, which yielded in the system baseline of a manipulator arm and a heterogeneous avionic architecture with a dedicated mapping of the main functionalities onto the hardware entities.

Finally and with the focus onto the robotic subsystem, an operational analysis based upon task and actions for the single sub-flight phases has been carried out. Investigating every phase with respect to communication, errors, post- and preconditions as well as needed resources for every task enabled a preliminary evaluation of the needed overall budgets for communication and computational power.

7 Operations

The operations analysis in the frame of RTES focused on the definition of operational sequences and control mode strategies for an active debris removal (ADR) mission. ADR operations should lead to an optimal combination of mission robustness, safety and efficiency. Robustness means that failures should not occur during M&C operations and can be reached by intensive tests and operator training. But one main characteristic of ADR missions is to cope with unforeseen events, as the status of the object to be removed is not fully known in advance. Therefore safety shall take care that unforeseen activities and mission failures do not lead to catastrophic events, like the deterioration of the space environment and the injury of people on ground. On top of that mission efficiency is as well requested to optimize the on-board and ground resource utilization and in the case of commercial missions to reduce the allocated mission budget.

Based on these principles, following operational rules were selected:

- Non-supervised autonomy should be limited to mission phases where the mission risk is very low (e.g. check-out) or when the autonomy is mandatory (far and mid-range navigation).
- Supervised autonomy should be applied to phases where the collision risk is low and the autonomy capability available (navigation in close vicinity, manipulation for grappling operations).
- Tele-operation should be considered for phases where the autonomy capabilities are not developed enough for complex manipulation tasks.
- Interactive operations allow generating in contingency cases with operator on ground the data requested for resuming the interrupted operation. Pose data of the client can be interactively defined on ground and sent back to the on-board system as well as target positions for manipulation tasks.

One important aspect in the implementation of such operational rules is the possibility to switch between the modes without leaving the operational timeline. If during a supervised autonomous operation, the operator has to control directly in tele-operation modus the actuators or in case of failure some pose data have to be generated interactively on ground, the system control shall allow such operational mode changes. This is possible by controlling the mission, subsystem and task states and keeping these states consistent all the time in the system control. This approach allows managing mission contingencies and avoids rescheduling complex operations too often. This finally brings together mission safety and mission efficiency.

8 Conclusions

Within the project RTES it could be shown and demonstrated that for the removal of large satellites as well as of small debris parts the necessary technologies for the close range approach and capture are available. Especially the interaction between visual navigation, GNC and capture elements were considered in the frame of possible system concepts. Furthermore, it was shown that corresponding control systems and an adequate operational concept are required, which have same main modifications and extensions compared with conventional approaches.

Although, of course, other concepts, like net capture solutions or harpoon-based concepts, are also candidates for the considered application from our point of view a robotic solution has some advantages, especially concerning the reliability and the repeatability. And, as in the automotive industry, a robotic arm can be established as standard, well-developed component in space missions, reducing the development costs significantly.

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