ReCoBot – Reconfigurable Robot for On-Orbit Satellite Maintenance, Manipulation and Repair

Pascal Becker[1], Jakob Weinland[1], Stefan Scherzinger[1],
Robert Wilbrandt[1], Arne Roennau[1] and Rüdiger Dillmannn[1]

***Abstract*— On-Orbit maintenance is a great chance to extend the lifetime of space hardware like satellites. But as these space walks are costly and dangerous for human astronauts, it is currently done only for certain space hardware, e.g. the International Space Station (ISS). With ReCoBot we present a robotic approach to make on-orbit maintenance, manipulation and repair more cost efficient and future proof. A seven-degree of freedom arm with an identical interface on each end is able to locomote over a corresponding structure. This gets possible through a symmetrical robot design and kinematic so the manipulator can use its base as tip and vice versa. In combination with standardized space coupling interfaces it gets possible to move the robot along a structure to increase its workspace.**

I. INTRODUCTION

In this work, we present the ReCoBot - a reconfigurable robot for maintenance, repair, and reconfiguration of modular satellites. In contrast to robotic arms previously used in space, such as the Canadarm 2 (CSA), the arm developed here is small and at the same time highly flexible in order to be able to move over the satellite structure itself with the interfaces at both ends.

The kinematics of the robot has the necessary flexibility to move safely around corners and is strong enough to reconfigure the structure. It is planned, that the designed robotic arm is also able to perform this task with some restrictions in the Earth's gravitational field for testing and validating purposes. Despite gravity, the experiments and findings can be used to investigate the capabilities with respect to on-orbit servicing. The highly flexible reconfiguration robot can thus also be used for terrestrial applications such as the inspection or repair of structures if these are equipped with corresponding interfaces. The design as well as the construction required efficient structural and material optimization for weight reduction. Likewise, the selection of sensors, actuators, and electronics required a systematic, structured overall design. For this reason, certain test scenarios for servicing were designed and continuously taken into account while developing the system. The resulting robot is compatible with the existing iBOSS satellite structures [1], in particular the iSSI interfaces built into them. Two active interfaces are built within the robot. The satellite structure uses only passive ones. The whole software controlling the robot is based on the robot operating system (ROS) [2]. Therefore, robust and at the same time specialized controllers were designed, implemented and methods for motion planning were transferred to the new kind of moving manipulator. While moving over a satellite structure the arm holds itself with one of its intelligent Space System Interface (iSSI) until the other end of the arm has reached the final position in the next interface and has locked the active and the passive interface. With a constant switch of base and tip, movement along the structure is possible.

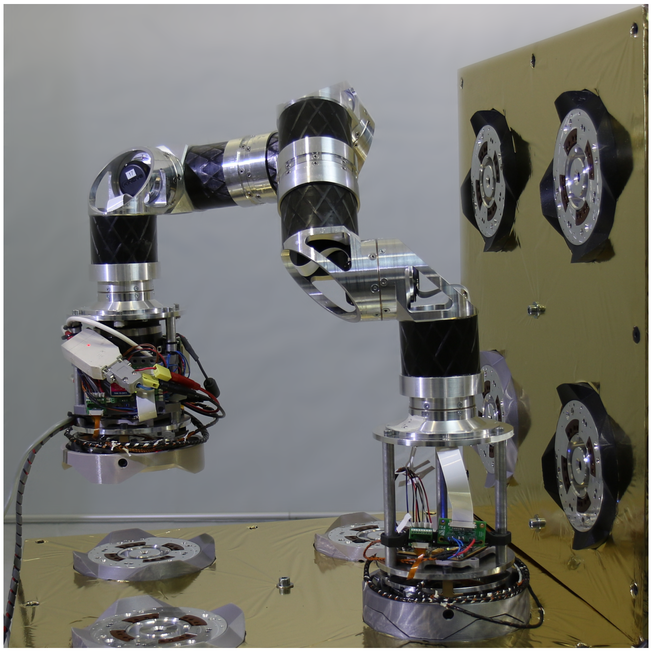
Fig. 1: The symmetrical kinematics concept of the ReCoBot allows the robot to move along a structure of corresponding interfaces. Here it is approaching the next interface with its tool center point in order to connect there.

With the concrete implementation of ReCoBot, this paper contributes valuable design decisions and insights that can support further research on-orbit manipulators. An additional contribution is the control and motion planning framework needed for manipulation and locomotion under dynamically closing kinematic chains. A suitable test setup with modular satellite cubes was built up for the practical and most realistic evaluation of the overall system. In this context, the capabilities of the newly developed reconfiguration robot such as manipulation, position change, and locomotion via

---

This work was funded by the Deutsches Zentrum für Luft- und Raumfahrt (DLR) under grant number 50RA2010 (ReCoBot - ReConfiguring and Manipulation RoBot).

[1] All authors are with FZI Research Center for Information Technology, Haid-und-Neu-Str. 10-14, 76131 Karlsruhe, Germany {`scherzinger, weinland, wilbrandt, pbecker, roennau, dillmann`}`@fzi.de`

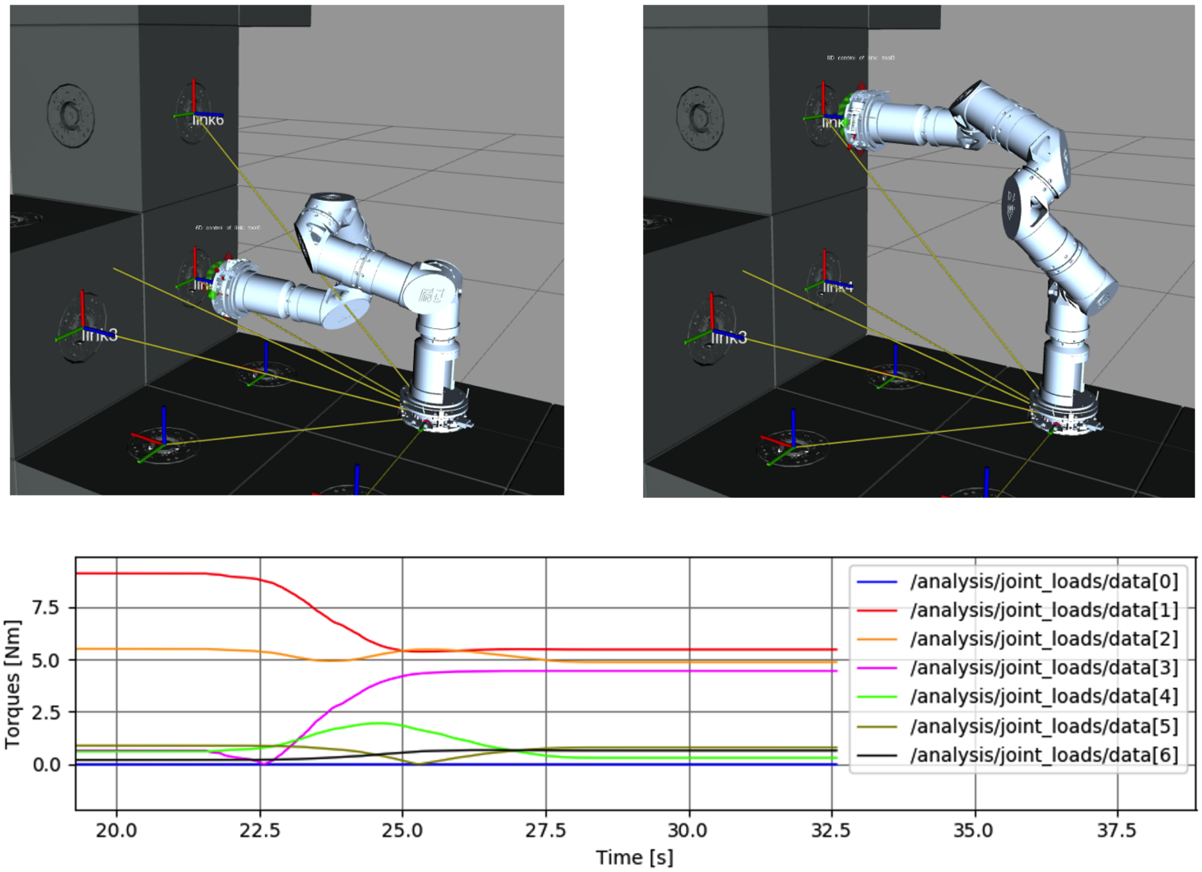

Fig. 2: Examination of the joint angle load during a movement. The two upper configurations describe start and end point and the curves below describe the calculated trajectories. The underlying mass distribution of the manipulator can be dynamically adjusted.

distributed interfaces were tested holistically and qualitatively.

The structure of this paper is as follows. In Section II, we present the related work. In Section III, we describe our concept. In Section IV, we describe the evaluation and provide some experiment results. Finally, we provide conclusions and perspectives in Section V.

II. RELATED WORK

Currently, multiple universal space interfaces exists and try to implement a standard. One of these, also used within the ReCoBot, is the intelligent Space System Interface (iSSI) from the iBOSS GmbH. It combintes multiple functions at once, like coupling, power, thermal heat and data exchange [3]. Next to iSSI, there exists other solutions like the Standard Interface for Robotic Manipulation (SIROM) [4] or the HOTDOCK interface [5]. Both implement similar capabilities to connect payloads in planetary and orbital applications.

Also the concept of a flexible manipulator for on-orbit servicing is not totally new. In projects like MOSAR-WM [6], its successor MAR [7], or the arm from Zeis et al. [8] flexible and universal robotic manipulators for space missions have been playing a role. But even they all try to solve the same problem, each concept differs slightly from the others e.g. by the amount of degrees of freedoms or the coupling interface.

III. CONCEPT

With the flexible manipulator ReCoBot we developed a robotic arm for on-orbit servicing, maintenance and repair. As the workspace of a firmly mounted robot is rather limited, we decided to enable locomotion by a symmetric design. The tool tip, as well as the robotic base, are both equipped with an identical interface, an active iSSI. The satellite itself is, on the other side, equipped with passive interfaces along its surface. While both ends of the arm are in a locked state, one can be unlocked and the arm can move to a new position. If this trajectory maneuvers into another passive interface on the satellite structure, the interface can be locked and the old base can be unlocked. With a combination of these trajectories and actions, the manipulator is able to walk along a given structure.

As this concept must work in the gravity field of the Earth, the hardware has to be designed such that all necessary actions are doable within 1g. Especially the possibility of changing the base and the tool tip required an extensive analysis of the occuring forces and torques.

Furthermore, the whole analysis, design and development, implementation and testing had to be done within one year.

A. Analysis of the requirements for an 1g environment

A simulation environment was set up for the rough estimation of the loads. A kinematic simulation of a manipulator with interfaces for reading out the joint angles served as the basis. By means of an idealized actual setpoint control on joint levels, the manipulator could be brought into different configurations. For the calculation of the reaction forces in the joints, an analysis tool based on the Recursive Newton-Euler Algorithm (RNEA) was implemented in the form of a so-called ROS controller in the ROS Control Framework. This custom implementation uses the Kinematics and Dynamics Library (KDL) [1] open source library at its core. The tool can be added for manipulators to be investigated and provides information about occurring loads at a given course of the joint angle positions under direction specification of gravity. The tool uses the given kinematics of the manipulator and allows the dynamic adjustment of the individual masses of the connecting segments, which can be executed via sliders in a graphical user interface. Thus, the effect of heavy components on the required motor torques can be estimated and conclusions for the dimensioning can be drawn. Figure 2 shows the procedure exemplarily on an intermediate version of ReCoBot. Since the robot kinematics is already defined via a special format (URDF) at runtime of the analysis, the overall optimization kinematic and mass distribution has to be done iteratively. This is done by manually adjusting the kinematics and repeating the simulation and evaluation with the analysis tool. So far, loads are calculated based on gravitational force and dead weight. Dynamic loads, such as Coriolis terms, could easily be added. The necessary joint velocities are already available. Inertial forces would require additional joint accelerations, which can then be accounted for in the implemented algorithm. One of the advantages of the RNEA for this use case is the implicit co-calculation of the reaction forces of all mechanical restraints, especially the five other spatial directions of the motor axes. This means that, in addition to the required motor torques, the mechanical reaction forces of the motor mountings can also be calculated and used for dimensioning the components.

B. Requirements for the overall system

For the pre-selection of the actuators, we could initially refer to the first results from section III-A. The simulated loads on the joints made it possible to determine a performance class of the actuators at the beginning and thus to delimit the necessary installation space. The selection criteria for the actuators included

- Power ratio (Nm to g)
- ROS compatibility
- Installation space in weight
- operating voltage
- availability

With these criteria, we were able to compare actuators from AUBU MRJ Serials, Elephant Robotics, and many others. In the end, however, the choice fell on actuators from Kinova. These can be operated with 24V in a small installation space. Since the FZI already had experience with the Kinova Jaco arms, it was also known that these actuators are already compatible with ROS.

For the ReCoBot, we therefore use Kinova geared motors of the second generation.

C. Mechanical concept

For an initial size estimation of the robotic system, preliminary work of the IBOSS project [1] was used. In this project, minimum dimensions for a possible arm were calculated in relation to the IBLOCK cubes. As a result, it was determined that such a robot must have a reach of at least 1140mm.

Instead of the five degrees of freedom considered at the time, we decided on a system with seven degrees of freedom in this project for reasons of redundancy and trajectory planning. In order not to additionally restrict the ReCoBot in its free trajectory planning, possibilities were sought for both of the following concepts to route all data and communication elements such as cables internally in the robot.

Two different concepts have been developed. One based of carbon structures and one with 3d-printed parts.

1) Carbon concept: The carbon concept is an aluminum CFRP tube construction. The joint housings were milled from an aluminum block. In the first ReCoBot concepts, this aluminum block was only provided with through holes on which a Kinova actuator could be flanged on one side. A CFRP tube with a length of 70mm was glued at right angles to this. An aluminum flange at the end of the tube was used to mount another Kinova actuator. The shape of the joint housing was initially chosen to be as simple as possible in order to be able to manufacture it with simple means within the institute workshop if necessary, without the use of special tools. However, initial simulations showed that such a design would exceed the maximum torques of the selected motors many times over. For this reason, a start was made on optimizing the joint housing. After several iterations and a final one based on Autodesk CAD topology optimization a final design was ready. Some of the different iterations are shown in figure 3

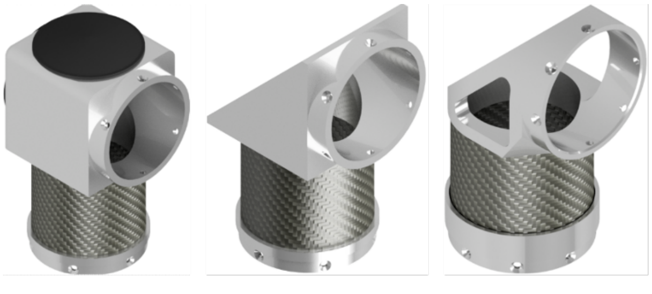

Fig. 3: Optimization of the ReCoBot segments. Far left the original concept. In the center, optimization of the joint housing by analyzing the pairs of active surfaces and guiding support structures. On the right, a version optimized with CAD.

2) 3d-printed concept: In order to circumvent the limitations of design optimization with regard to the manufacturability of the system, another concept was developed

---

[1] http://wiki.ros.org/orocos_kinematics_dynamics

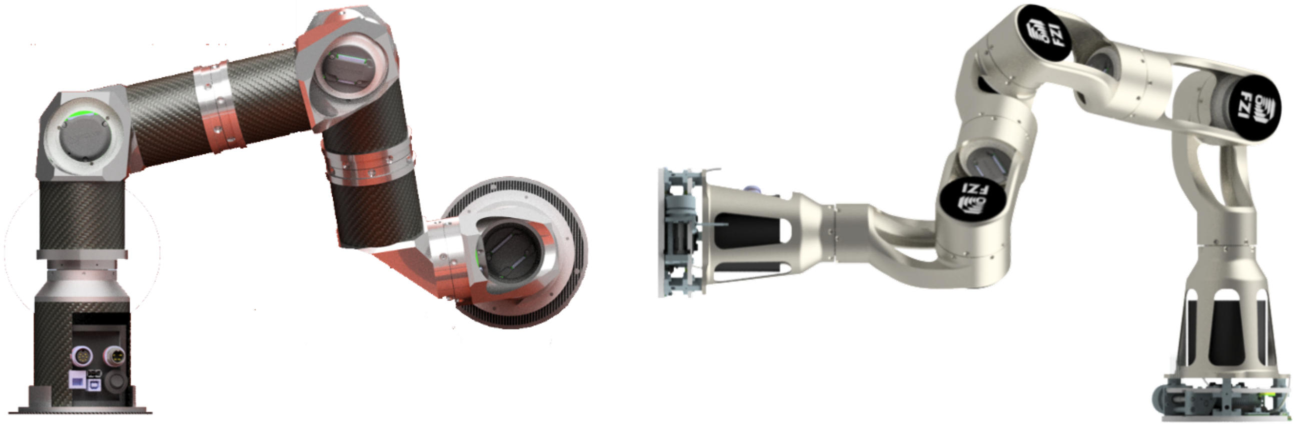

Fig. 4: The two ReCoBot concepts developed. Left, iteration 2 of the ReCoBot carbon arm, made of CFRP tubes and aluminum joint housings. On the right, the 3d-printed titanium alloy arm.

in addition to the carbon concept. Additive manufacturing enables function-optimized design, allowing further weight savings to be achieved. However, even with this manufacturing method, 3D metal printing, design principles must be considered. For example, in order to avoid internal stresses within the component, care should be taken to maintain a constant wall thickness. Open designs are preferable to closed designs in terms of production technology. In addition, elements that require low tolerances or have a large overhang must be reinforced by appropriate support structures, surfaces must be reworked depending on the quality required.

D. Electrical concept

The main focus in the design of the electronics was also not to additionally restrict the ReCoBot in its movements, which is why care was taken to place them exclusively inside the arm. First, considerations were made about the arrangements of the components inside the arm. Kinetically optimal distributions, such as a mass distribution in the center of the arm to prevent high moments at the first and last actuators, were not easily possible. One reason for this is the serial control of the selected Kinova motors. Although they can be connected in a daisy chain, this chain cannot be forked without considerable additional effort. Therefore, to meet the time restrictions of the project, the decision was made to install control elements such as the controller, control device, and distribution boards in the end piece of the robot. The arrangement is shown in Figure 5. On the opposite side of the ReCoBot, both space and connections for a jumper battery are provided.

Fig. 5: Kinovo motor controller and motors connected in series.

E. Software concept

ReCoBots software is roughly divided into four layers. Figure 6 shows an overview. The top layer refers to the sequence control. At this level, ReCoBot is controlled by scripts that use the software interfaces of the underlying layers to execute concrete motion sequences. By combining sequences of motions, locomotion can thus be described via specific iSSIs and also manipulation tasks. The scripts are written in Python and encapsulate the complexity of the underlying implementation with ROS. For a maintenance mission, tasks and action sequences could be programmatically formulated at this level by suitably trained technical personnel. The underlying layer describes the various high-level control concepts available to compose the motions. It includes compliant joint control, joint-based control, Cartesian control, and motion planning for locomotion. The Cartesian control capabilities are also used for direct teleoperation of manipulation tasks with ReCoBot and complement the script-based control with intuitive manual control using joysticks or similar input devices. The third layer represents the abstraction of the hardware. It receives the control commands of the high-level control layer and provides a bidirectional data exchange with the underlying hardware. The lowest layer describes the driver level of the individual components, such as the control of the motors in the joints and the opening and closing of the iSSI interfaces.

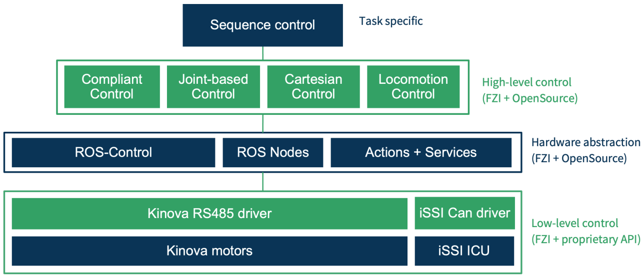

Fig. 6: Software architecture with four main layers and components. The top layer of sequence control is implemented with scripts. At the lowest level, ReCoBot is controlled via the motors of the joints and the iSSIs as end effectors.

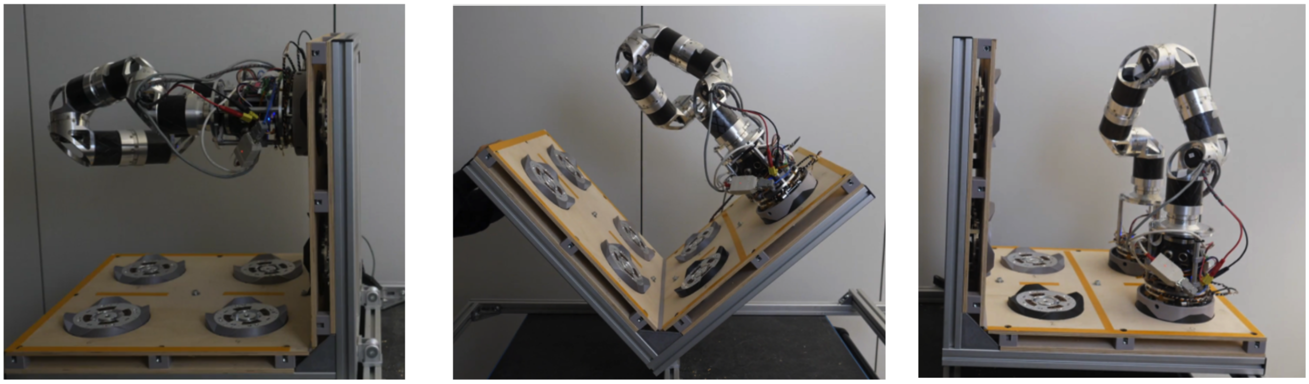

Fig. 7: Setup to tilt the ReCoBot easily to change orientation and gravital impact.

IV. EVALUATION

ReCoBot was already tested and evaluated during the development phase. The software concepts for control and path planning were continuously tested in simulation at an early stage. The drivers for the motors and the iSSIs were initially developed at component level and functionally tested. After endurance tests of the RS485-based driver, all joints were integrated step by step.

Figure 7 shows the final setup for locomotion tests with the complete system. The setup was initially designed without the tilting device. In the course of the evaluation with the fully integrated ReCoBot, limitations in the outermost motors became apparent. The direction and the influence of gravity can be partially adjusted via the tilting. The iSSIs available in the project were distributed in a regular grid with 30cm spacing on the side walls. This allows the accessibility of the iSSIs for different step sizes and the change between horizontal and vertical iSSIs to be investigated. An analog environment was set up for the simulation.

V. CONCLUSIONS

In this paper, we presented a flexible robotic manipulator for on-orbit missions. The ReCoBot is able to locomote itself over structures like satellites etc., as long as these have reachable interfaces mounted on their surface. One goal of the design is to enable the robot also to work in 1g environment for the ease of testing and evaluation. One of the next steps is to do the space qualification tests for the robot and also to evaluate the movement and motion possibilities with more powerful motors in the first and the last joint.

REFERENCES

[1] M. Kortman, S. Ruhl, J. Weise, J. Kreisel, T. Schervan, H. Schmidt, and A. Dafnis, “Building block based iboss approach: fully modular systems with standard interface to enhance future satellites,” in *66th International Astronautical Congress (Jerusalem)*, 2015, pp. 1–11.

[2] M. Quigley, K. Conley, B. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, A. Y. Ng, *et al.*, “Ros: an open-source robot operating system,” in *ICRA workshop on open source software*, vol. 3, no. 3.2. Kobe, Japan, 2009, p. 5.

[3] J. Kreisel, T. A. Schervan, and K. Schroeder, “Game-changing space system inter-face enabling multiple modular and building block-based architectures for orbital and exploration missions,” in *Proceedings of the International Astronautical Congress, IAC*, vol. 7, 2019.

[4] J. Vinals, J. Gala, and G. Guerra, “Standard interface for robotic manipulation (sirom): Src h2020 og5 final results-future upgrades and applications,” *i-SAIRAS 2020*, 2020.

[5] P. Letier, T. Siedel, M. Deremetz, E. Pavlovskis, B. Lietaer, K. Nottensteiner, M. A. Roa Garzon, J. Sánchez Garcia, J. L. Corella, and J. Gancet, “Hotdock: Design and validation of a new generation of standard robotic interface for on-orbit servicing,” in *International Astronautical Congress, IAC 2020*. IAF, 2020.

[6] M. Deremetz, P. Letier, G. Grunwald, M. A. Roa Garzon, B. Brunner, B. Lietaer, and M. Ilzkovitz, “Mosar-wm: A relocatable robotic arm demonstrator for future on-orbit applications,” in *International Astronautical Congress, IAC 2020*. IAF, 2020.

[7] M. Deremetza, “Concept of operations and preliminary design of a modular multi-arm robot using standard interconnects for on-orbit large assembly mathieu deremetza*, gerhard grunwald b, francesco cavenago c, máximo a. roab, marco de stefanob, hrishik mishrab, matthias reinerb, shashank govindaraja, alexandru buta, irene sanz nietoa, jeremi ganceta, pierre letiera, michel ilzkovitza, levin gerdes d, martin zwick d,” in *Proceedings of the International Astronautical Congress, IAC*, 2021.

[8] C. Zeis, C. de Alba-Padilla, K.-U. Schroeder, B. Grzesik, and E. Stoll, “Fully modular robotic arm architecture utilizing novel multifunctional space interface,” in *IOP Conference Series: Materials Science and Engineering*, vol. 1226, no. 1. IOP Publishing, 2022, p. 012096.