# NEW APPROACH ON ROBOTIC ARM DESIGN: FULLY MODULAR ARM ARCHITECTURE UTILIZING NOVEL SPACE INTERFACE

Virtual Conference 19–23 October 2020

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## ABSTRACT

Robotic systems become more and more important for space applications due to the flexibility in tasks they can perform such as docking assistance, supporting extra-vehicular activities (EVA), as well as maintenance tasks. For these purposes multiple different robotic arms have been developed, especially for missions which are intended to demonstrate on-orbit servicing (OOS) and assembly (OOA) capabilities. The current paradigm is the design of specialized robotic manipulators to meet the requirements for a specific mission profile.

This research aims to develop a modular robotic arm for multi-purpose and multi-mission use that can be individually configured for the mission at hand.

The underlying concept for the robotic part of the system is a rotational joint which rotates under an angle of 45 degrees to the normal axis. This eliminates the need for different types of joints, reduces the complexity of the modular system and the system requires less stowage space compared to a traditional universal joint set-up. The modular design offers further advantages such as a flexible assembly and reconfiguration in orbit, re-use of modules and the possibility to utilize different end-effectors and tools. Each module is based on the iBOSS (intelligent Building Blocks for On-orbit Satellite Servicing and Assembly) concept and consists of one rotational actuator with a tubular structural section attached to both sides. Each end of a structural section contains an iSSI (intelligent Space System Interface), giving each module two multi-functional interfaces. The interface includes a mechanical connection, power and data transfer and the means for heat exchange between modules. The modules can be connected using the iSSI and thus forming the robotic arm system. With each added module the overall system gains one degree-of-freedom. The iSSI can not only be used to interconnect the modules but also for mounting the robotic arm to the spacecraft or to attach different types of end-effectors or sensors.

This paper will outline the concept of the modularization of the robotic arm and its mechanical and weight-optimized development, design and sizing. Besides the full-size demonstrator based on the iBOSS concept and the iSSI, a smaller version is also presented, which is dedicated for the use in more compact applications such as cube-sats and rovers. Here, an additional challenge needs to be faced as the intended functionalities need to be integrated in even less building volume.

Finally, the first test results of the four degree-of-freedom, full size demonstrator will be presented.
The paper will present the concept of a novel modularized robotic arm and its mechanical and weight-optimized development, design and sizing. It features modules containing one joint and two multi-functional interfaces, which allows for OOS and OOA.

## 1 INTRODUCTION

At present, robotic applications play a major role in unmanned exploration with rover systems. Furthermore, they are routinely used for berthing, cargo transport or EVAs on the ISS and are therefore indispensable for manned space flight. In the future, however, robotic applications will assume an even more fundamental position in space activities [1-7].

Due to the increase in satellites operated in orbit new concepts and solutions are needed to guarantee safe and sustainable access to space. One enabling technology in this regard is robotic on-orbit servicing, which includes e.g. repair, maintenance and disposal of satellites. In addition, the assembly of large structures and additive manufacturing ("3D printing") in orbit are interesting concepts, as such technologies allow the development of new classes of spacecraft using autonomous robots.

However, currently robotic arms for use in space are mainly designed only for one mission and thus for one specific purpose or application. This usually results in high effort and costs making robotic arms unattractive for a large number of missions. To overcome these challenges a new approach using a modular architecture in combination with a different kinematic compared to the current state-of-the-art is presented in this paper. Using a modular approach makes the robotic system highly flexible to comply with different types of missions and requirements, such as degrees of freedom or arm length, without the need to change the design. Furthermore, the system can even be modified during the mission. The alternative structure, which utilizes a joint rotating under a 45° to the normal axis, increases the redundancy of the system and makes it possible to get to hard to reach places.

## 2 MODULARIZATION APPROACH

The modularization approach is based on the iBOSS Project (intelligent Building Blocks for On-orbit Satellite Servicing and Assembly) which adapted a modularization on component level, meaning one module would house, for example a reaction wheel, a propulsion unit or an antenna with the necessary electronics. Combining modules with all necessary components and subsystems would result in the final, working satellite. To enable the connection between the modules, the iSSI (intelligent Space System Interface) has been developed which will also serve as connecting element for this robotic arm concept. This interface is capable of initiating a mechanical connection and transfer power, data and thermal energy. [8]

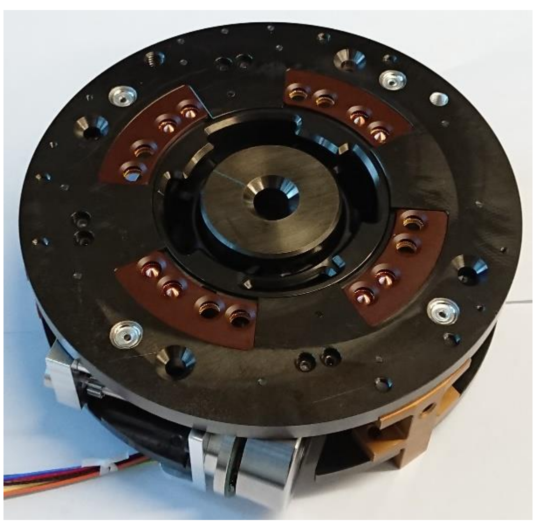

Figure 1: The iSSI in its current version with integrated features for power and data transfer

Transferring this concept to the robotic arm system the joint assembly is the relevant component which in this case is the same for every module. Figure 2 shows a simplified view of the basic setup for the robotic module. The motor and gearbox with an integrated bearing are the key mechanical elements of the joint and enable the rotational movement of the arm. On both sides of the joints two tubular cross-sections are fitted which represent the structure of each module. At the end of every tubular section one iSSI is integrated making it possible to connect the modules with each other, to the spacecraft or to different tools and end-effectors. Also, every module houses the relevant electronics to drive the motors and communicate with adjacent modules and the host spacecraft's avionics.

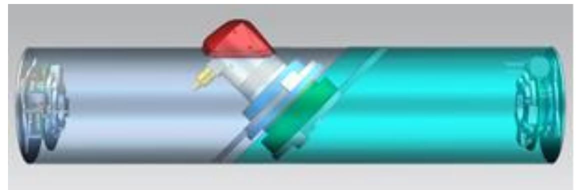

Figure 2: Conceptual setup of a robotic arm module

## 3 ROBOTIC BASICS

Robotic systems can be seen as combination of a mechanical system with a control system, comprised of actuators and sensors [9]. From this type of system the sub-group called robot manipulators is derived, which is the most applied among the whole group. The robots in this subgroup can be defined as systems composed by links, joints and end-effectors [10]. The development of a modular manipulator combines all these techniques with a modular structure.

### 3.1 Reconfigurable or Modular Robots

Reconfigurable robots have been approached in different cases and interesting devices have been proposed. The work of Fukuda and Nakagawa, who developed a system of individual cells, which could work together in applications such as maintenance in a storage tank, is one example [11]. There are other notable works of reconfigurable robots using modules that can be combined in different ways for configuring complex robots [12-14]. Other, newer approaches focus in the locomotion [15-16] and space applications [17-18]. In every case the modules can be combined from one degree of freedom (DOF) up to n-DOF, the limit being the number of available devices. The implementation of parallel joints makes a robot become redundant [19].

### 3.2 Redundant Robots

These kind of robots have benefits as well as challenges. One benefit is the possibility to reach a position with any orientation [20]. For a high degree of redundancy, a non-stop functionality can be applied, i.e. if a motor breaks down, the loss can be compensated using the rest of the functional motors, keeping the tasks achievable. Moreover, a redundant robot can be seen as a non-redundant robot, where the big links of the non-redundant could be fragmented in smaller links, therefore it is possible to fold these big links, requiring smaller volumes.

The challenges can be found in the actuation, where for more links, more motors are required, which in turn results in a heavier kinematic chain. Furthermore, the solution of the inverse kinematics (IK) problem is complex and can result in having multiple solutions or none at all [21]. This represents a significant reduction in the operability of a redundant robot.

### 3.3 Modular Redundant Robot

Modular redundant robots combine the benefits and challenges of the redundant robot, plus the benefit of the re-configurability. This entails the ability to attach or detach joints to an original kinematic chain, which can be integrated from 1-DOF to n-DOF. This chain can also be employed as parallel robots, using detached joints one beside the other.

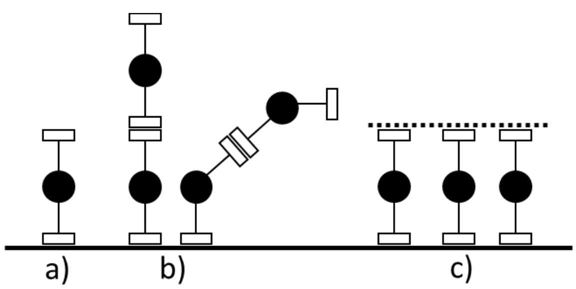


Figure 3: Modular robot possible configurations: a) single joint, b) joints combination and c) joints working in parallel.

## 4 CONTROL

For this work, three levels of control were defined: the visual interface and animation of the models, the IK solution and the actuators.

### 4.1 Visual Interface

The visual interface allows to simulate the operation of the robots (off-line), to verify their behavior without risking the real demonstrators. In addition, the same commands can be sent to the actuators (on-line), for the operation of a real device. The implemented software for this control level, is CoppeliaSim [22], due to its versatility for importing the CAD models and its compatibility with other software and interfaces. Its integration also involves the use of joysticks as position and orientation inputs (Figure 4) for both cases: simulation and operation.

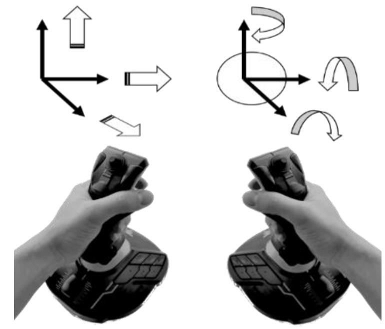

Figure 4: Joystick as input for simulation and operation. Left for the translation und right for the rotation

### 4.2 The IK Solution

The IK is essential to simulate and operate robots. Thus, the interaction offered by CoppeliaSim with mathematical packages as Matlab opens the possibility of applying diverse solution algorithms. However, CoppeliaSim has prebuilt some IK algorithms, one of those is the Damped Least Squares (DLS), which is optimized by the developers for using the minimum computing resources, giving a very responsive solution off-line and on-line. The time cycle per iteration could reach up for a simple model (Table 1).

Table 1. Cycle time table for solving IK using DLS, gotten from CoppeliaSim main view. For the higher values means the feasible iteration solution in the step size.

| | Simulation step time [ms] | | | |
|---|---|---|---|---|
| Model | 1 | 10 | 50 | 100 |
| None | 0.46 | 1 | 1 | 1 |
| 3-DOF | 0.5 | 0.99 | 1 | 1 |
| 8-DOF | 0.44 | 0.99 | 0.99 | 1 |
| 24-DOF | 0.17 | 0.99 | 0.99 | 1 |

In a first instance this DLS is employed, with the expectative of using other algorithms employing Matlab.

### 4.3 Actuators

Following the outline, the control commands are sent to the third level of control, which is composed, in this case, by three different devices: motor controller board, which are dedicated devices for the regulation of the appropriate currents for their respective torques in the motors, motor and encoder.

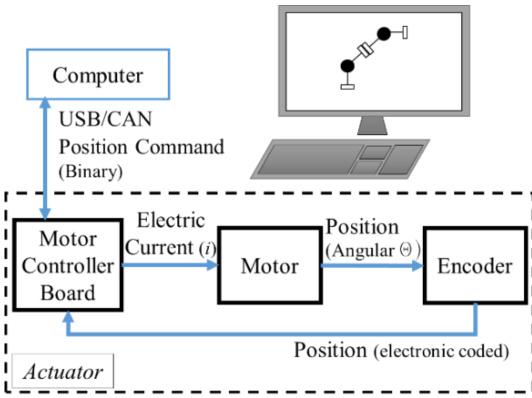


Figure 5: Actuator scheme. It is composed by basically the three devices in the dashed line box: a motor controller board, a motor and an encoder; they can be seen as a closed subsystem.

## 5 CUBESAT ROBOT MANIPULATOR

This demonstrator is designed as a small robot manipulator, which can be packed in a 1-unit (1U) CubeSat volume (standard for one kind of nanosatellites [23], where one unit is considered a squared volume with 10 cm per side [24]). This robot is based on a previous design [25], keeping the same joint distribution. In Table 2 the model expressed in the Denavit-Hartenber representation is shown.

Table 2. Mathematical model of CubeSat robot manipulator expressed in the Denavit-Hartenber convention.

| Link | Alpha | a | D | theta |
|---|---|---|---|---|
| 1 | pi/4 | 0 | $d_1$ | $q_1$ |
| 2 | -pi/2 | 0 | $d_2$ | $q_2$ |
| 3 | pi/2 | 0 | $d_3$ | $q_3$ |
| 4 | -pi/2 | 0 | $d_4$ | $q_4$ |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| n-1 | pi/2 | 0 | $d_{n-1}$ | $q_{n-1}$ |
| n | -pi/4 | 0 | $D_n$ | $q_n$ |

The actuators configuration was integrated by high performance brushless Maxon motors with an embedded incremental encoder (ECX SPEED 8M), which can be highlighted by their high power density and a dedicated positioning motor controller, also provided by Maxon (EPOS4). The structure of the links is optimized for supporting the whole kinematic chain at any configuration, giving it a new shape, which also requires less material (Figure 6). The use of bearings is also integrated to each joint, for gaining joint stiffness. Two kinematic chains were integrated one with 8 DOF printed in polymer and other printed in aluminum with 24 DOF. The CAD model of one kinematic chain is displayed in Figure 7. This concept has been enhanced in a modular device called MARGE.

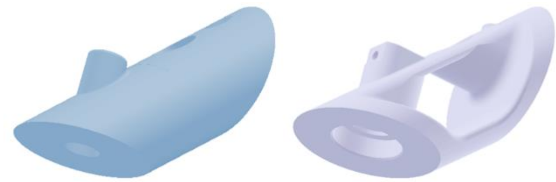

Figure 6: Comparison of the links of the CubeSat robot. Left: the original link form. Right the optimized weight and material requirements form.

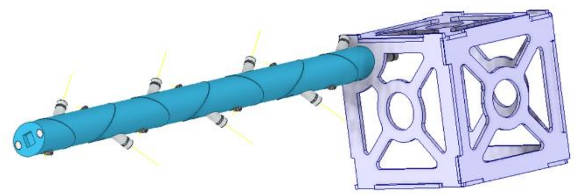

Figure 7: CAD model of the CubeSat robot with 8DOF. The representation includes also the motors and the base, which has a 1U CubeSat standard volume

## 6 MARGE

### 6.1 Concept

The demonstrator MARGE provides the proof of concept for a fully modular robotic manipulator under gravity conditions. It is designed with three modules, providing three DOF. A schematic of the demonstrator is shown in Figure 8. Each module consists of two links with one joint in between. Each link is equipped with an iSSI at its end, providing the connection to the adjacent module. The interfaces (I/F), each consisting of a connection of two iSSIs, are marked as solid black circles in the figure. The joints are marked as solid grey circles. To the end-effector of the manipulator a payload, also equipped with an iSSI, can be attached, which is shown as a black rectangle (I/F 4). The demonstrator is connected to the ground at I/F 1.

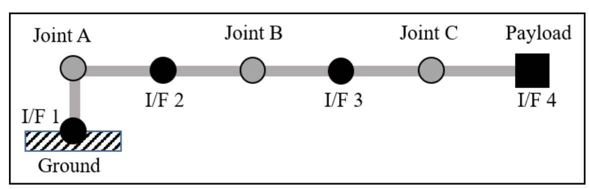


Figure 8: Schematic of demonstrator MARGE

In addition to the three DOF, the work space of the manipulator can be modified by means of changing the relative position of the coupled iSSI´s at each I/F. The iSSI has four discrete coupling positions, rotary arranged in 90°-steps. By the relative position of the iSSI´s at an I/F, the alignment of the modules´ joints is defined. With their 45° inclination, the joint axes of two adjacent modules can be arranged either parallel or perpendicular to each other. Therefore, the entire manipulator´s work space is affected by the iSSI´s coupling positions at each I/F.

### 6.2 Dimensioning

For the dimensioning of MARGE the requirements of a payload mass capability of at least 5 kg and a module length of 600 mm are defined. For the shape of the structure a tubular cross section is defined. Furthermore, a stiffness requirement is established for the structure to ensure sufficient accuracy of the manipulator. In the position, where the highest bending loads and therefore displacements occur, the total displacement of the end-effector due to bending of the structure must not exceed 2 mm. Assuming sufficiently low velocities and accelerations during operation, inertia effects are of a small magnitude. Therefore, the manipulator is designed strength-related for a static load case under gravitational force. To account for the additional loads during operation, a margin of 1.5 is added to the static loads. For determination of the dimensioning loads a simplified model of the manipulator is built for a multibody simulation (MBS). The simulation is conducted with Simscape Multibody. A graphic representation of the model is shown in Figure 9.

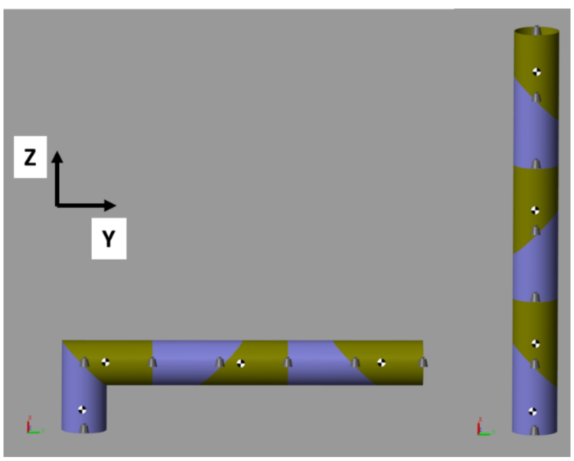


Figure 9: MBS model of MARGE in initial (left) and final (right) position

Each module of the MARGE manipulator is idealized as two rigid tubular aluminum links with a friction-free, ideally stiff rotational joint in between. The modules are connected via ideally stiff iSSIs. Initial mass assumptions for the iSSI-interfaces and joint components are made and added to the respective locations as point masses.The mass of the tubular primary structure is distributed continuously. Additionally, a 5 kg point mass is added to the end of the manipulator as payload. The initial position is a grounded first link and horizontal alignment of all other links as shown in Figure 8. In this position, the highest bending loads act on the structure, the iSSIs at I/F 1 and the joint A. It provides the initial position of the simulation. An enforced motion is then applied to joint A in form of an (1-cos(ω t)) trajectory. It is chosen such that the joint rotates by 180° within 10 s from its initial position (Figure 9 left) to its final position (Figure 9 right). The joint angle as well as the resulting bending moments and joint torque for an exemplary configuration are shown in Figure 10.

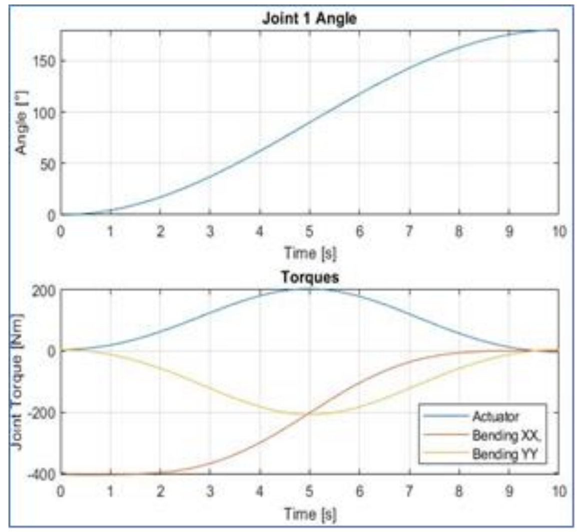


Figure 10: Joint angle (top) and torques (bottom) for joint A

Based on the MBS results from the initial assumptions, structural components are sized, suitable drive components are selected, and their physical properties are used to update the MBS model. Analysis of the local behavior in the individual structural components is supported with finite-element-analysis (FEA). The global loads of the MBS results are implemented in FEA models to determine local stresses and strains. Figure 11 shows the stresses and displacements of one link (between I/F 1 and joint A in Figure 8) due to bending loads. Modeling and post-processing is conducted with MSC Apex Iberian Lynx, MSC Nastran 2018 is used as solver.

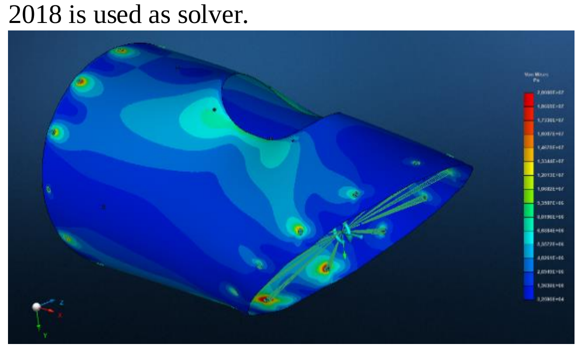

Figure 11: Stress distribution and displacement of one link due to bending loads (MSC Apex)

### 6.3 Demonstrator

In this section, the final design of the demonstrator MARGE is presented. An overview of one module is shown in Figure 12. In the figure, the outer structure is displayed transparent. On the left-hand side, the iSSI of the module´s drive side is visible. On top of the module, a motor cover with ventilation slots is located.

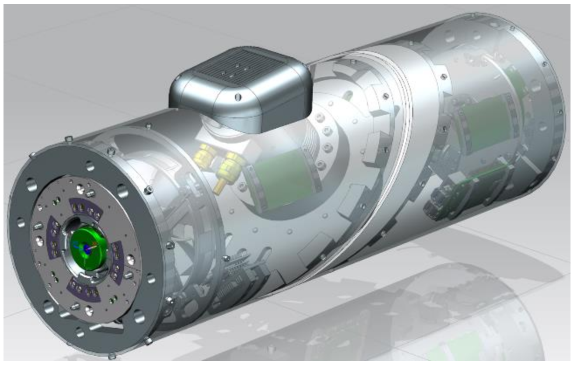

Figure 12: Isometric view of a MARGE module

The final design comprises a tubular primary structure with an outer diameter of 200 mm and a wall thickness of 3 mm. The mean length of one link is 300 mm. All load-carrying structures are made of aluminum Al-7075. As actuator, the servo unit RD 70x18 by TQ Robodrive is selected. It consists of a brushless motor and an absolute encoder as well as a safety brake. The absolute encoder is used for joint position control. Furthermore, a gear unit SHG-32-160-2SH by Harmonic Drive is used. It provides a gear ratio of 1:160 and has an integrated output bearing capable of carrying all loads during operation of the demonstrator so that additional bearings can be omitted. Both drive unit and gear are equipped with a hollow shaft for cable feedthrough. The selected combination of drive unit and gear provides a rated torque of ca. 200 Nm and a repeatable peak torque of ca. 400 Nm at a power consumption of 270 W per joint.
Each module contains a Raspberry Pi which is equipped with a CAN-adapter and communicates with the interface control unit (ICU) for control of the iSSI as well as with the drive unit´s servo controller. Via the iSSI´s data interface (DIF), all the modules´ Raspberry Pis are connected to an Ethernet network that can be accessed from a central control computer outside the manipulator. In Figure 13 a cross section view of a MARGE module is shown. For clarity, structural components are colored in the figure. The left side of the module in the figure is the drive side, the right side the output side.

The iSSIs on the drive side and the output side are connected to the tubular primary structure via adapter rings. In the module, the motor is located at the drive side while the gear is mounted at the output side for space-saving purposes. Both are connected directly via a flange (yellow). The motor shaft is guided through the gear´s hollow shaft via an extension and drives the gear from its output-facing side. Load introduction into the tubular main structure occurs via adapter structures (purple and green). All electronic components such as the ICU and the Raspberry Pi are mounted to the inner wall of the primary structure via bonded adapters. For cooling of the motor and its controller, each module is equipped with a fan. Non load carrying structures, such as the motor cover (blue), electronics adapters and cable guides are made of 3D-printed resin.

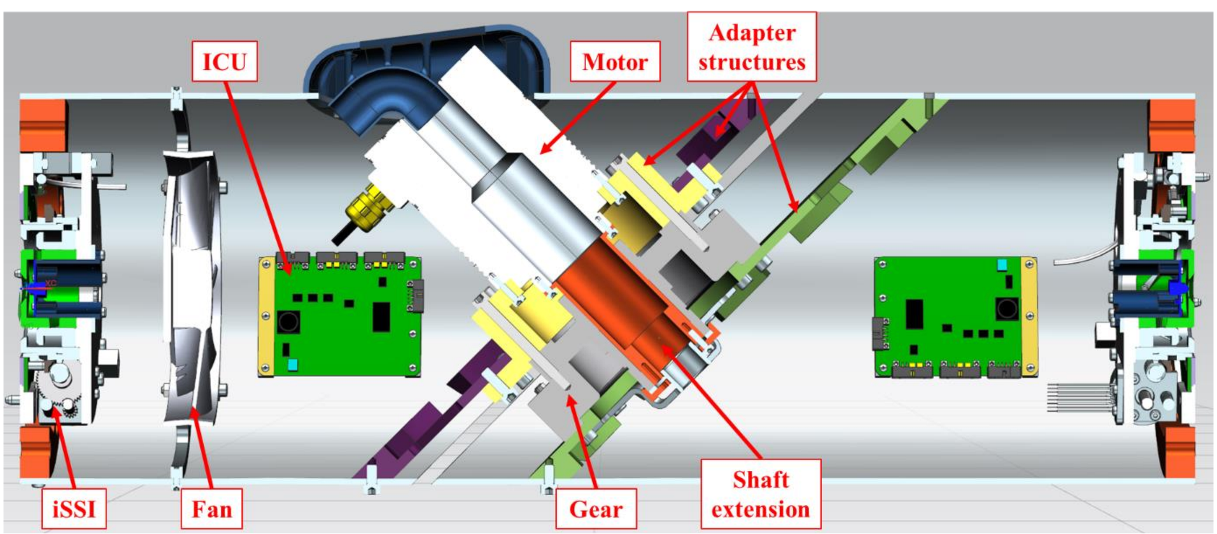


Figure 13: Section view of MARGE module

## 7 OUTLOOK

Within this project the developed demonstrators are expected to show the general feasibility of such a concept. Besides the application for space missions it is also envisioned to transfer the concept idea to terrestrial robotic applications. The modular character of the concept could help to flexibly adapt existing product lanes to new products that have different requirements towards the need robotic capabilities. This could potentially reduce the setup times for robotic manufacturing lines, for example in the automotive industry, drastically and thus highly increase the flexibility of the production process.

## 8 CONCLUSION

A concept for a fully modular and highly redundant robotic manipulator for space application and transfer potential for terrestrial use is presented within this paper. The applicability of the multifunctional space interface iSSI is shown. Solutions for the inverse kinematics and control of a modular robot are presented. The feasibility of the concept is proven by one demonstrator with numerous DOF at the magnitude of a Cubesat with focus on kinematics and control. Furthermore, an on-ground demonstrator of larger magnitude with 3 DOF is designed to proof the potential for applications in terms of OOS and OOA of future space structures as well as the terrestrial applicability in industrial volume production.

**Acknowledgement**

The research leading to these results has received funding from the DLR Space Administration under grant agreement No. 50RP1960A and No. 50RP1960B by the German Bundestag.

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