Fully Modular Robotic Arm Architecture Utilizing Novel Multifunctional Space Interface

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Abstract. The current paradigm in space robotics is the design of specialized robotic manipulators to meet the requirements for a specific mission profile. This research aims to develop a novel concept of a modular robotic arm for multi-purpose and multi-mission use. The overall approach is based on a manipulator formed by serial connection of identical modules. Each module contains one rotational joint. The joint´s, rotation axis is tilted under an angle of 45° to the normal axis, which requires less stowage space compared to a traditional joint configuration. A manipulator can be reconfigured in orbit by adding or removing modules and end effectors, therefore modifying the degrees of freedom (DoF) as well as the workspace. Redundancies are introduced, since defect modules may be removed or replaced. This paper outlines the overall concept of modularization of a robotic arm. The development and mechanical design of a terrestrial demonstrator based on the multifunctional interface iSSI (intelligent Space System Interface) is presented, which is intended for OOS and OOA activities. Furthermore, a variant of the modular robotic system with 24 DoF is presented, which can be stowed in a Cubesat-sized environment. It can operate in spaces with limited accessibility and is dedicated for tasks like inspection and delicate repairs. Finally, an outlook to further research potential and future use cases for the modular robotic system is given.

1. Introduction

Due to increasing orbital traffic and the growing amount of space debris, greater considerations need to be taken around maintaining a safe access to space. One measure to reduce the growth of debris and make spaceflight more sustainable is the concept of On-Orbit-Servicing (OOS), which, amongst others, describes the repair, maintenance and upgrade of spacecraft in orbit to extend their lifetime. To minimise the need for human intervention during such inherently risky tasks, the application of robotic systems is unavoidable. These systems need to be highly failure-tolerant and flexible, considering the variety of possible tasks to be performed during OOS-activities. In the presented project HOMER (Highly-Redundant, Modular Robotic Systems for Flexible Use in Space and Automotive Manufacturing), a novel approach for the design of such robotic systems is taken by modularising a manipulator, thereby making it redundant and easily adaptable to multiple tasks. Furthermore, the application of a multifunctional interface as module connector allows for self-reconfiguration during operation. The manipulator concept uses an unconventional kinematic chain with a joint rotation axis offset of 45°, minimising stowage space and significantly increasing operational flexibility.

2. Modularisation Approach

The modularization approach for a robotic manipulator is based on the project iBOSS (intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly) [1]. Vision of the project is the development of a fully modular satellite architecture by subdividing the common satellite bus at subsystem level. The subsystems are then integrated into standardised building blocks, each providing distinct services to the satellite infrastructure. By combining the standardised subsystem blocks, a fully modular satellite is formed. A concept of a modular iBOSS-satellite is shown in Figure 1. The satellite has extensive On-Orbit-Assembly (OOA) and OOS-capabilities. As a standardised connection between the subsystem modules, the multifunctional interface iSSI (intelligent Space System Interface) was developed within the project iBOSS. It combines mechanical coupling, power and data transfer in one device. Furthermore, it can serve as grappling point for a servicer as well as a robotic end effector. The interface is androgynous and has a 90° rotation symmetry, providing four different coupling positions. It has redundancies in terms of power and data transfer and in the decoupling mechanism. The iSSI has a mass of 1 kg and a diameter of 138 mm. Its power transfer capacity is 50 A at 100 V, data transfer can occur via optical Ethernet (1 Gbit/s) and CAN (0.5 Gbit/s) interfaces [2]. A photo of the iSSI interface is shown in Figure 2.

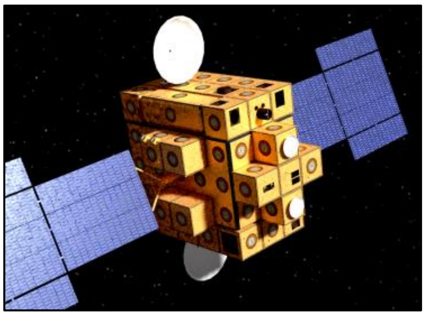


Figure 1: iBOSS satellite concept [1].

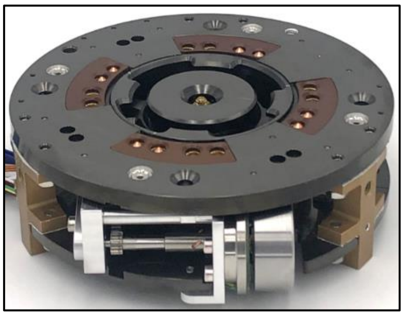
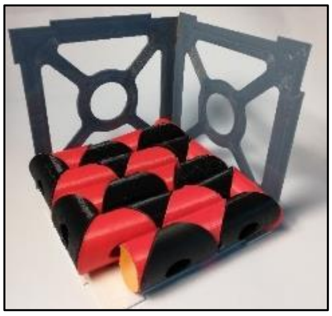


Figure 2: iSSI interface.

In order to implement OOS operations on an iBOSS satellite, a suitable robotic manipulator is necessary to interact with the modules by way of an iSSI unit. Current space robotic systems are generally designed for a specific purpose or application, resulting in high design effort and costs which makes them unattractive for many missions. To overcome these obstacles, a modular arm design is developed. A modular manipulator can adapt itself physically, modifying its length and Degrees of Freedom (DoF) during operation as necessary. Hence, within the project HOMER, the iBOSS satellite modularisation concept is transferred to a robotic arm system.

3. HOMER concept

The overall idea of the HOMER-concept is the goal of packing a robotic manipulator in a minimal volume in combination with a modular, flexible and highly redundant design. This concept combines two novel approaches in the robotics field: the shape and kinematics proposed in the twist concept [3], and the flexibility provided by iSSI [2] for the modularisation. The 45° joint axis offset allows for minimal stowage space and provides the ability to reach around obstacles and operate in small spaces. In HOMER, two demonstrators are developed. One demonstrator, the “Little Inspection and Servicing Arm” (LISA) features 24 DoF and can be folded in standard CubeSat volumes. Furthermore, it demonstrates the effect of a highly redundant design in terms of failure tolerance. The intended use-cases for a LISA-manipulator in space are primarily inspection tasks and delicate repairs within OOS-activities. In Figure 3 a) a manipulator representation of the HOMER concept is shown, which is packed to the base volume of a 1U CubeSat unit (10 x 10 x 10 cm^3). Figure 3 b) shows the same manipulator in extended state with its capability to reach around obstacles and corners.



a)

b)

Figure 3: HOMER arm in stowed and extended state.

As second demonstrator, the “Medium-sized Arm for Reconfiguration and Grappling Exercises” (MARGE) is developed. MARGE consists of three modules which are equipped with iSSI-interfaces, allowing for reconfiguration of the manipulator during operation. Modules can be removed and reattached. Therefore, it demonstrates the modularity and reconfiguration concept. In space applications, a manipulator of this magnitude can be used for manoeuvring satellite modules such as the iBOSS building blocks and thus perform OOS-tasks to the extent of OOA of entire spacecraft. The basic layout of a HOMER module is shown in Figure 4 where the link structures are shown transparent and the joint´s rotational axis is marked with a dashed arrow. A detailed description of the demonstrators LISA and MARGE is given in section 5. and in section 6.

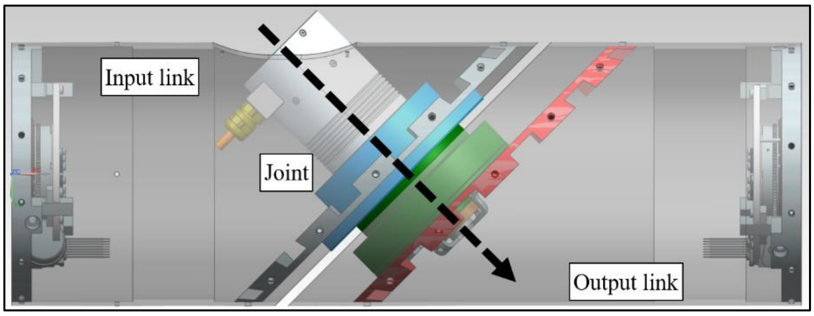


Figure 4: Module layout of HOMER concept.

4. Control

The robot control is built as a kinematic control, for trajectory following, the inverse kinematics (IK) are solved. These functionalities are loaded in the simulation environment software CoppeliaSim [4], which administrates the simulation and operation of the demonstrators. In manual operation, the Cartesian trajectories are input using joysticks, and the corresponding articular trajectory is calculated using the Damped Least Squares (DLS) as IK solver from the Reflexxes Motion Libraries [5]. The joint rotation sequence for required trajectories can be loaded and played automatically.

4.1. Graphic interface

The visual interface gives a mimic reference during the operation, where a virtual robot is employed as a puppet whose articular positions are sent to the demonstrators. Subsequently, the operations can be confirmed comparing the behaviour of the puppet and the real demonstrator. For each demonstrator, a suitable virtual environment (VE) with its respective IK solver is created. In Figure 5 (LISA) and Figure 6 (MARGE) the demonstrators are displayed in their virtual environments.

4.2. Motor controllers
The actuators level is related to the motor controlling with position regulation as control paradigm. The motor position control strategies are preloaded by the motor controller fabricant. In general, for both of the demonstrators, the actuation scheme is the same as presented in Figure 7, where the articular positions are distributed via CAN bus to the joint controls and each joint has its own rotary position control loop.

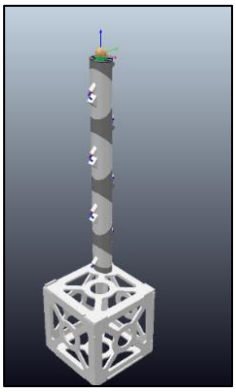


Figure 5: LISA in VE.

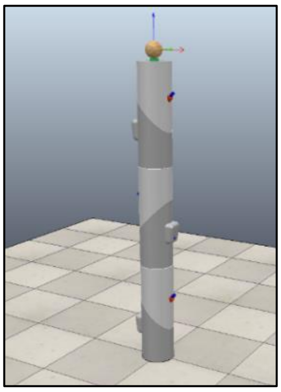


Figure 6: MARGE in VE.

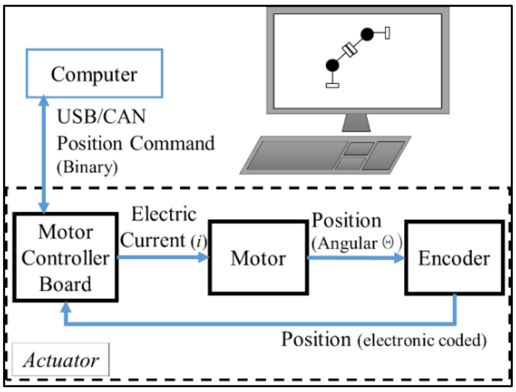


Figure 7: Command flux and actuation scheme [6].

5. Cubesat demonstrator LISA
LISA proposes a new approach on space robotics, as a compact but long robot. It has a modular design, where each module is a single link, and counts with one motor. In order to simplify servicing, modules and motors can easily be manually replaced. In contrast to MARGE, self-reconfiguration during operation is not intended. In Figure 8 a section of LISA with 5 DoF is displayed. Figure 9 shows a detail view of a LISA module with labelled components, where n denotes the module number.

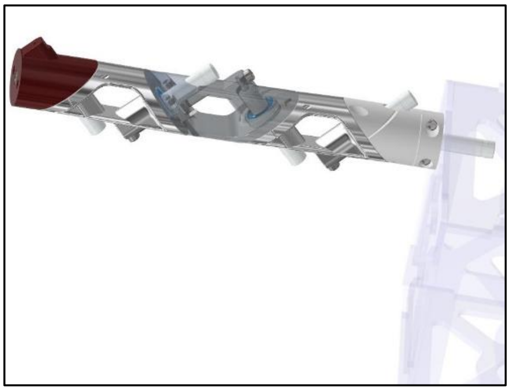


Figure 8: Model of LISA with 5 DoF.

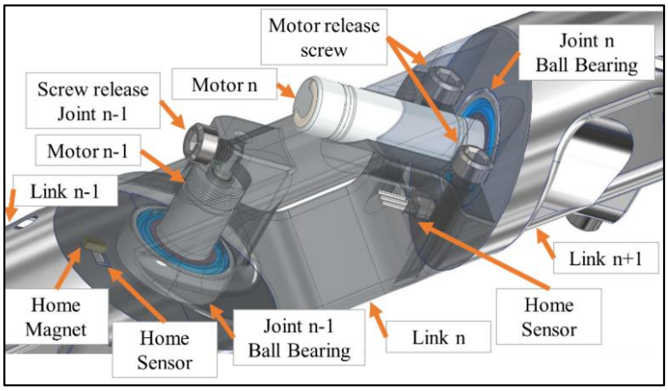
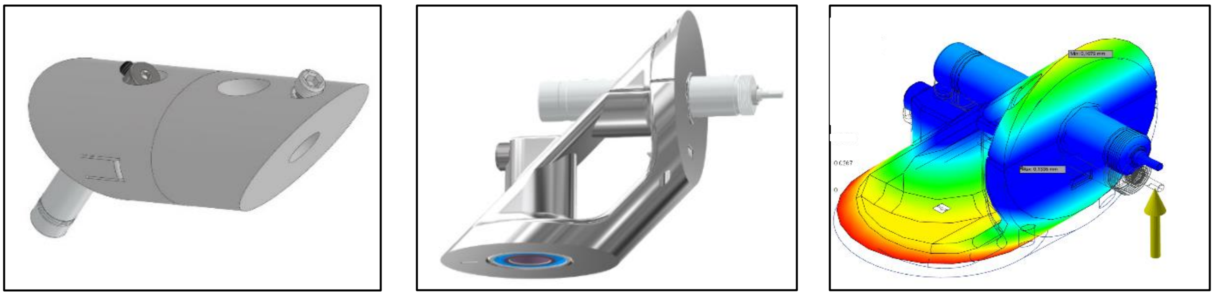


Figure 9: Detail view of LISA modules.

LISA has 24 DoF, (25 modules) a length of 1125 mm and a mass of 1250 g. It is foldable in a 2U CubeSat. The control devices are not mounted inside the modules but in a separated box. To maintain the modularity, every module can be easily unplugged from the external cable harness. For the actuation commercial motors and controllers from Maxon are used, namely ECX SPEED 8M and EPOS4. Each motor is equipped with a gearbox (1024:1) and an incremental encoder. The motor-gearbox combination can exert up to 1261.01 mNm, with an efficiency of 66.9%. Communication to the motor controllers is realised via CAN protocol. The operation of the robot is performed using kinematic solutions to the required positions.

The design of the links results from an iterative process. From the initial design (Figure 10 a), the shape is optimized for the SLM printing process (Figure 10 b). On each iteration a structural analysis using Finite-Element Analysis (FEA) is performed, shown in Figure 10 c).



a) b) c)

Figure 10: Design stages of LISA module: a) concept, b) optimised, c) stress analysis.

6. Reconfigurable demonstrator MARGE

6.1. Concept

Focus of the demonstrator MARGE is the reconfigurability of a modular manipulator during operation, making use of the capabilities of the iSSI interface. MARGE consists of three modules and has a rotatable base, providing four DoF in total. Each module is equipped with iSSI interfaces at its ends. A CAD-model of the MARGE setup is shown in Figure 11. Additionally, there is a schematic representation on the bottom right in the figure, where the iSSI-connections are shown as solid black circles and the modules´ joints as grey circles. The iSSI serves as ground connection as well as end effector. Due to the iSSI´s coupling symmetry, the relative orientation of the modules and therefore the joint axes can be varied in 90° steps, directly varying the kinematic properties of the manipulator. In Figure 12 a configuration of MARGE is shown, where all joint axes are parallel aligned (referring to a fully stretched arm). The workspace corresponding to this configuration is shown as a disc-like point cloud in Figure 13 a). In both figures, the manipulator´s base is marked a circle, the position of the end effector as a rectangle. Below the point cloud, the modules with the joint axis orientations are indicated. Rotating the central module of the configuration from Figure 12 by 180° along its longitudinal axis changes the workspace to the spherical point cloud shown in Figure 13 b). Therefore, by self-reconfiguration, the workspace of the manipulator can be modified.

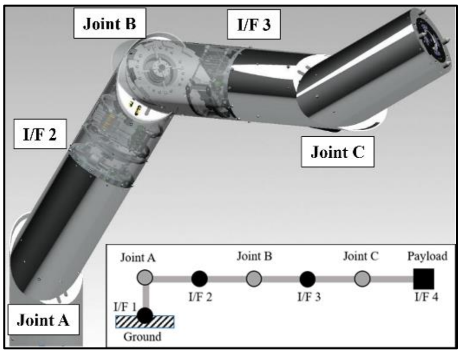


Figure 11: Model of MARGE with schematic representation (bottom right).

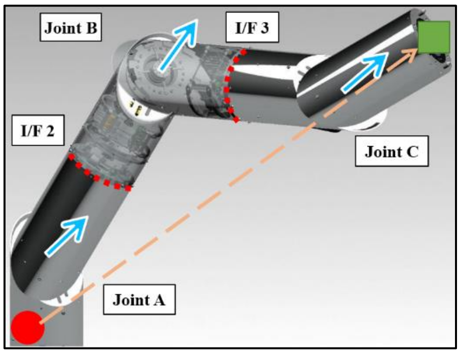
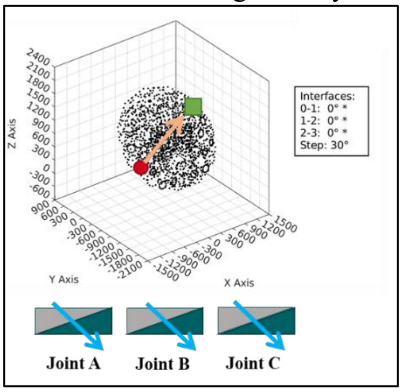


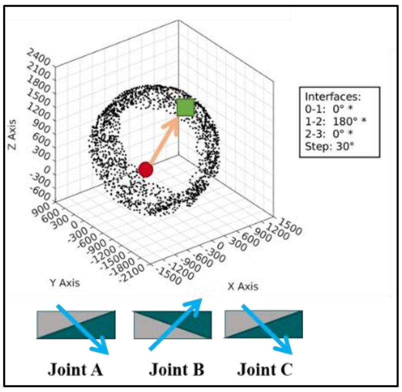
Figure 12: Joint rotation axes and position vector of MARGE.

The kinematic models of both demonstrators according to the Denavit-Hartenberg (DH) [7] standard are shown in Table 1 for LISA and in Table 2 for MARGE. To account for the variable axis alignment described above, the offset S is added as parameter to the standard DH formulation for

MARGE. As an integer value from 0 to 3, the offset represents the coupling position of the iSSI and incorporates the self-reconfigurability in the DH notation.



a)



b)

Figure 13: Workspace of MARGE depending on the module orientation.

Table 1: Model of LISA in the DH convention.

Link	α	a	D	θ
1	$\pi/4$	0	d_1	q_1
2	$-\pi/2$	0	d_2	q_2
3	$\pi/2$	0	d_3	q_3
⋮	⋮	⋮	⋮	⋮
n-1	$\pi/2$	0	d_{n-1}	q_{n-1}
n	$-\pi/4$	0	d_n	q_n

Table 2: Model of MARGE in the DH convention.

Link	α	a	D	θ
1	$\pi/4$	0	d_1	$S\cdot\pi/4+q_1$
2	$(-1)^S\cdot\pi/2$	0	d_2	$S\cdot\pi/4+q_2$
3	$(-1)^S\cdot\pi/2$	0	d_3	$S\cdot\pi/4+q_3$
4	$\pi/4$	0	d_4	q_4

6.2. Module design

6.2.1. Mechanical design. For MARGE, a requirement of 5 kg is set as load-carrying capacity. The allowable displacement at the end effector due to bending is defined as 2 mm. In the intended space application of MARGE, accelerations and velocities during operation will be of small magnitude. Therefore, inertia effects are neglected for the terrestrial demonstrator and static load-conditions with margin 1.5 are used as design load case. Load determination for design and actuator selection is conducted via multibody simulation (MBS). Initial assumptions for joint drives, the iSSI interfaces and the payload are modelled as point masses on rigid links with ideal joints. The model is shown for two positions in Figure 14. Suitable drive components and structural properties are selected, and the MBS model is updated accordingly. Local stress analyses are performed by means of FEA. An exemplary stress distribution for the input link at joint A is shown in Figure 15 for the load case of position 1 in Figure 14.

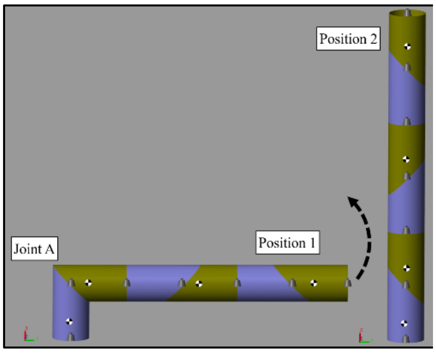


Figure 14: MARGE MBS (Simscape).

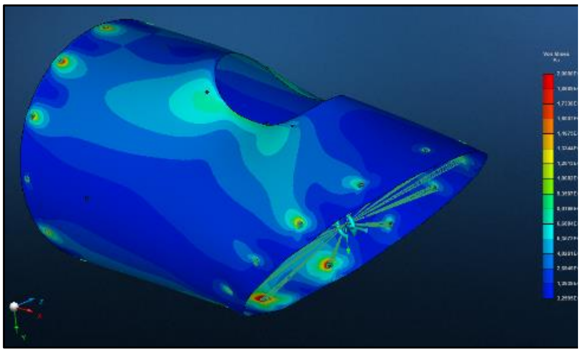


Figure 15: Link stress distribution (MSC Apex).

The final design of the MARGE demonstrator modules features a tubular primary structure from aluminium EN AW 6082 with an outer diameter of 200 mm, a wall thickness of 3 mm and a total module length of 600 mm. All other load-bearing structural components are made from EN AW 7075. A section view of the module is shown in Figure 16, where the drive side is on the left. The joint drive consists of a hollow shaft servo unit with safety brake and absolute encoder. The unit drives a Harmonic Drive gear (160:1) unit with an integrated output bearing. Load transmission to the tubular primary structure from the gear unit occurs via adapter structures. Furthermore, there are racks for electronics on each side, which house the devices for power handling, controls, and communication. An assembled module is shown in Figure 17 for different joint positions.

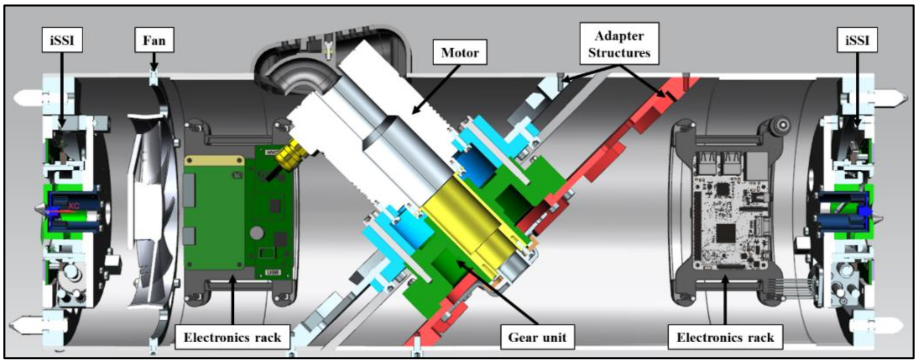


Figure 16: Section view of MARGE module.

6.2.2. Power and data infrastructure. The power is supplied by a 50 V main bus, which is transferred between the modules via the iSSI´s electrical interface (EIF). The joint motor operates with 48 V, for other electronic devices there are DC/DC converters to 24 V and 5 V.

Communication between the modules occurs via Ethernet over the iSSI´s optical data interface (DIF). The modules contain a single board computer (Raspberry Pi), representing an Ethernet-device so that the entire manipulator forms an Ethernet network. Inside each module, there is a CAN-network with the servo controller and the iSSI interfaces. The Raspberry Pis are addressed with the movement and iSSI control commands by their IP address. The commands are sent to the CAN-devices via a USB-CAN adapter. An overview of the power and data infrastructure inside a module is shown in Figure 18. A summary of the main components inside a MARGE module is given in Table 3.

Figure 17: Module of MARGE demonstrator.

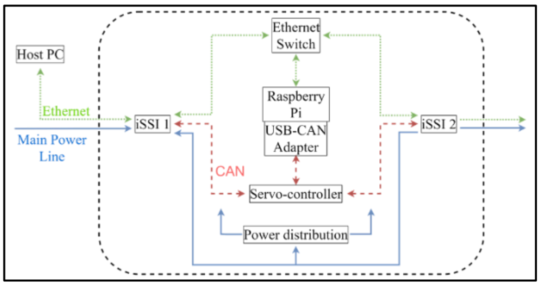


Figure 18: MARGE power and data infrastructure.

Table 3: Main components of MARGE.

Component	Description
Motor unit	TQ Robodrive RD 70x18
Gear unit	Harmonic Drive SHG-32-160-2SH
Servo controller	Copley Accelnet APV-090-30
Single board computer	Raspberry Pi 3B+
USB-CAN adapter	KVASER Leaf Light HS v2 CB

7. Summary and outlook

Within the project HOMER, the general feasibility of a highly redundant modular robotic system is proven by means of two terrestrial demonstrators. Solutions of the inverse kinematics for a modular manipulator with high DoF are presented. The capability of the iSSI interface for robotic application is proven as well as the concept of self-reconfiguration. Both demonstrators provide individual use cases such as inspection and repairs (LISA) and OOS/OOA tasks (MARGE). In subsequent research, the concept will be evolved to a space specific design with highly integrated lightweight structures and suitable electronics and mechanisms. Furthermore, capabilities for autonomous operation will be developed, which provide a high potential for application of artificial intelligence.

In addition to the presented use cases of the HOMER concept in space, there is a high transfer potential to terrestrial applications. The modular, highly redundant design can increase flexibility during industrial serial production. Tooling-times can be reduced and production lines can be quickly adapted to multiple products. Furthermore, the HOMER concept provides numerous applications for harsh terrestrial environments, i.e. deep sea or radiation, significantly reducing the necessity for human presence in such dangerous environments.

Acknowledgement

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