DESIGN AND DEVELOPMENT OF A RELOCATABLE ROBOTIC ARM FOR SERVICING ON-ORBIT MODULAR SPACECRAFT

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ABSTRACT

The raise of orbital robotics opens a new horizon of possibilities for upcoming space missions. In the context of a global space sustainability, this paper deals with the design, development and testing of a new generation of robotic manipulator for on-orbit maintenance and servicing. This device tackles especially modular missions related to assembly and reconfiguration of modular satellites, coupled with the paradigm of standardization of spacecraft featuring standard interconnects. This robotic system benefits from an innovative multidisciplinary design for performing manipulation and relocation tasks over compatible spacecraft structures. The proposed robotic manipulator is experimentally evaluated on a representative ground demonstrator in a laboratory environment.

1. INTRODUCTION

The current expansion of the on-orbit satellite number is raising the challenge of the sustainability of operational and safe near- and far-terrestrial orbits while increasing the spacecraft lifetime [1]. On-orbit servicing, on-orbit assembly and reconfiguration of modular spacecraft emerge as necessary and relevant techniques to address this upcoming situation while remaining cost effective, high performing, reliable, scalable and flexible [2]. To increase these capabilities and to facilitate this shift of paradigm in designing and deploying satellites and spacecraft, standardized and versatile key enablers needs to be developed [3]. Interconnects and small-medium scale versatile orbital robots are considered presently as promising assets for opening new horizons of possibilities and configurations for such future space missions [4].

Based on these context and technologies, the H2020 EU funded MOSAR project [5] has been successfully proposed and completed for developing some of the key solutions for this technological transition. MOSAR aims at designing modular spacecraft for enabling assembly and reconfiguration of satellite on-orbit. As illustrated in Fig.1 and [6], two spacecrafts are involved in MOSAR, a

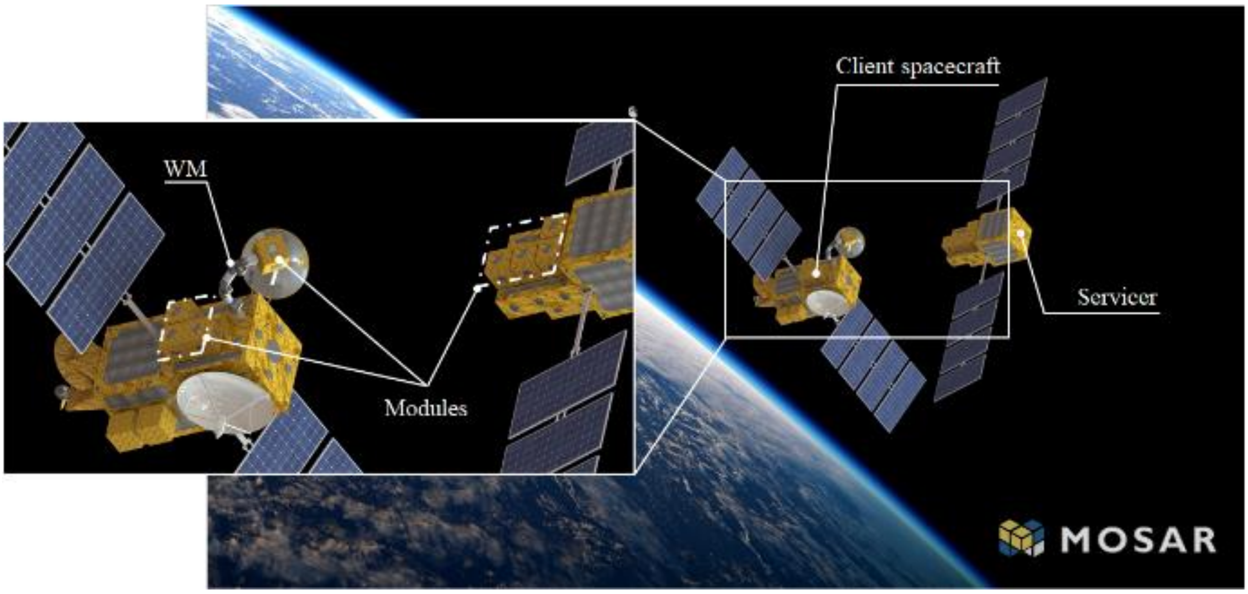

Figure 1. Artist representation of the MOSAR's on-orbit servicing concept.

modular client satellite equipped with reusable modules, and a servicer bringing alternative modules. The connections between each subsystem, spacecraft or module, is performed through standard interconnects (SI) and for performing the autonomous assembly and reconfiguration tasks, a repositionable robotic manipulator (aka. “Walking Manipulator” or WM) is acting.

This paper deals in particular with the design and development of a 7-Degree Of Freedom (DOF) relocatable robotic arm demonstrator for such servicing on-orbit modular spacecraft [7,8]. This Technology Readiness Level (TRL) 4 robot, illustrated in Fig. 2, features a symmetrical and anthropomorphic kinematics, and standard interconnects at each tip for mechanical, data and power connections to the spacecraft. It also embeds its own power and data avionics as well as servo and robot control units. The overall length of the robotic arm is 1.6 meters for an approximate weight of 30kg and has a lifting capability of 10-kg payloads at 1g in its entire workspace.

The WM has been successfully tested in laboratory conditions on a representative ground testbed. A series of scenarios combining relocation and manipulation operations has been performed to assess the WM demonstrator.

Figure 2. MOSAR’s relocatable robotic arm demonstrator.

The structure of this paper is as follows: Sec. 2 provides an overview of the robotic system. Sec. 3 to 6 detail design aspects ranging from mechanics to subsystems, avionics, software and control, while Sec. 7 describes the experimental results achieved with the ground demonstrator. Sec. 8 finally provides a conclusion and work perspectives.

2. SYSTEM OVERVIEW

Assuming compatible spacecraft structure and spacecraft modules equipped with SIs, the two basic operations considered for the walking manipulator are (1) re-localization to a new attachment point on the satellite, and (2) manipulation of a spacecraft module using the SI attached to the arm (Fig. 3 & 4).

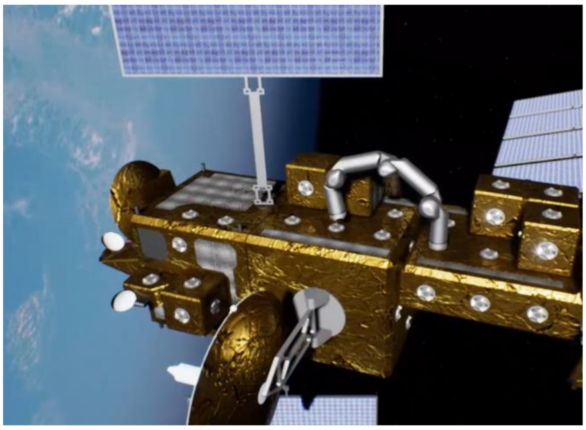

Figure 3. Artist representation of the re-localization operation.

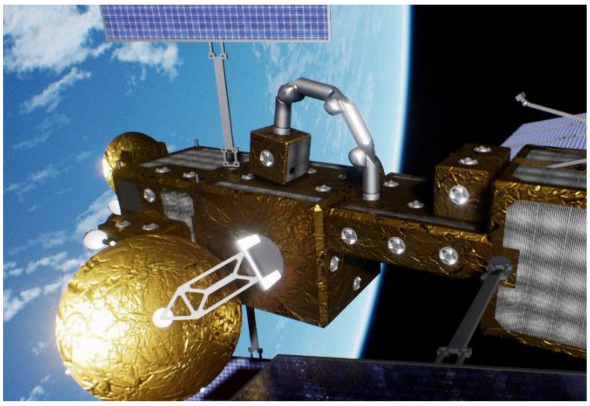

Figure 4. Artist representation of the manipulation operation.

3. MECHANICS

The walking manipulator concept, depicted in Fig. 5, comprises the following mechanical elements:

- End effectors (HOTDOCKs): Each extremity of the walking manipulator is equipped with a Standard Interconnect , namely HOTDOCK [9]. These interfaces allow the robot to relocate, since the arm can be attached to a supporting structure on both sides.

- Motorization (Robotic joints): The walking manipulator is equipped with seven revolute joints according to the following symmetric configuration $R \perp R \perp R \perp R \perp R \perp R \perp R$, where R indicates a revolute joint and $\perp$ the orthogonality between two successive joint axes. Motors have been sized for lifting a 10kg payload at 1g across the entire workspace of the manipulator.

- Structure (Limbs): The overall configuration of the manipulator is based on a human-like arm with asymmetric joints. The arm is 1.6-meter long and weighs approximately 32.5kg.

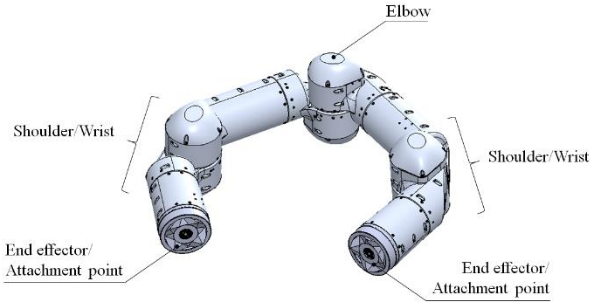

Fig. 5. Overview of the MOSAR-WM.

3.1. END-EFFECTORS

The two tips of the walking manipulator are equipped with active standard interconnects, namely HOTDOCK. HOTDOCK is an androgynous standard robotic mating interface that supports mechanical, data, power and thermal transfer.

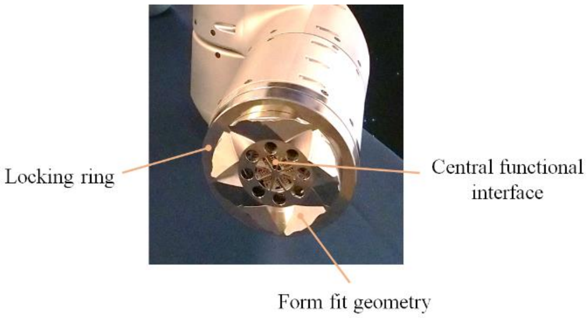

Figure 6. WM's wrist active HOTDOCK.

As shown in Fig. 6, HOTDOCK features the following coupling elements:

- A mechanical interface that provides alignment, coupling and mechanical load transfer. It is composed of fixed elements (main body structure and the form fit geometry) and a movable locking ring to allow connection with another device. Furthermore, the geometry of HOTDOCK makes it androgynous and 90-degree symmetrical.
- A central functional interface comprising a contact plate with spring-loaded pins and pads that enables:
  - transfer of electrical power;
  - transmission of data through CAN or SpaceWire protocol;

3.2. ROBOTIC JOINTS

Each joint of the walking manipulator is equipped with a rotary hollow shaft actuator for enabling cable routing inside the arm.

Two actuator sizes, depicted in Fig. 7, have been designed to fulfil the requirements linked to the Earth demonstrator.

Figure 7. Robotic drive units – elbow/wrist (left) and shoulder (right).

Key features of the elbow/wrist and shoulder joints are respectively:

- Nominal Torque: 170Nm, 300Nm
- Maximum output speed: 3rpm
- Accuracy: +/-0.025deg/90arcsec
- Repeatability: <0.001deg
- Weight: 2.4kg, 3.6kg

3.3. STRUCTURE & KINEMATICS

The structure of the WM is composed of eight subassemblies, as depicted in Fig. 8, split into three main subassemblies: wrist, shoulder and elbow. Tabs. 1 & 2 and Fig. 9 describe the main structural parameters and joint limits of the WM.

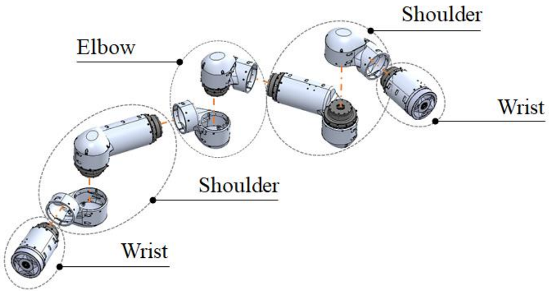

Figure 8. WM structure.

Table 1. MOSAR-WM's Denavit Hartenberg parameters.

a [mm]	α [deg]	d [mm]	θ_{off} [deg]
80	90	345	0
-80	-90	0	0
75	90	455	0
-75	-90	0	0
80	90	455	0
-80	-90	0	0
0	0	345	0

Table 2. MOSAR-WM’s joint limits.

Joints	**Joint limits [deg]**	
	min	**max**
1	-175	175
2	-175	45
3	-175	175
4	-175	45
5	-175	175
6	-175	45
7	-175	175

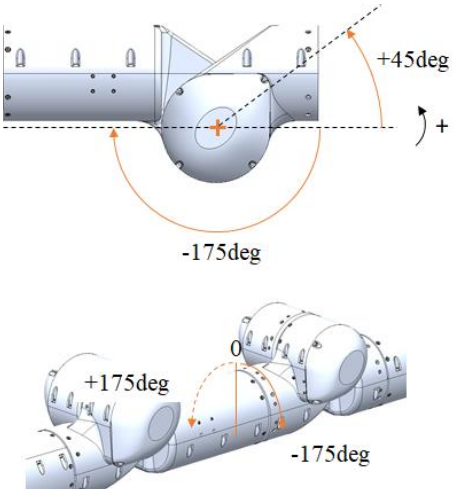

Fig. 9. MOSAR-WM’s joint limit definition.

4. AVIONICS

Fig. 11 illustrates the detailed WM avionics and electrical architecture while Fig. 10 shows the avionics layout inside the WM. The WM Controller (WMC) is the central avionics component. It manages the internal control of the arm, of the two HOTDOCK at the WM tips, and the communication with the satellite on-board computer (OBC). The WMC uses an Intel NUC board, running Ubuntu 18.04 LTS 64-bit. This solution, equivalent to the spacecraft OBCs, offers the required compactness while providing a standard platform to integrate the different software applications.

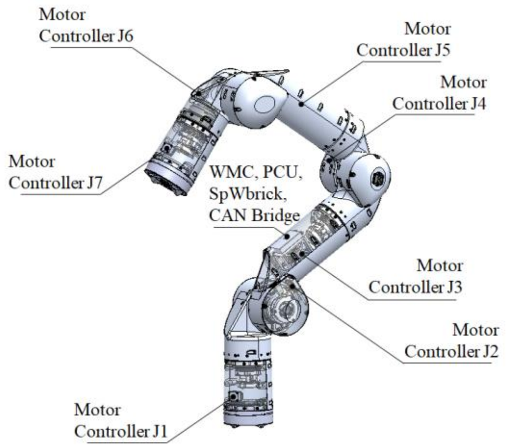

Figure 10. Integration of the avionics inside the WM.

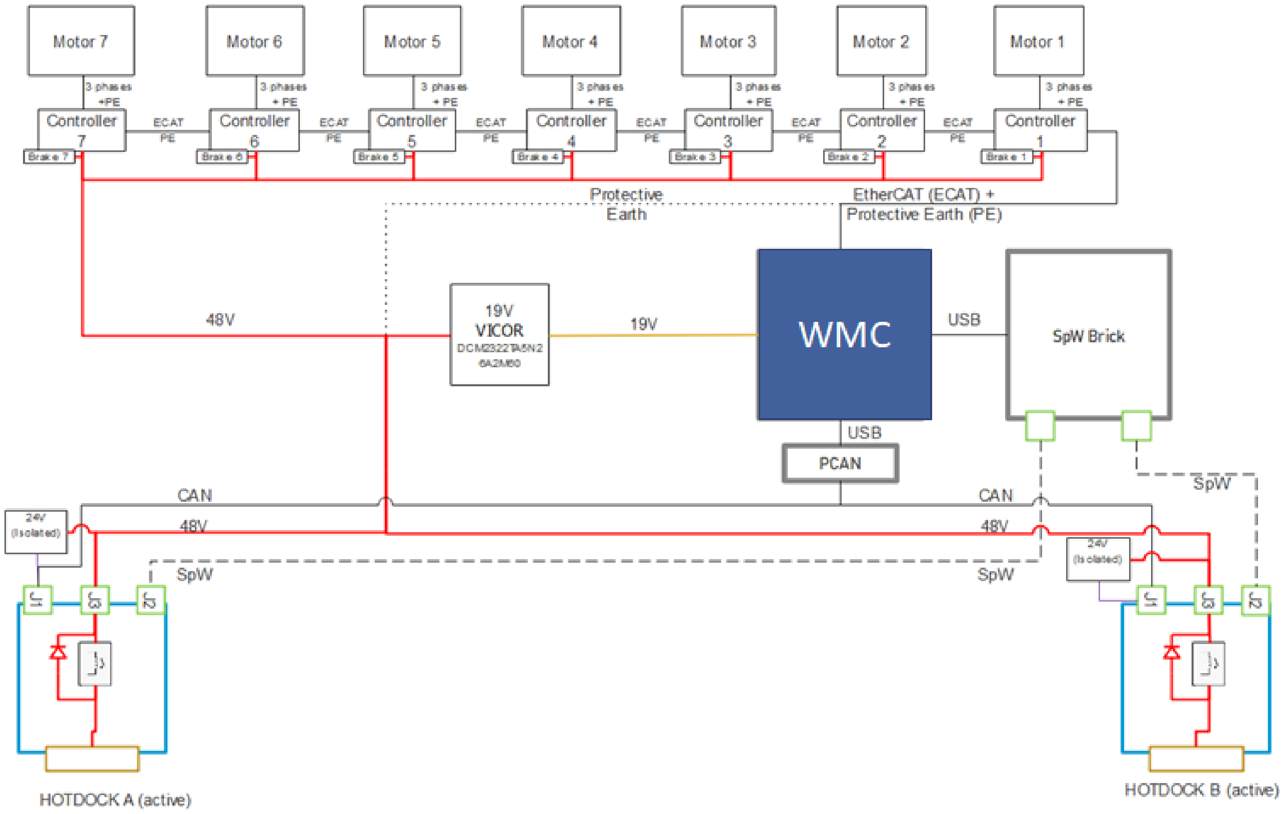

Figure 11. WM's avionics architecture

The WMC interfaces the three main data buses running along the robotic arm:

- SpaceWire bus for "high level" non-deterministic telemetry and telecommand (TM/TC) communication with the servicer OBC through the RMAP protocol. This relies on a Star-Dundee SpaceWire Brick Mk3, connected by USB to the WMC. The Brick also ensures the transmission of the SpaceWire signal between the two HOTDOCK extremities.
- CAN bus for local control of the HOTDOCK interfaces. This is done with a USB-CAN interface.
- EtherCAT bus for low-level deterministic communication with the joint drivers. This is done by the implementation of an EtherCAT Master application on the WMC and replacement of the Ethernet drivers by EtherCAT driver, to allow the connection directly though the WMC Ethernet port.

Each joint of the WM is equipped with a local controller for the closed loop position/current control of the actuator and the measurements of the joint sensors. All joint controllers are interfaced through the EtherCAT bus, managed by the WMC, which ensures real-time exchange of information required for the control algorithm of the arm at 2 kHz.

The robotic arm is powered by the servicer 48V power bus, through the power interface connector of HOTDOCK. The 48V bus is directly interfaced with the joint drivers that will manage the power interfaces to the motors and sensors of the joints. Local DC/DC convertors provide the required 24V to power the two HOTDOCKs and 19V for the WMC. The arm is able to control the power transfer, passing through the interfaces, thanks to power relays embedded in HOTDOCK. This allows to power-on a module connected at the end-effector and communicate with it through SpaceWire.

5. SOFTWARE

The WM comprises a series of software units to control the different operations that should be performed (see Fig. 12):

- The robot monitor and control, split in two main parts:
    - A low-level control software for controlling the robotic joints over Ethercat, either through the servo control units to move in position mode, or through the WMC in torque mode;
    - A high-level control software to enable/disable the arm motions and set the position or torque commands to each robotic joint at high rate, based on advanced control methods (e.g. Cartesian Impedance Controller);
- The HOTDOCK monitor and control, a low-level software that manages the CAN bus communications between the WMC and the HOTDOCKs;
- The TM/TC Engine, a Spacewire communication handler to convert high-level information from the spacecraft OBC into low-level information for HOTDOCKs and robot control.

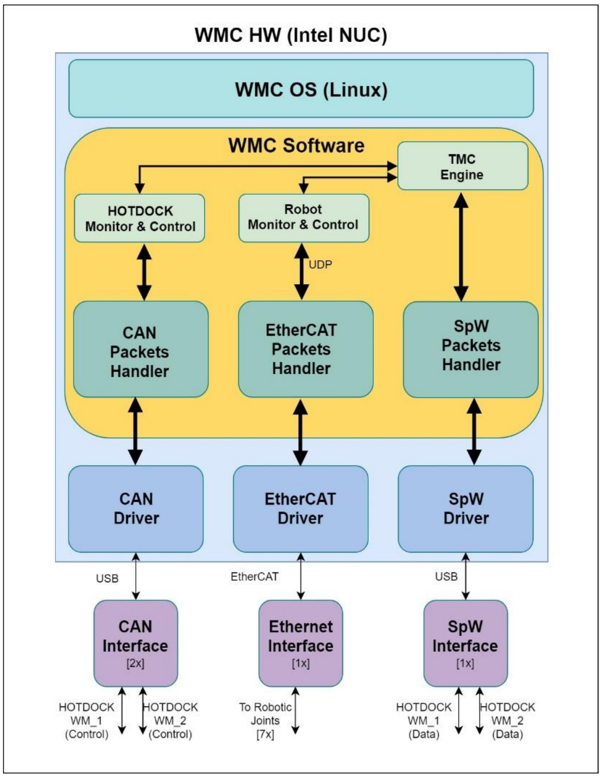

Figure 12. WM software architecture.

6. CONTROL

The control of the MOSAR-WM is based on impedance controllers, which allow a modulation of the mechanical impedance at the joint or arm level while interacting with the environment. In this way, the system successfully completes interaction tasks such as docking or grasping objects, while making it very robust to external perturbations [10].

The Impedance Controller has two modes of operation. The first one is in Cartesian space, which sets the desired impedance at the tool center point (TCP). The second one is at joint level, for setting individual desired joint impedances. In both cases, stiffness and damping matrices are predefined, i.e., they are controller

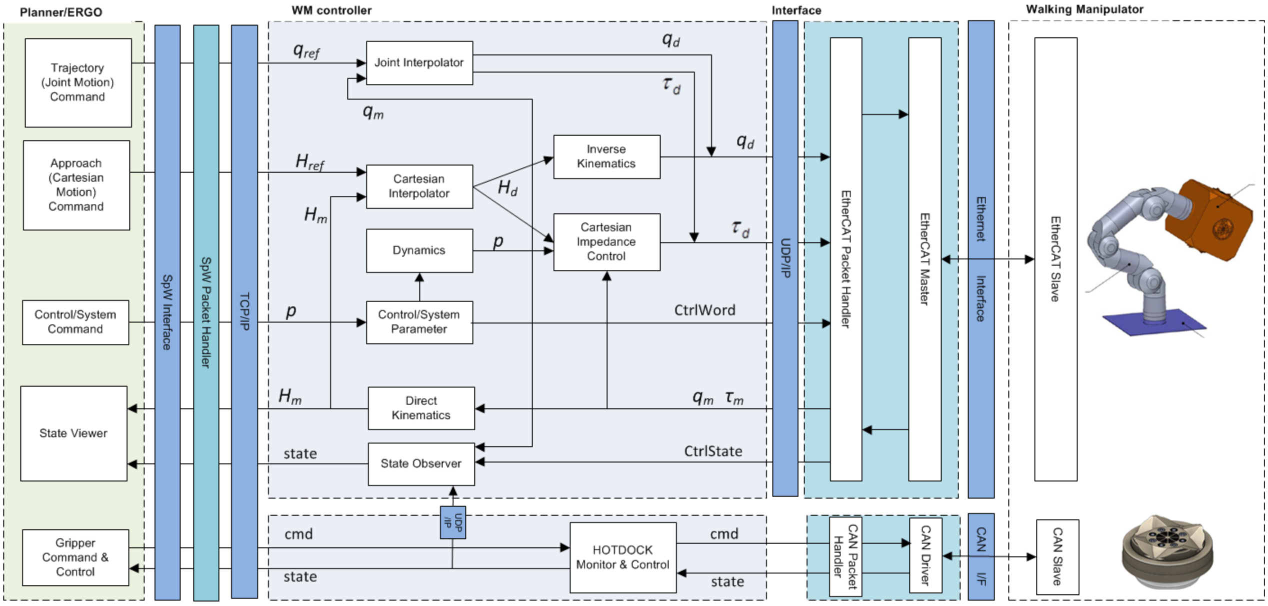

Figure 13. WM's control architecture.

parameters that define the compliant behaviour [11].

Besides the torque control mode, the WM can also be controlled in position mode, which is mainly used for scenarios where the robot moves freely in space, without contacts with the environment.

The general control architecture for the robot is shown on Fig. 13; it includes all the components to control the walking manipulator from top-level (planning and command generation) to low-level control. Each joint of the WM is equipped with a local controller for the closed loop position/current control of the actuator and the measurements of the joint sensors. All joint controllers are interfaced through an EtherCAT bus (master/slave), which ensures the real-time exchange of information required for the control algorithm of the arm at 500 Hz (minimum).
The WM controller communicates with the WM via an encapsulated data layer, which hides the specific communication details (i.e. the Master I/F and the CAN Driver). That means, that data packets are interfaced to the appropriated communication bus using an internal API (IP-based) to local SW processes running close to the OS/Driver layer and in charge of the encoding of the high-level information in the appropriated low-level format. The data communication between the WM controller and the EtherCAT Master must fulfil the real-time requirements, given by the control rate of the WM. As both software modules are running on the WMC, the implemented interface is based on the UDP/IP protocol.

Fig. 13 also shows the interface to the planner. On the left, the planning component provides a coarse, collision-free trajectory to the WMC, which is then interpolated and commanded to the actuators at high rate. Therefore, the interface between the planner and the WMC is characterized by an asynchronous command mode: the planner sends commands as a queue of events, according to the current execution state of the WMC. It has to act as a state machine, which fires new commands if the on-going command has been finished. The command interface from the Planner to the WMC mainly includes two operational commands:

- A transfer motion between the current joint angle configuration to a desired one, described by a list of joint configurations. This motion is fully expressed in the joint space of the manipulator arm and is performed by an interpolator, which handles the intermediate via points in a continuous way, controlled by a simple position controller.
- An approach/docking motion, which is expressed in the Cartesian space (tool centre point of the manipulator w.r.t. a reference coordinate system, e.g. the local reference of the servicer satellite). This motion results in a straight-line impedance-controlled motion from the last (reached) pose of the transfer motion to the desired alignment pose. We assume that this Cartesian motion will not drive the manipulator into the limits of its workspace.

Both actions give continuous feedback to the planner about the current execution state.

7. EXPERIMENTAL RESULTS

Within the MOSAR project, a series of scenarios has been performed on a ground demonstrator to assess the WM concept during operations [12, 13]. The MOSAR's setup, illustrated in Fig. 14, is representative of the MOSAR's mission scenario and concept of operation introduced in Sec. 1 of this paper. It is composed of a ground segment (mission control centre and ground support equipment) and a space segment (servicer and client spacecrafts, modules and the WM). The following of this section illustrates notable results achieved during the MOSAR demonstration. More details about this demonstration and related results can be found in [8, 12, 13, 14].

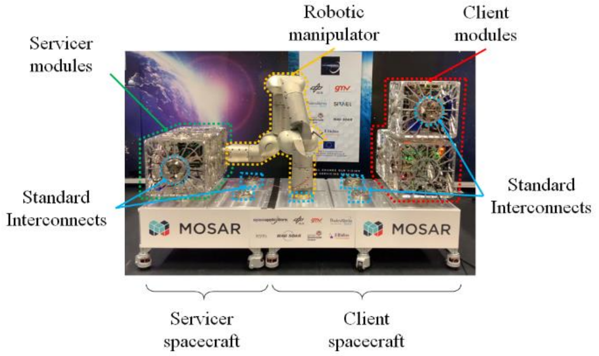

Figure 14. MOSAR test setup.

The manipulation results obtained during the test campaign validate the ability of the WM to perform successful manipulation operations of 10kg spacecraft modules at 1g. Fig. 15 illustrates in particular the manipulation of a module from the servicer spacecraft to the client spacecraft. Here the robot grasps a module's SI located at (40cm,40cm,20cm) from its base and positions it at (100cm,40cm,60cm) from its base.

Fig. 15. Manipulation sequence of a spacecraft module from the servicer spacecraft.

The relocation results obtained during the test campaign validate the ability of the WM to perform successful relocation operations from one SI to another in planar and 3D configurations. Figs. 16 and 17 illustrate in particular walking sequences on the demonstrator structure, respectively on parallel levels and on orthogonal surfaces. In Fig. 16, the WM managed to reach an SI located at 80cm horizontally and 40cm vertically from its attachment point, while in Fig. 17 it reaches the vertical panel SI located at (80cm,20cm,20cm) from its initial attachment point and then the top panel SI located at (20cm,0,-20cm) from the side panel SI..

Fig. 16. Walking sequence on/from spacecraft modules.

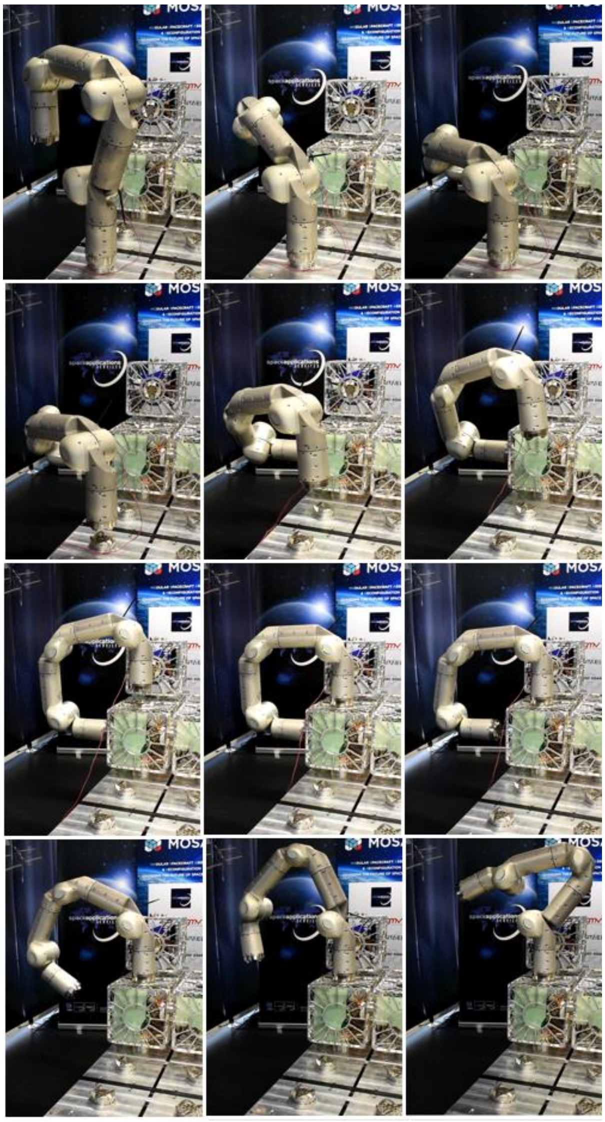

Fig. 17. Walking sequence on the side and self-lifting on the top of a spacecraft module.

8. CONCLUSIONS & PERSPECTIVES

This paper describes the MOSAR-WM demonstrator, its integration and its experimental results performed in the scope of the H2020 MOSAR project.

MOSAR-WM is a small size and weight robotic manipulator (1.6m/32.5kg) with a redundant and symmetrical anthropomorphic kinematic structure (7DOF). MOSAR-WM has the main capability of relocating and lifting itself using standard interconnects as end-effectors. It has also the capability to lift substantial payloads (10kg at 1g in the entire workspace). It specifically embeds its own intelligence and internal harnessing (WMC, servo control units, data and power buses) and run position and impedance based control (since the framework is known, vision system is not needed).

Experimental results performed during the MOSAR project test campaign demonstrated the ability for MOSAR-WM to perform successfully its scope of operations on ground.

Thank to these features and results, this is making the MOSAR's Walking Manipulator a precursor and unique robotic system w.r.t. the existing state of the art in the category of autonomous anthropomorphic small relocatable robotic manipulator, currently developed at TRL4 and targeting future on-orbit servicing applications.

Future work will mainly focus on the characterization of the robotic performances and on maturation of the WM concept. Maturation aspects include TRL increase and further developments related to modular robotics, in the ESA TRP MIRROR project [15], and its application to cooperative robotics for building very large assembly in space within the ESA OSIP SKYBEAM study.

9. ACKNOWLEDGEMENTS

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