MOSAR-WM: A relocatable robotic arm for future on-orbit applications

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MOSAR-WM: A relocatable robotic arm demonstrator for future on-orbit applications

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Abstract

In the past few years, the raise of space robotics yielded novel potential applications. The utilization of more advanced and capable robotic manipulators opens a whole new horizon of possibilities for future space missions, ranging from On-Orbit Servicing (OOS) of existing satellites (for refuelling, Orbital replacement unit (ORU) or de-orbiting) to On-Orbit Assembly (OOA) and reconfiguration of modular spacecraft. This paper deals with the design and primary Manufacturing, Assembly, Integration and Testing (MAIT) activities of a novel robotic manipulator demonstrator for such on-orbit applications. MOSAR-WM is a 7 degree of freedom (DOF) manipulator, 1.6-meter long, symmetrical and relocatable (aka. "walking" capable). Its overall structure is human-like with asymmetric joints. Manipulator joints are hollow-shaft for internal cable routing, and include cutting-edge space-compatible technologies. Each joint embeds a torque sensor in addition to position sensors (incremental and absolute encoders). The kinematic architecture of MOSAR-WM offers a wide end effector workspace, and its stiff structure guarantees a high accuracy and repeatability while allowing compactness for launching and storing purposes. Each extremity of MOSAR-WM is equipped with a HOTDOCK standard interface that allows for mechanical connection, powering and controlling the arm. Manipulator avionics consists in seven joint controllers (one per joint) and an embedded computer called Walking manipulator controller (WMC) running a real time operating system. The WMC receives high-level commands from the external computing unit through the connected HOTDOCK interface. It also calculates the dynamic model of the robot to provide proper feed-forward terms for the joint control. Depending on the desired behaviour, the gains of the joint control loop are adaptive for optimal performance in position control. In addition, a Cartesian impedance control is implemented to allow for compliant operations. The joint controllers are daisy-chained through EtherCAT, while the control of each HOTDOCK is performed through a CAN bus managed by the internal WMC. MOSAR-WM is developed in the context of the European Commission's Space Robotic H2020 MOSAR project. It aims to validate the developed technologies at Technology Readiness level (TRL) 4 in a space representative scenario.

Keywords: Space robotics, Relocatable Robot, Mechanism Design of Manipulators, Motion Control of Manipulators

Acronyms/Abbreviations

Walking Manipulator (WM), Extra-Vehicular Activity (EVA), Payload Deployment and Retrieval System (PDRS), Shuttle Remote Manipulator System (SRMS), Orbiter Boom Sensor System (OBSS), Mobile Servicing System (MSS), Mobile Remote Servicer Base System (MBS), Space Station Remote Manipulator System (SSRMS), Special Purpose Dexterous Manipulator (SPDM), Japanese Experiment Module Remote Manipulator System (JEM-RMS), Robot Component Verification on ISS (ROKVISS), European Robotic Arm (ERA), Standard interconnect (SI), Walking Manipulator Controller (WMC). Telemetry (TM), Telecommand (TC), Tool Centre Point (TCP).

Fig. 1. Artist representation of the MOSAR project

1. Introduction

The growing interest in on-orbit assembly coupled with the raise of advanced robotic systems is stimulating the development of new paradigms for future space missions [1]. In this context, autonomous or remote-controlled robotic manipulators are becoming widely used for diverse space applications, ranging from on-orbit servicing of existing satellites (for refuelling, ORU or de-orbiting) to on-orbit assembly and reconfiguration of modular spacecrafts [2]. Robot manipulators are a relevant technology for highly dexterous and accurate operations in extreme environments such as outer space. They are also able to perform position and force control tasks with compliance, capable of supporting cooperative tasks (EVA) or autonomous ones.

Robotic manipulators are present in space since decades. Well known on-orbit applications are the different robotic systems embedded in the space shuttle and attached to the International Space Station, namely PDRS (composed of SRMS and OBSS), MSS (composed of MBS, SSRMS, OBSS, SPDM), JEM-RMS, Strela, ROKVISS and later on ERA. They have been progressively installed year after year to enhance the maintenance abilities as well as assessing new technologies on-orbit. ETS-VII is also notable as the first unmanned satellite (experimental) equipped with a robotic arm for performing autonomous rendezvous docking operations.

Other robotic manipulators have been developed for targeting future on-orbit missions including among other: DEXARM [3] a robot arm comparable to human arm for human equivalent intervention and applied in EUROBOT a three-arm robot for supporting an ISS crewmember during EVAs; CAESAR [4] a robot system for on-orbit services, or even DSXR a self-deployable and relocatable manipulator for assembling, berthing and inspecting the lunar orbital platform-gateway (LOP-G).

Aforementioned robotic systems are mainly targeting conventional or dedicated missions; however, new paradigms involving modular spacecraft and standardisation of components are also emerging, requiring the development of new advanced robotic systems and related technologies.

H2020 EU funded project MOSAR [5] is one of these new developments. MOSAR aims at designing modular spacecraft and related key technologies to enable on-orbit assembly and reconfiguration, as illustrated in Fig. 1. It involves two types of spacecraft: a modular client satellite equipped with replaceable modules, and a servicer, bringing replacement modules. The connection between each subsystem (spacecraft or modules) is performed through standard interconnects (SI), and a repositionable walking robot (MOSAR-WM) allows performing autonomous assembly and reconfiguration tasks.

The structure of this paper is as follows: Sec. 2 provides an overview of the MOSAR-WM system. Sec. 3 to 6 detail the design aspects related to MOSAR-WM's mechatronic subsystems, avionics, software and control. Sec. 7 presents the initial results of the manufacturing, assembly, integration and testing phase and Sec. 8 provides a conclusion on the work achieved so far and presents the perspectives on future activities.

2. System Overview

The two basic operations considered for the walking manipulator (WM) 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. 2 & 3).

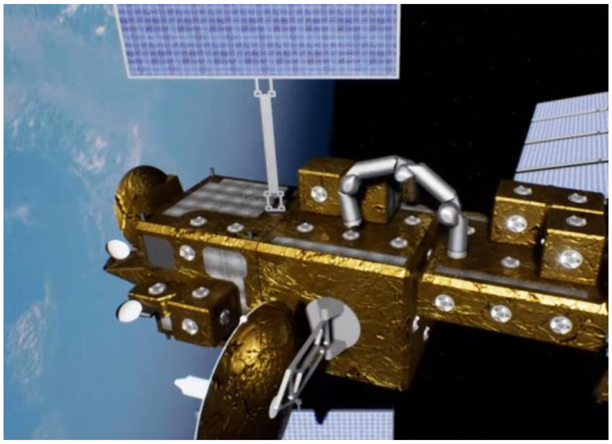

Fig. 2. MOSAR-WM re-localization operation.

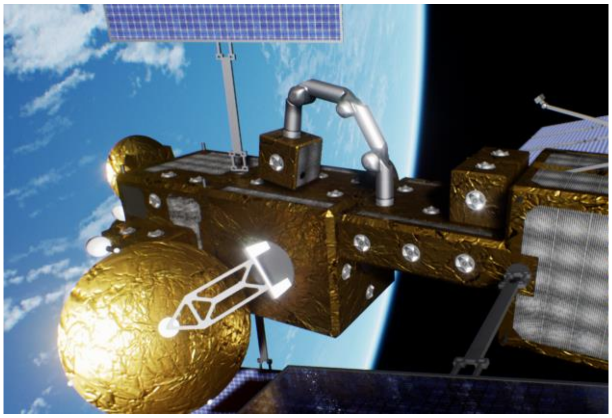

Fig. 3. MOSAR-WM manipulation operation.

The walking manipulator comprises the following elements:

- Structure (Limbs): The walking manipulator is composed by eight structural elements. The overall configuration of the manipulator is based on a human-like arm with asymmetric joints (See Fig. 4 & 5). The arm is 1.6-meter long and weighs approximately 30kg.

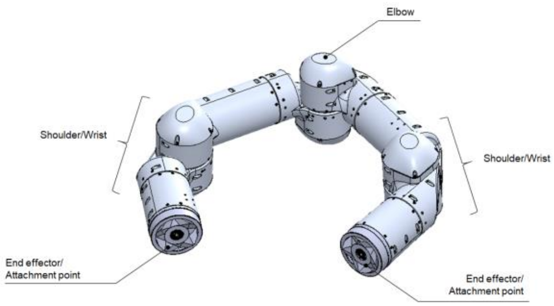

Fig. 4. Overview of the MOSAR-WM.

- 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 (see Fig. 6). Motors have been sized for lifting a 10kg payload at 1g across the entire workspace of the manipulator.

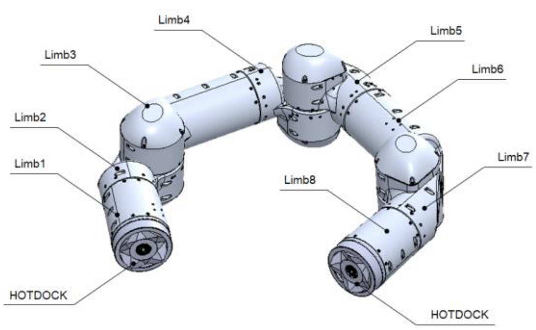

Fig. 5. Limb description for the MOSAR-WM.

- End effectors (HOTDOCKs): Each extremity of the walking manipulator is equipped with a Standard Interconnect (SI), namely HOTDOCK as illustrated in Fig. 5. These interfaces allow the robot to relocate, since the arm can be attached to a supporting structure on both sides.

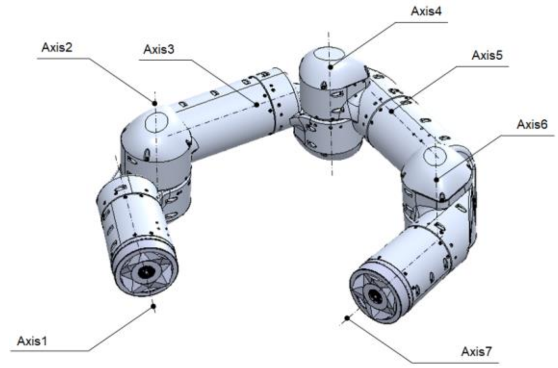

Fig. 6. Axis definition for the MOSAR-WM.

- Avionics: In order to perform motions, control its robotic joints and receive/forward power and data through its structure, the walking manipulator is equipped with independent avionics as illustrated in Fig. 7. Each motor is driven by a dedicated joint controller (driver) while the control of the WM displacement at arm level is performed by an embedded computer called Walking manipulator controller (WMC) running a real time operating system.

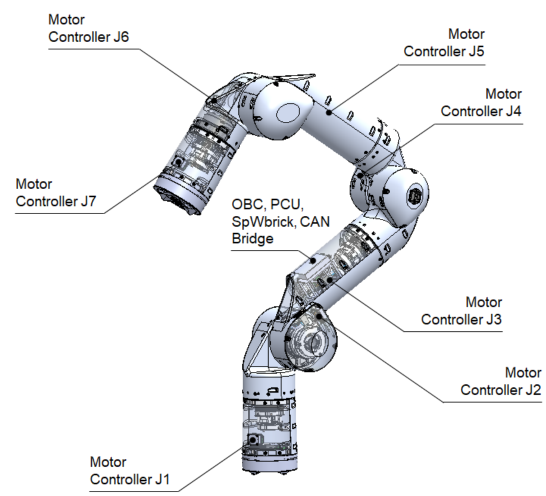

Fig. 7. Integration of the avionics inside MOSAR-WM.

All the motions of the WM are mainly based on two types of elementary actions:

- Transfer motion: it is the action to move the WM free end-effector from its initial position to a target position in joint space. It is typically used for coarse collision-free motions of the WM during the different operations. The first step consists of configuring the WMC in Position control mode, which is then replicated to the configuration of the joint drivers. Then the joint transfer trajectory is sent by RMAP command on the SpaceWire bus to the WMC, that interpolates the sequence of points and define the successive position set-points for the joint drivers. Based on the feedback of the joint sensors Telemetry (TM), the WMC confirms to the spacecraft On-Board Computer (OBC) when it reaches the goal position.

- Approach motion: it is the action to perform the final approach of the WM end-effector to reach the position ready for the connection of the end-effector SI to the payload or satellite bus (also equipped with a SI). A similar motion is also applicable when a spacecraft module is manipulated by the WM to align with another module and/or the satellite bus. The motion is based on a Cartesian trajectory in order to ensure as much as possible a suitable approach angle. In order to mitigate potential initial alignment errors, an impedance control scheme is applied to enable the guidance using the form fits of the SI, by estimating the contact forces using the joint torque sensor. The first step consists of configuring the WMC in impedance control mode, which is then replicated in the configuration of the joint drivers. Then the Cartesian trajectory is sent by RMAP command to the WMC, which performs kinematic conversions and dynamic computations to derive the required set-points for the joint drivers. Based on the feedback of the joint sensors TM (position, torque), the WMC iterates and updates the set-point until the SI TM confirms their proper alignment. The SI are then ready for latching/connection. This information is confirmed to the spacecraft OBC through the RMAP TM (either from the WM end-effector SI or the satellite module SI), which then sends the command to stop the process. In order to ensure proper contacts of the surfaces, it is also possible to have a local validation of the alignment in the WM itself by using the estimated contact force.

3. Mechatronic Subsystems

This section describes the main mechanical subsystems developed and embedded in MOSAR-WM: the standard interfaces and the motor joints.

4.1 MOSAR-WM end-effectors

The two tips of the walking manipulator are equipped with a SI, namely HOTDOCK, depicted in Fig. 8.

HOTDOCK is an androgynous standard robotic mating interface, developed by Space Applications Services NV (Belgium), supporting mechanical, data, power and thermal transfer. It is primarily designed to allow on-orbit modular assembly and reconfiguration of spacecraft elements. HOTDOCK simplifies the replacement of failed modules and allows for payloads swapping. At the same time, HOTDOCK provides chainable data interfaces for multiple module configurations.

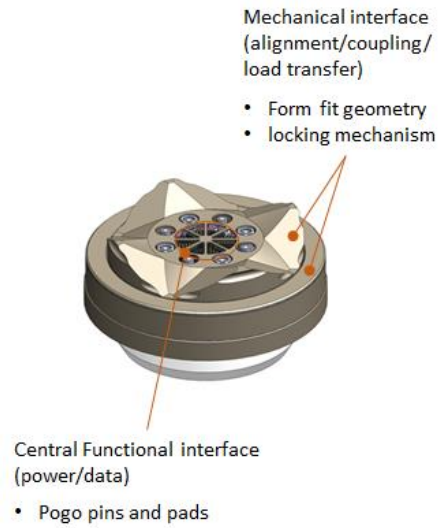

Fig. 8. HOTDOCK standard robotic mating interface.

HOTDOCK features the following coupling elements:

- A mechanical interface that provides:
  - alignment;
  - coupling/connection;
  - mechanical load transfer capability.

  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;

HOTDOCK embeds its own controller for local management (actuator, sensor, TM/TC communication) and rear connectors harnessing giving access to the power/data interface pins and the internal controller/powering of the device.

Key characteristics of HOTDOCK are summarized below:

- TRL: 4
- mass: 1.5kg
- approach admissible misalignment: +/-15mm and 10 degrees
- maximum approach angle: 60 degrees
- coupling admissible misalignment: 2mm
- coupling time when positioned: 20-30sec

- Maximum voltage: 120V
- Maximum current: 20A
- Maximum data rate: 200Mbit/s

4.2 MOSAR-WM joints

Each joint of the walking manipulator is equipped with a rotary hollow shaft actuator for enabling cable routing inside the arm.
The design of the joints is based on the following components:

Motor:
- Frameless Brushless DC (BLDC) motor. This type of motor offers the following features: design flexibility, hollow shaft, high torque density and compactness.

Reducer:
- Strain wave gear to transmit the required output torque. This type of reducer offers the following features: backlash-free, extremely high positioning accuracy, excellent repeatability, high torque capacity, high efficiency, high ratio in a compact and simple design.

Sensors:
- Magnetic Incremental encoder to provide an accurate motor shaft position. Used for the commutation and input speed control.
- Magnetic Absolute encoder to provide an accurate output shaft position.
- Torque sensor to provide an accurate measure of the output shaft torque. Used for the compliance control of the arm.
- Temperature sensor to monitor the temperature of the motor.

Safety:
- Electromagnetic brake mounted upstream the reducer to ensure a maximal braking torque.
- Electrical and mechanical end-stops mounted on the structure to respectively notify end positions of the joints and block mechanically the joints if needed.

Guiding:
- Precision Bearings to guide accurately the motor and output shafts, and also carry the loads with a high stiffness.

Two actuator sizes, depicted in Fig. 9, have been designed to fulfil the requirements linked to the Earth demonstrator operations.

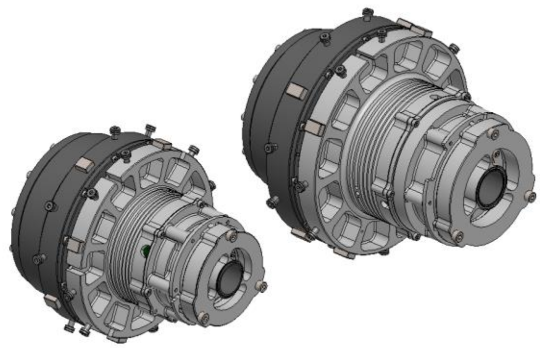

Fig. 9. Joint drive units – elbow/wrist (left) and shoulder (right).

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

4. Avionics & Electrical Architecture

Fig. 10 describes the detailed WM avionics and electrical architecture. 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 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.

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

- SpaceWire bus for “high level” non-deterministic 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 Architecture

In the MOSAR application, the WM is connected to the spacecraft OBC through a chain of SpaceWire links. This might introduce unpredictable latency affecting the impedance control of the arm. Impedance control is needed to press the standard interfaces together, mitigating the possible misalignments to enable a successful locking of the mechanism. This is handled locally by the WM Controller, which reads the torque measurements and commands the joints at a very high rate

The software running on the WMC is depicted in Fig. 11. It consists of three branches, each of them associated with a specific data bus of the robot:

- The TMC Engine is the software module in charge of the SpaceWire bus interface and performs the conversion of the high-level commands received from the spacecraft OBC through RMAP in the appropriate low-level commands required for the control of the WM arm and the HOTDOCK end-effectors.

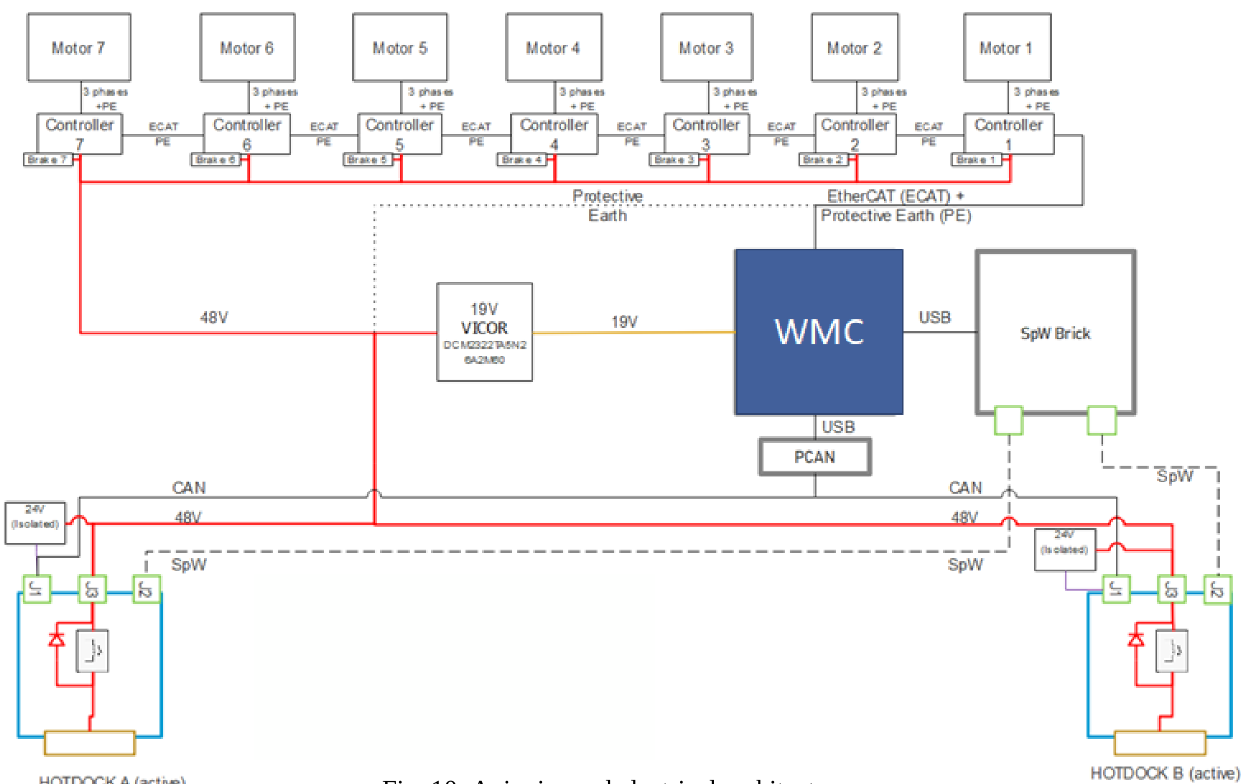

Fig. 10. Avionics and electrical architecture

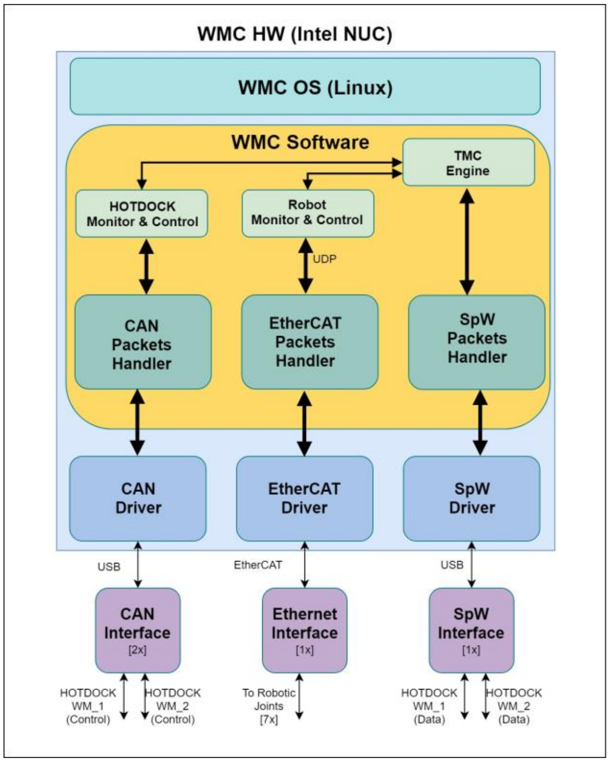

Fig. 11. Software architecture

- The Robot Monitor and Control software module is in charge of the management and control of the robotic arm. It is interfaced with the EtherCAT handler, which is based on the open source EtherLAB Master library. The EtherCAT handler runs in real-time, to ensure good performances of the control algorithms. Specific attention is given to limit the jitters and delays in the communication (e.g. real-time patch, CPU isolation….).

- The HOTDOCK Monitor and Control software module is in charge of the management and control of the two HOTDOCK end-effectors of the arm that are interfaced to it through the CAN bus.

6. Robot 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 [6].

The Impedance Controller has two modes of operation. The first one is in Cartesian space, which sets the desired impedance at the tool centre 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 parameters which define the compliant behaviour [7].

Cartesian impedance control achieves a desired dynamical relationship, the impedance, between external forces and movements of the robot. This is important for the WM in order to cope with possible inaccuracies and to ensure compliant interaction with the environment. This is possible thanks to the torque interface available in the WM. Indeed, the Cartesian impedance control takes as input a desired position and orientation in the Cartesian space, often referred to as virtual equilibrium, and computes the generalized 6 degrees of freedom forces (i.e. three translational forces and three rotational torques). By applying the Jacobian transformation, these generalized forces are then transformed into joint space, a torque vector with seven elements. This torque vector is the input to the joint torque controllers. The torque controller ensures that the desired torque is commanded into each joint. By virtue of the torque sensors, located at each joint, inertia shaping is possible. Indeed, thanks to the torque controller, the apparent inertia of each joint is scaled down, thus maximizing the performance of the robot.

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. 12; it includes all the components to control the walking manipulator (WM) 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).

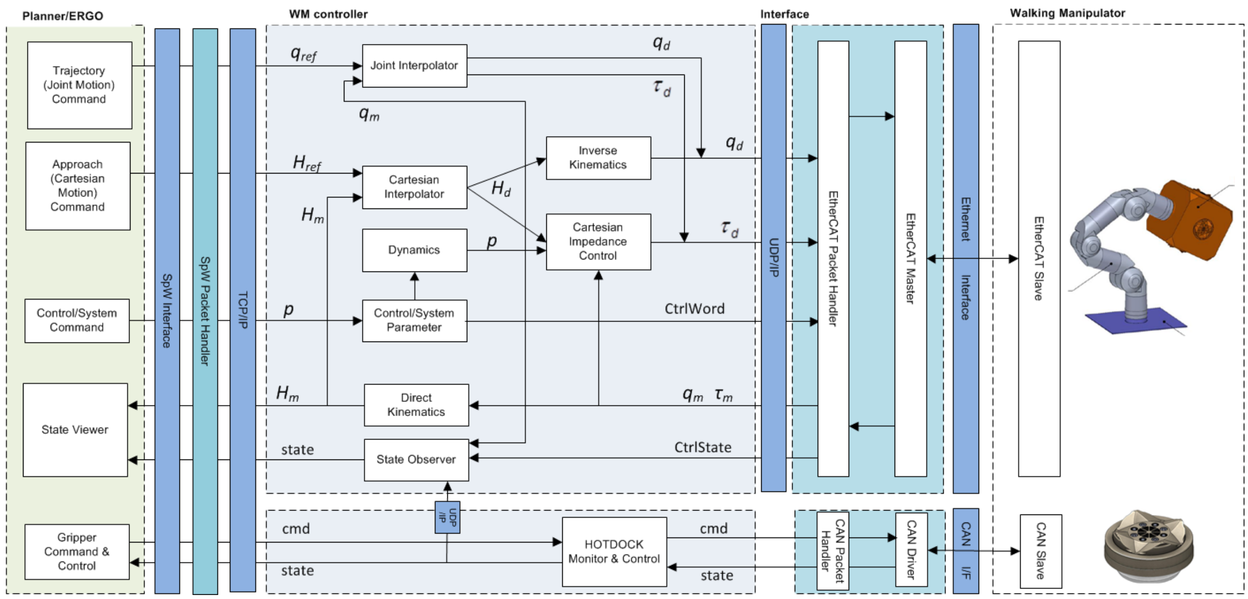

Fig. 12. Robot control architecture

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. 12 also shows the interface to the planner. At 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. Primary Results

As part of the detailed design and early MAIT phases of the MOSAR project, one elbow joint (Fig. 13) and the HOTDOCK interfaces (Fig. 15) have been manufactured, assembled, integrated and tested successfully. They have been interfaced with the avionics components to validate the first version of the control software.

The elbow joint prototype has been integrated in a dedicated 3D printed prototype casing, see Fig. 14. Early tests of position and torque controls have also been successfully performed to validate the accuracy and compliance behaviours or the motor joint.

In parallel to the development of the MOSAR-WM motorization, successful integration of HOTDOCK standard interfaces has been performed (see Fig. 15), validating the full functionality of the device when executing the docking and deploying the central functional interface [8].

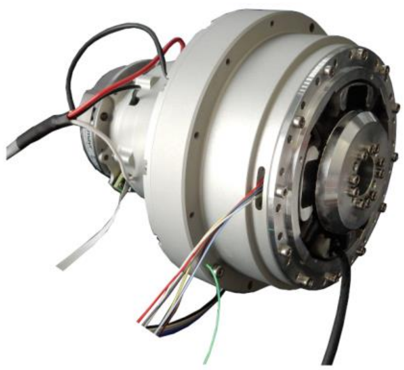

Fig. 13. MOSAR-WM Robot Joint.

Fig. 14. MOSAR-WM elbow prototype.

Fig. 15. HOTDOCK Standard Interface.

8. Conclusion

This paper introduced MOSAR-WM, a relocatable robotic manipulator for future on-orbit applications. In comparison to other robotic manipulator concepts for future on-orbit applications, MOSAR-WM tackles modular missions related to assembly and reconfiguration of satellites, coupled with the paradigm of standardisation of spacecraft modules. MOSAR-WM benefits from an innovative multidisciplinary design (mechanics, avionics, electronics, software and control) for performing manipulation tasks as well as relocating itself over the spacecraft structure. First MAIT of mechatronic subassemblies and key technologies of the MOSAR-WM, motor joint and HOTDOCK standard interface, have been successfully performed. Future work will be focused on performing the complete hardware and software integration as well as testing the MOSAR-WM within the MOSAR demonstrator. In parallel to this activity, the approach of relocatable robotic systems using standard interconnects is extended through the ESA project MIRROR, depicted in Fig. 16, where a multi-arm installation robot for on-orbit large assembly is being developed.

Fig. 16. Artist representation of MIRROR primary concept.

Acknowledgement

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