DESIGN AND IMPLEMENTATION OF THE LIGHTWEIGHT ADVANCED ROBOTIC ARM DEMONSTRATOR (LARAD)

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ABSTRACT

Beyond the current ExoMars programme, the European Space Agency (ESA) is investigating a range of technology developments and exploration mission opportunities leading to a future Mars Sample Return Mission (MSR), a critical next step in the exploration of Mars. To fulfil their scientific objectives, all of these missions require an arm with a long reach capable of performing a variety of tasks in stringent environmental conditions, such as low gravity sampling and precise sample handling and insertion. As part of an activity co-funded by the UK Space Agency, a consortium of UK companies has developed LARAD, a Lightweight Advanced Robotic Arm Demonstrator to address some of the underlying challenges related to both the design as well as operation of long arms. This paper describes the current state-of-the-art in planetary robotics and provides an overview of the top-level architecture, mechanical and mechanism design, electrical and software architectures for the LARAD demonstrator.

1. INTRODUCTION

The design and operation of planetary robotic arms is extremely challenging and unique problem. A number of missions have successfully explored planets [1], however only a handful of robotic arms have been designed, flown, and operated. Planetary surface robotics systems therefore belong to a class of their own, where robustness and minute accuracy must be achieved with limited mass, power, and processing capabilities [1]. The Mars Robotic Exploration Preparation (MREP) programme [2] already addresses the development of some of the key underlying technologies, including some aspects of instrument placements as part of the DELIAN project; with a 1m-long robotic arm [3]. Since the inception of these projects, a range of potential applications have been identified which require longer, but lightweight and capable robotic arms. A number of future missions will require an arm capable of performing a variety of tasks in stringent environmental conditions such as low gravity drilling (e.g. Phobos Sample Return [4]), or precise sample handling and insertion (e.g. MSR). This project positively complements current developments to address a number of operational scenarios beyond the envelope of these past projects.

The Scope of LARAD is therefore to address:

1. The design of a demonstrator based on a number of novel and state-of-the-art UK hardware and software technologies, leading to the development of a representative model of a flight robotic arm.
2. The provision of a hardware and software platform that can be used to support a range of projects to plan and rehearse operation of specific payload (e.g. sampling) with full mass instrumentation.
3. The provision of validated hardware and software simulation models of the arm.

2. DESIGN ARCHITECTURE

Review of past and future missions highlighted the need for a versatile design that can accommodate a range of mission scenarios. This development focused therefore on the development of a generic solution to a range of applications while addressing specific scenarios identified in Fig. 1, these include:

- The deployment of a payload element with a mass up to 6kg at 2m, in 1g.
- The dextrously operation (i.e. in most orientations) of a 4kg end-effector at 2m, in 1g,
- The application of a 15N reaction force at the end effector at 2m for tool operation e.g. drilling
- The precise insertion of tools, containers in the dextrous workspace of the arm.

As a demonstrator operating in 1g, the arm must manage a range of conflicting requirements. On the one hand, it must provide a long reach, stow compactly and minimise mass. This will drive the kinematic design of the arm, the design of its actuators and structural elements. On the other hand, it must be dextrous and precise enough to perform insertion operations while being able capable of handling significant mass at 2m. This will also influence the kinematic design as well as drive the sizing of the arm structure and torque requirements, especially for operation in 1g.

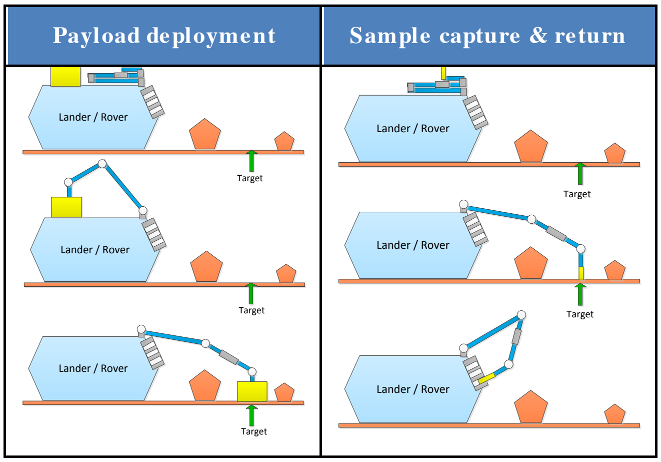

Figure 1. LARAD reference scenario

The LARAD demonstrator consists of three major parts:

- A representative Ground Segment element consisting of an Operation Planning Software used to plan and rehearse arm trajectories.
- A representative Planetary Robotic Arm system consisting of:
  - o An On-Board Computer (OBC), tasked to translate the trajectories from Ground to joint-space control for the actuation of the individual joints of the arm.
  - o The Robotic Arm (RA) itself, comprising a number of joints, limbs and an end-effector interface providing the necessary mechanical and electrical support.

Table 1. Baseline summary

Criteria	Baseline
Configuration	6 Degrees of Freedom (DoF)
Motors	DC Brushless
Sensor	Zettlex inductance sensor
Gearbox	Harmonic Drive, spur gear and planetary gear chain
Bearings	Angular Contact
Joint Structure	ALM Titanium
Limb structure	Titanium Silicon Carbide (TiSiC)
Motor control	In-joint custom-made electronics
Data harness	CANbus

Kinematic design

The selected kinematic design is based on a 6DoF (Degrees of Freedom) configuration with a spherical joint, allowing a good range of motion while enabling the use of a closed-form inverse kinematics solution to be derived analytically. This allows the implementation of the inverse kinematics equations on-board without requiring the need for iterative algorithms. To date, most of the planetary robotic arms that have flown are designed with up to 5DoF to address specific surface operations. The design and implementation of a 6DoF arm, with an additional joint in line with one of the limbs, provides an extended range of motion enabling new operations to be investigated.

3. MECHANICAL ARCHITECTURE

As part of the key design drivers affecting the design and implementation of the arm, the total deflection of the manipulator was selected as being critical. As such, the structural design and joint design aimed at minimising the inherent deflection, maximising deflection knowledge, while still aiming at a low mass.

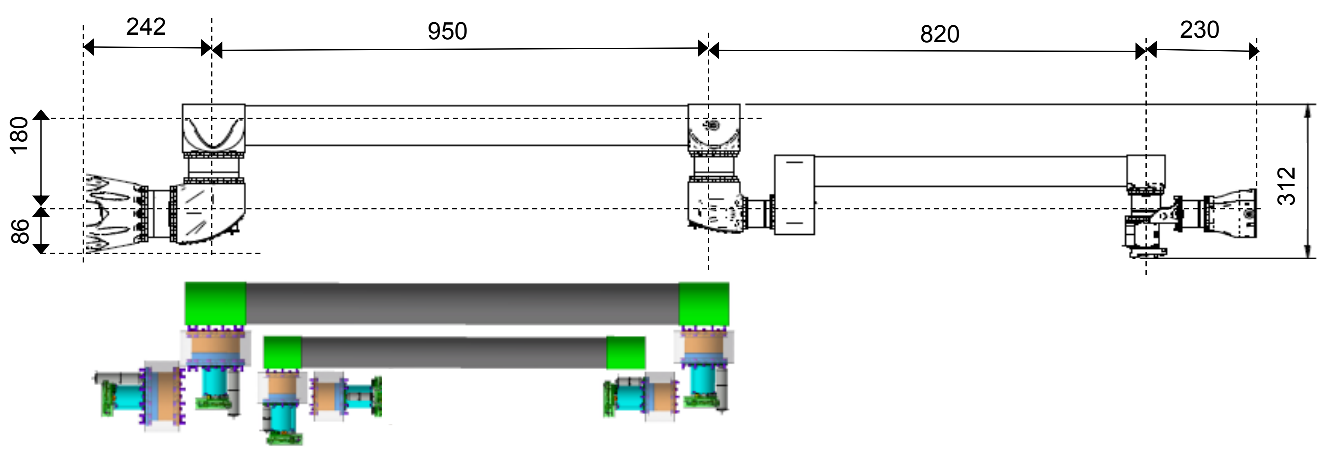

Figure 2. LARAD kinematic design, deployed (top) and stowed (bottom) configuration

This approach was selected to provide a stiffer arm that can be operated without necessarily implementing visual servoing, but could still implement mechanical impedance though joint control. The residual deflection will be compensated through a number of techniques including gravity compensation. Focussing on mass optimisation, rather than deflection, would result in a lower arm mass, but in increased deflection at 1g.

Titanium ALM structures

Based on past developments, the project provided a unique opportunity to investigate the use of two key new manufacturing methods, namely optimised Titanium ALM and the used of Titanium/Silicon carbide (TiSiC) metallic composites. The use of ALM titanium for the joints interfaces allowed the use of optimisation techniques to minimise the mass of the parts for a given range of load cases. This topological optimisation process starts with 1) the identification of the key interfaces and allowable volume, then 2) the identification of the load paths for each load cases and their superposition onto a consolidated load path model, that is use to 3) drive the design of a new CAD model that follows the design intent of the optimisation process. The ALM part design concludes with a final FEA to check it fulfils the original stress and deflection requirements.

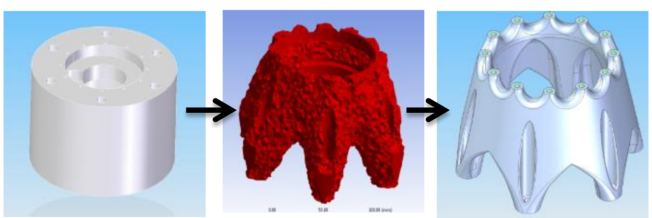

Figure .3 ALM topology optimisation process; interface and volume definition (left), superimposed load paths (centre), resulting final part (right)

The analysis of the ALM structures resulted in the design of a set of organic-looking parts, each with unique geometrical features. To maximise the accuracy of the machined parts, an investigation was conducted to identify the best manufacturing process adapted to each of the part to produce. Part size, geometrical features, local curvature, surface finish, all had a part to play in the selection of the specific ALM process to be used for a specific part. As such, both Laser Sintering (SLS) and Electron-Beam Machining (EBM) were used to produce the 9 ALM parts, with sometimes multiple tries necessary to hone in on the perfect print. As part of the post-machining, each part is subjected to a Hot Isostatic Process (HIP) to relieve the internal stresses of the part before being scanned and analysed to compare the CAD against the as-built geometry to further evaluate the suitability of each of the ALM processes for a specific part. The parts were then post-processed through vibration grinding to improve the surface finish.

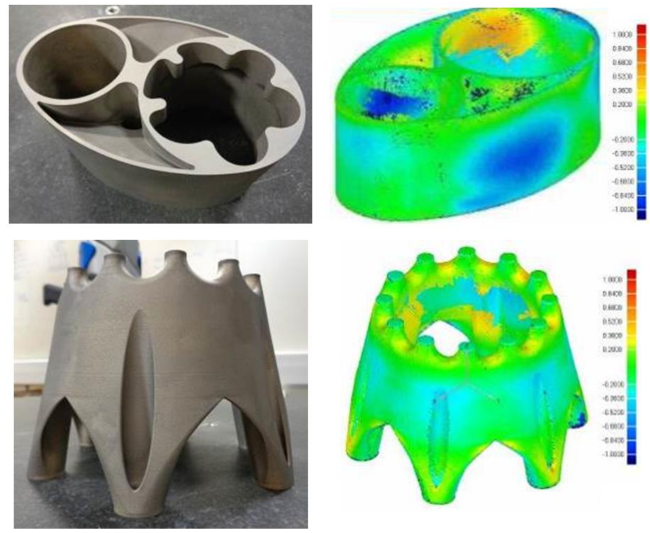

Figure 4. ALM builds (left), and metrology investigation (right)

The ALM process is in practice similar to casting, where the volume is close to a net shape, but still need further machining of the key interface prior to any integration. The design must also accommodate features to facilitate this machining, including reliable datum planes, extra feature to clamp parts, etc. A rule of thumb would see the cost of a part being 50% ALM manufacturing, 50% final machining cost.

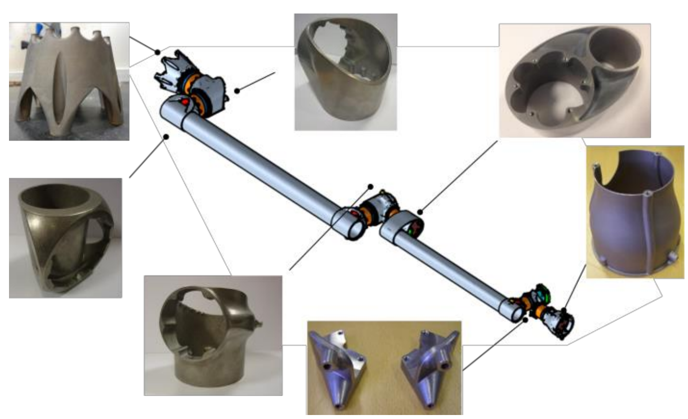

Figure 5. ALM parts along the LARAD manipulator

TiSiC metallic composite structures

The manufacture of the limbs required the use of a range of processes to make the Titanium Matrix Composite (TMC) tube first, mate it with the ALM parts and perform the diffusion bonding between the parts. A Hot Isostatic Process (HIP) is used to create the tube out of multiple layers of titanium foil and silicon carbide fibres around a solid steel mandrel. The ALM parts are then dressed for mating with the ends of the tube and a temporary electron-beam weld is performed in vacuum to enable the diffusion bonding of the two parts during another HIP cycle. As the part go through each of the stages, the accuracy of the mechanical alignments of the various elements is critical to minimise any post machining of the interfaces.

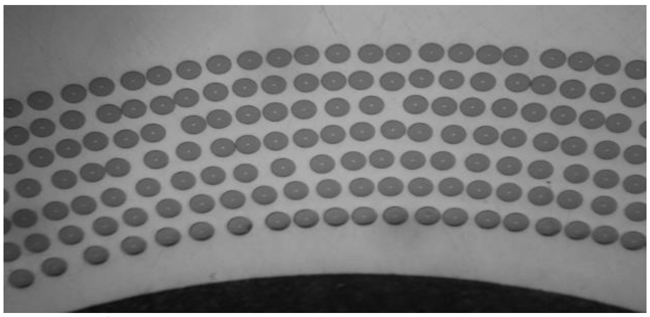

Figure 6. TiSiC metallic composite transverse cut, SiC fibers (dark grey) embedded in a Ti matrix (light grey)

Similar to the manufacturing of the ALM parts, a great deal has been learnt about the end-to-end process, including its challenges, that led to the rebuilding of the limbs at different stages of the manufacturing and integration process.

The TiSiC metallic composite structure used for the limbs possess both high strength to weight ratio and stiffness, thus providing a low mass, stiff structure. This combination aimed at minimising the inherent deflection of the arm in operation and is the main component of the ~2m limbs. The first limb consists of a tube 80mm diameter with 8 ply of 140µm SiC fibers. Similarly, the second limb consists of a tube 60mm diameter with 4 ply of 140µm SiC fibers. The combined limbs are anticipated to provide 3.10mm deflection for a total mass of 3.26kg in the worst loading case with the tip loaded with 6kg (+10% margin). Testing on the first limb up to 250 N, shows good agreement between the measured deflection (1.75mm) with the modelling of these composite structures (1.79mm calculated).

Diffusion bonding

Once manufactured, the ALM Ti joint interfaces are joined through diffusion bonding directly to the TiSiC metallic composite (in what is believed to be a first in the industry). This process results in a monolithic Titanium structure incorporating both parts, reducing therefore the number of mechanical and thermal interfaces in the arm.

Figure 7. Integrated structures of the first (left), and second limbs (right)

This process would be of interest in typical lunar scenarios, or similar setup where half the manipulator is in direct sunlight and the other half in the shade, leading to large thermal gradients across the arm structure (e.g. ~200+ degrees). The structure created through this process provides a single complex Titanium piece, with a view to improve deflection and accuracy of the manipulator in high temperature gradients when compared to the use of multiple heterogeneous materials with different coefficients of thermal expansion (CTE).

4. MECHANISMS ARCHITECTURE

As a platform meant to be operated in 1g, the torque requirement at the base is more than an order of magnitude larger than at the end effector. A single joint design/size is impractical and must be optimised. To target a lightweight arm design, different sized joints need to be implemented along the arm.

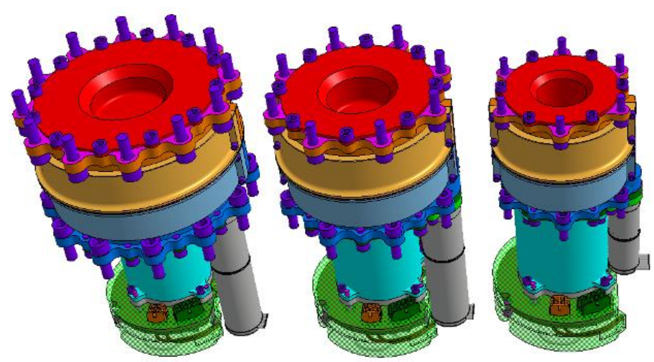

Figure 8. Modular Actuation Cores (MACs), resulting joint designs

For the purpose of the LARAD implementation, three different-sized joints are designed based upon the worst-case joint torque requirement at each joint. Two large-sized joints are placed at the base of the arm where the most torque is needed. One medium-sized joint is placed in the middle section of the arm and three small sizes are at the tip of the arm. The joints can therefore be designed with the same architecture and electronics, creating a family of joints that can be readily re-used to create alternative arm configurations including smaller sizes or lower DoF solutions. These self-contained actuator units are referred to as Motion Actuator Core (MACs)

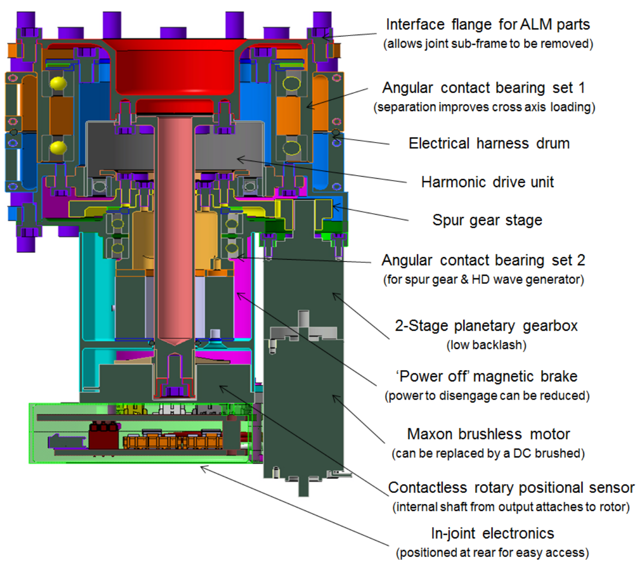

Figure 9. Internals of a MAC

The MACs are powered by Maxon DC brushless motors, providing a good power to weight ratio and with a strong heritage for space and planetary applications. The gear chain is based on a set of planetary gears (2-stage), spur gear (4:1) and harmonic drive (100:1). The spur gear stage is used in the joint design to offset the motor from the centre line, creating a volume behind the harmonic drive to mount a brake unit and a sensor. To prevent the arm from sagging under gravity when unpowered, or to limit power consumption to the arm during extended duration during tool operation, the magnetic brake is applied to the input of the harmonic drive. The location of the brake takes advantage of the gear reduction provided by the harmonic drive, so that the brake can be much smaller and benefits from low backlash characteristic of the harmonic drive. The joint is therefore capable of holding its position unpowered for loads beyond the operating joint torque figure.

A contactless inductance sensor from Zettlex Ltd provides high resolution position feedback of the joint output. The technology provides very high resolution sensing (up to 24bits), ease of integration, and graceful degradation while being rugged and unaffected by dust and metal swarf ingress. The sensor allows for relaxed positioning of the rotor to the stator, without any degradation of the resolution performance.

Figure 10. View of the Zettlex position sensor prototype, rotor (left), stator (right)

To minimise backlash and cross plane deflection, angular contact bearing is used to increase the joint stiffness. The joint output bearing design determines the stiffness performance of the joint in all axis's except the joint rotation axis where the harmonic drive is having the most significant impact. The joint design features two angular contact bearings in a back-to-back configuration.

Table 2. MAC family sizes performance summary

	Small	Medium	Large
Mass	0.87 Kg	1.35 Kg	2.01 Kg
Diameter	80 mm	100 mm	120 mm
Powered torque	21 Nm	129 Nm	270 Nm
Unpowered	50 Nm	150 Nm	300 Nm
Max rate	0.7 rpm	0.9 rpm	0.4 rpm
Min rate	0.015 rad/s	0.03 rad/s	0.01 rad/s
Power rating	5 W	15 W	25 W
Resolution	3 mdeg	3 mdeg	3 mdeg

The resulting joint designs cover the 3 torques requirements from 21 Nm for the small joint, 129Nm for the medium joint to 270Nm for the large joint. Similarly, based on the kinematic analysis, the joint speeds have been optimised to facilitate specific operations such as instrument placement and insertions that will require coordinated motion of all the joints. The speed of the joints therefore has been set for the 3 sizes to 0.7rpm, 0.9 rpm, and 0.4 rpm, for the small, medium and large joints respectively.

Note that for a flight arm, pending on the verification and validation philosophy, the current joints could be oversized if testing in 1g with full payload mass is not required. The resulting joints would therefore be smaller and more compact.

Figure 11.Integrated MACs (w/o electronics) with some ALM parts, large (left), medium (centre), small (right)

The manufacturing and integration of the actuators started with the production of a prototype that enabled the verification of some of the characteristics of the joint, the identification and correction of minor design issues while providing a test article for the development of the electronics firmware and the OBC control system. Once integrated, the MACs were subjected to a number of low-level tests to verify some of their inherent characteristics including position knowledge, minimum increment, and rates range. As such, the MACs were found to resolves around ~0.002deg thanks to the inductance sensor output. The minimum positional increment during open loop tests on the breadboard joint was found to be ~0.003 degrees (0.05 mrad). These characteristics will be re-visited over the course of the forthcoming characterisation activities at joint and arm levels.

5. ELECTRICAL ARCHITECTURE

The electrical architecture significantly drives the design and implementation of the arm as well as the selection of the technological solution implemented as part of this concept. Early trade-offs were performed to evaluate the benefits of centralised and decentralised motion control against the size and complexity of the harness routing, motor technology selection, joint mass, modularity and scalability. Ultimately a distributed setup was selected with in-joint drive electronics to enable the use of DC brushless motors (worst-case harness scenario and more reliable in vacuum than DC brushed motor) while minimising the harness size and sensors noise. This option provides the minimum harness solution and enables the design of identical joint electronics without the need for specific customisation. The electronics are then daisy-chained and can implement redundant buses to and from the OBC and the payload as needed. This architecture readily allows the implementation of various DoF arms with the same joints design.

Electronics

As well as functionality and modularity, one of the key design drivers for the electronic module is volume. With the electronics module incorporated into each joint on the arm, it must be implemented into a small enough volume, suitable for all the joint sizes. The module has been designed as two PCBs, one with the main electronics and the second with the power and databus connectors. The size of the lower PCB has been chosen to maximize the available component mounting area while still fitting within the diameter of the joint. The entire electronics module is mounted inside a case to provide sealing from dust contamination and allow the electronics to exist as a standalone unit separate from the joint, if required. The design of the mechanism allows the volume of the electronic board to grow if necessary, allowing the module to be split in two or three PCBs as the design evolves from a COTS to a more representative flight implementation.

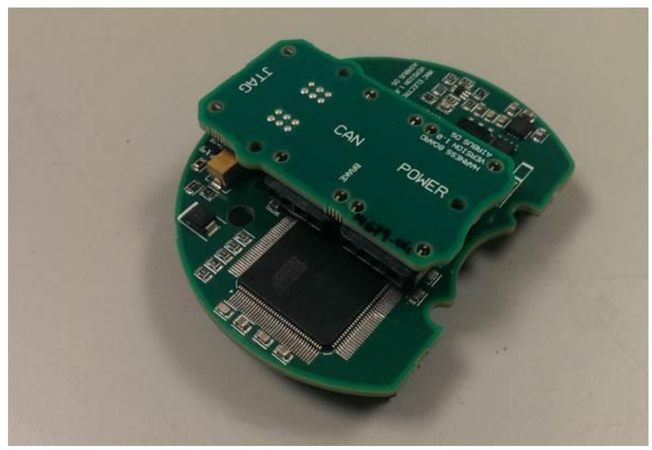

Figure 12. Fully assembled electronics board

The electronics for the LARAD arm have been designed around a distributed processing architecture. For LARAD, each joint is given ownership of its own drive and sensors, with the high-level control and synchronisation being provided by a central unit (On-Board Computer - OBC). This approach provides a dramatic reduction in the amount of harness required to route the information along the arm. All low-level control is provided locally, while only high-level commands are being transmitted along the arm. In the current setup, each joint electronics module provide actuation and sensory functions including: control of the motor and brake, reading of the local sensors for position and motor current draw, and communication via the CANbus to receive commands and provide telemetry to the OBC.

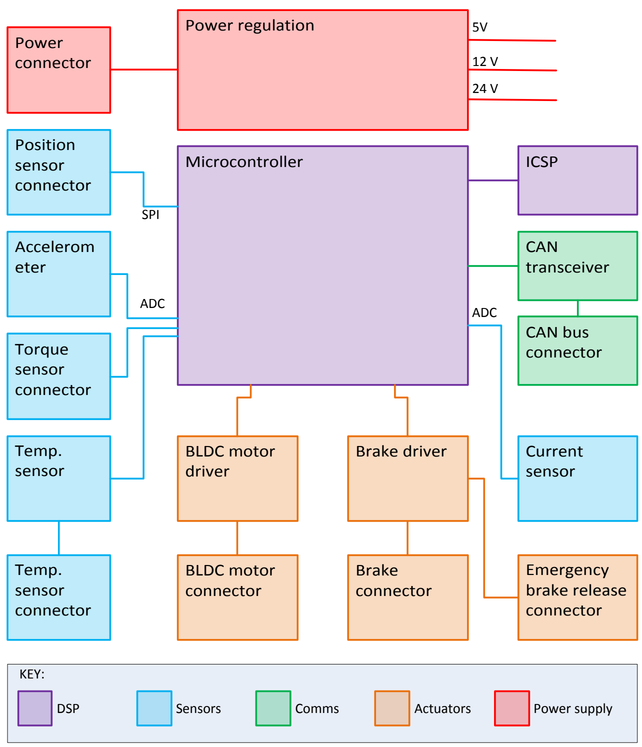

Figure 13. Architecture design for control electronics

Databus

To date CANbus has been selected as the main databus for the manipulator with speeds up to 1Mbps, one bus being dedicated to the MACs and the other servicing the end-effector and its payload. A separate study investigated the use of SpaceWire as the main databus through the arm, servicing both the actuators and the payload through a robust and fault-tolerant network. Different network topologies have been assessed in term of implementation complexity, latencies and fault recovery. The design of the electronics and its harness routing enables the removal and update of the electronics and harness fairly readily without the dismantling of the arm and its joints.

Harness management system

The robotic arm implements a harness management system that deals with the routing of the cables during the joint actuation. The selected concept, patented by Airbus, relies on a sliding loop of cable around the outside of the joint and allows it to physically cover in excess of +/- ~200° of motion. However, for practical reasons, the control of the joint limits it to close to +/- ~178°. However, because the joints do not implement hard stops, they can be reconfigured differently pending on the desired arm workspace or deployment needs (e.g. rover/lander/spacecraft configuration).

6. ON-BOARD COMPUTER AND SOFTWARE

The LARAD On-Board Computer (OBC) is based on a PCI-104 stack enclosed in a rugged aluminium case, which provides dual internal shock and vibration protection (NEMA4 rating, equivalent to IP66). The LARAD OBC fulfils several roles:

- Interfaces with the Ground Control System (GCS) (receive TC, transmit TM);
- Interfaces with the arm sensors and actuators;
- Mediation of the execution of the TCs received from the GCS by the OCS;
- Failure Detection Isolation and Recovery (FDIR);
- Facilitation of the configuration of other components of LARAD's data handling system.

The LARAD On-board Software (LAROS) uses the Robot Operating System (ROS) middleware. LAROS, instead of being implemented as a monolithic architecture has therefore been split into smaller specialist software modules (packages), each with clearly defined purpose, responsibility, and interface. These modules are implemented in C++ and can be evolved to better comply with typical flight software developments processes. To date, the overall OCS state-machine, Direct Motor Control and Joints Trajectory Tracking modes have been implemented. The other modes (e.g. EE Autonomous Placement Mode) have been preliminary designed and tested, however, their implementation will form part of future developments.

Ground Control System (GCS)

To plan and perform a range of complex operations, the arm requires a comprehensive operation and planning software suite that provides the end user with the capability to place the end effector precisely through a comprehensive GUI environment.

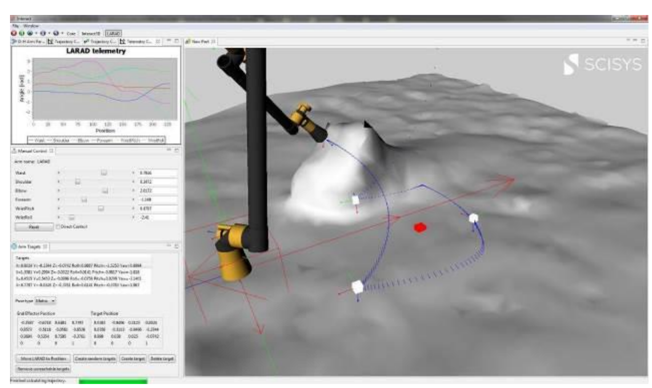

Figure 14. LARAD ground control system GUI

By modelling the arm's environment for collision avoidance and implementing point click target selection, complex placement operations can be possible: such as the placement of payload or the acquisition of a surface sample. The Ground Control Software system was built upon SCISYS Overseer Interact framework. It provides a convenient interface to manipulate the arm joint by joint or plan specific trajectories to a target. The GCS combines user interface, which is based on Overseer Interact that allows building plans for robots and monitors their execution, and a component to calculate obstacle-free path for the manipulator.

7. CONCLUSION

As a technology development activity, the LARAD project set itself a number of ambitious goals, integrating a wide range of new materials, manufacturing processes, sensors and design methods into a unique demonstrator. A number of generic hardware and software building blocks have been designed to address the needs of this project and beyond including scalable actuators, modular architecture (and databus) and operation planning.

Figure 15. LARAD fully assembled hardware

Throughout the process, a number of challenges have been experienced, each providing valuable lessons at each stage of the project, and across each constituting element of the arm. This allowed the team to fully capitalise on this development activity for future projects: new design methods have been devised; new ALM integration processes have been demonstrated, and a modular test framework has been setup.

The LARAD consortium produced an innovative system that aimed to provide a versatile platform to test and operate full-size payloads in a terrestrial setting. This will allow scientists and operation teams to develop first-hand experience of the planning and rehearsing of complex manipulator operations in a space or planetary context. As a demonstrator, the manipulator possesses the DNA of things to come, providing a stepping stone to address the design of future lightweight space arms, as well as a test platform to further develop the technology to address the needs of a range of future missions.

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