# LARAD – ARCHITECTURE AND IMPLEMENTATION OF A LIGHTWEIGHT ADVANCED ROBOTIC ARM DEMONSTRATOR FOR FUTURE SPACE AND PLANETARY APPLICATIONS

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ABSTRACT

To support a range of in-space and planetary activities, slender arms with a long reach are required to perform a variety of tasks in stringent environmental conditions (atmosphere/vacuum, thermal, dust, etc) such as surface sampling, dextrous manipulation of payload, tool or precise sample handling and insertion.
As part of an activity co-funded by the UK Space Agency (UKSA), 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. The 15kg terrestrial demonstrator is a 2m-long arm with 6 degrees of freedom. This arm is designed to deploy a payload with a mass up to 6kg in 1g or dextrously operating a 4kg end-effector at 2m. As a technological demonstrator, it uses an array of new manufacturing techniques and processes (optimised Titanium Additive Layer Manufacture - ALM), novel materials (Ti/SiC metallic composite), sensor (high resolution inductance sensor), and electronics. A modular joint design has been produced, featuring three mechanical sizes of joints, each with integrated low-level communication, motor drive and power conditioning.
The LARAD manipulator provides a unique representative platform to plan and rehearse operations with full mass payload and instruments in 1g without gravity offloading, removing the need for scaled-mass end-effector that would lose significant functionalities.
This paper focuses on the top-level architecture, the design of the arm and a discussion on the various subsystems before introducing the next development phases for this modular robotic manipulator.

## 1. INTRODUCTION

As part of the drive to explore and return samples from a range of planetary targets, the European Space Agency (ESA) is investigating a range of technology developments and exploration mission opportunities to the Moon, Phobos and Mars, leading up to a future Mars Sample Return Mission (MSR), the next critical milestone in the exploration of Mars. To fulfil their scientific objectives, all of these missions require slender arms with a long reach capable of performing a variety of tasks in challenging environmental conditions including surface sampling and precise sample handling and insertion. Similarly, a range of in-space activities such as in-orbit servicing, assembly and manufacturing require mass-efficient and capable systems to operate in space to perform a variety of manipulation operations including transfer and insertion of elements, and the precise placement of tools and end-effectors.

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 hardware and software technologies,
2) The development of a representative model of a flight robotic arm (i.e. laboratory arm with identified path-to-flight);
3) 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;

The following sections introduce the LARAD system from an architecture and implementation point of view, including the description of the various technologies used as part of the demonstrator.

## 2. OPERATIONAL CONCEPT AND ARCHITECURE

***Operational Scenarios and design drivers***
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 a specific strawman scenario allowing the manipulator to exercise some of its key functions, as shown in Figure 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. small drill
- The precise insertion of tools, containers in the dextrous workspace of the arm.

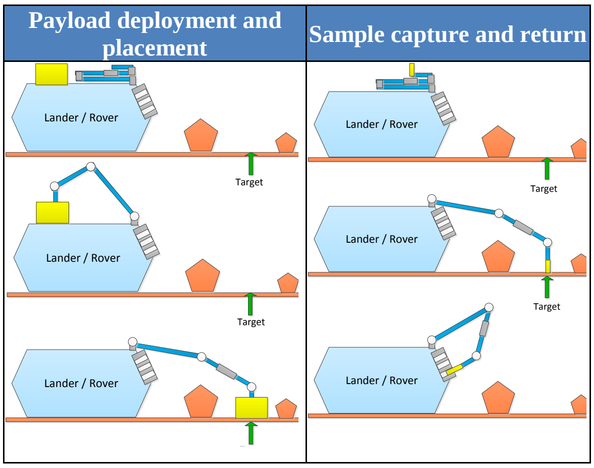

**Figure 1 - LARAD Reference Scenario**

The LARAD demonstrator consists of three major parts:
- A "Ground Segment" element consisting of an Operation Planning Software used to plan and rehearse arm trajectories.
- A representative Robotic Arm system consisting of:
  - 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.
  - The Robotic Arm (RA) itself. Comprising a number of joints, limbs and an end-effector interface providing the necessary mechanical and electrical support to the end-effector.

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, be dextrous and carry a sizeable payload at 2m. This will drive the kinematic design of the arm, the design of its actuators and structural elements. On the other hand, it must stow compactly, be precise enough to perform insertion operations, while minimising the mass of the system. 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.

***Kinematic design***

The selected kinematic design is based on a 6DoF configuration with a spherical joint, allowing a good range of motion while enabling the use of an analytical closed-form inverse kinematics solution. 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 to date have been designed with up to 5DoF to address specific surface operations [2]. 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.

***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 if centralised, more reliable in vacuum than DC brushed motor over extended periods) 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 and could in the near future make use of the Motion Control Chip (MCC) [3]/ MCC-X currently under developments by ESA.

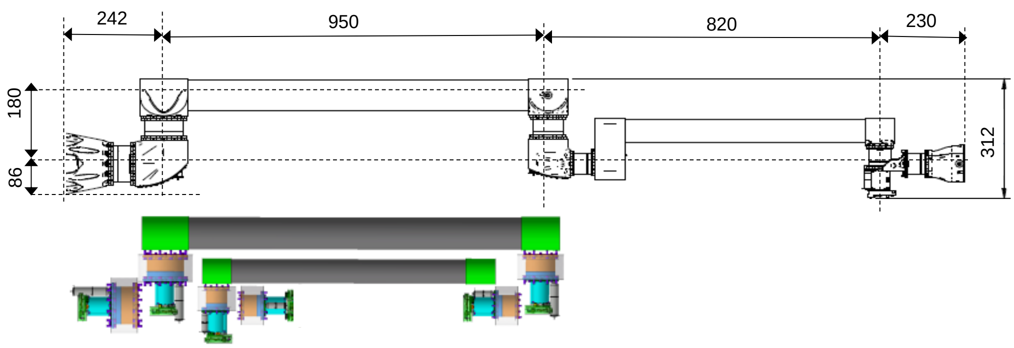

**Figure 1 - LARAD Kinematic design - Deployed (top) and stowed (bottom) configurations**

**Table 1 Baseline Architecture - Summary**

| Criteria | Baseline |
|---|---|
| Configuration | 6 Degrees of Freedom (DoF) |
| Motors | DC Brushless |
| Sensor | High resolution inductance sensor |
| Gearbox | Harmonic Drives and planetary gear chain |
| Limb structure | ALM Titanium and Titanium Silicon Carbide (TiSiC) |
| Motor control | In-joint custom-made electronics |
| Data harness | CANbus |

## 3. MECHANICAL SUBSYSTEM DESIGN

As part of the key design drivers affecting the design and implementation of the arm, the total deflection of the manipulator was selected to be the key design target. As such, the structural design and joint design aimed at: minimising the inherent deflection of the arm, maximising deflection knowledge, while still aiming at a low manipulator mass. This approach was selected to provide a stiffer arm that can be operated without necessarily implementing visual servoing, but could still implement mechanical impedance/compliance 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 Additive Layer Manufactured parts (ALM) and the used of Titanium/Silicon carbide (TiSiC) metallic composites.

The use of ALM titanium for the joints interfaces allowed the use of topological optimisation techniques to minimise the mass of the parts for a given range of load cases. This optimisation process starts with 1) the identification of the key interfaces and allowable volume, 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.

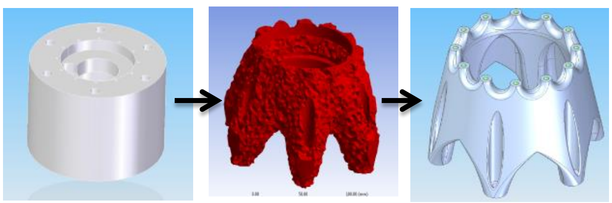

**Figure 2 – ALM Topology optimisation process - left- interface and volume definition, centre - superimposed load paths, right - resulting final part**

### *TiSiC Metallic Composite structures*

The Titanium Matrix composite (TMC) structures 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 fibres. Similarly, the second limb consists of a tube 60mm diameter with 4 ply of 140µm SiC fibres. The combined limbs are anticipated to provide 3.10mm deflection for a total mass of 3.26kg (~2m long) 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) and the modelling of these composite structures (calculated at 1.79mm).

### *Diffusion Bonding*

Once manufactured, the ALM Ti joint interfaces are joined through diffusion bonding directly to the TMCs (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. This process would be of interest in typical lunar scenarios, or similar setup, where half the manipulator is in direct sunlight and the other 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).

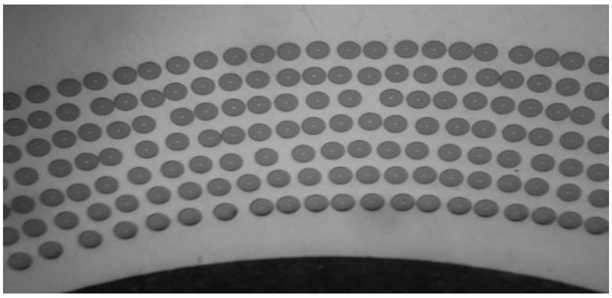

**Figure 3 - TiSiC Metallic Composite section - SiC fibers (dark grey) in a Ti matrix (light grey)**

## 4. MECHANISMS DESIGN - THE MOTION ACTUATOR CORES

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. For the purpose of the LARAD implementation, three sizes of joints are designed based upon the worst-case torque requirement at each joint. Two large-sized joints are placed at the base of the arm where the largest torque is experienced. Two medium-sized joints are placed in the middle sections of the arm and two small at the tip of the arm. The joints are designed with the same mechanical 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).

### *Architecture*

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, spur gear and Harmonic drive. The spur gear stage is used 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 to the arm during extended duration during tool operation, the magnetic brake is applied to the input of the harmonic drive. The joint is therefore capable of holding its position unpowered for loads up to the worst-case torque figures.

A contactless inductance sensor from Zettlex Ltd provides high resolution position feedback of the joint output. The technology provides high resolution sensing (up to 24bits, 17bits used here), ease of integration, and graceful degradation while being rugged and unaffected by dust and metal swarf ingress.

To minimise backlash and cross plane deflection, angular contact bearing is used to increase the joint stiffness. The bearing design at the joint output determines the stiffness performance of the joint in all axes 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.

### *Resulting Joints design*

The resulting joint designs, Figure 4, cover the 3 torques requirements from 21 Nm for the small joint, 129Nm for the medium joint to 270Nm for the large joint.

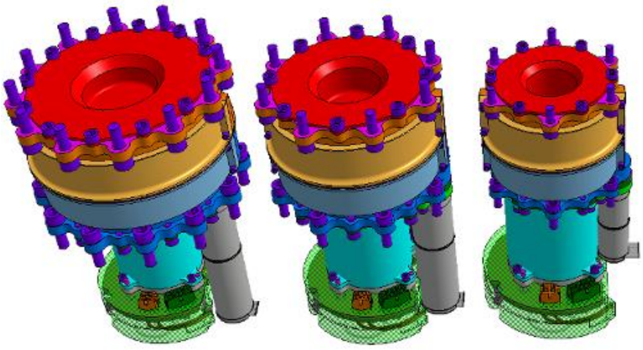

**Figure 4 - Modular Actuation Cores sizes**

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, if testing in 1g with full payload mass is not required, the current joints would be oversized. The resulting joints would therefore be smaller and more compact.

## 5. ELECTRICAL SYSTEM AND AVIONICS

### *Architecture & Design*

The electronics for the LARAD arm have been designed around a distributed processing architecture. Each joint is given ownership of its own drive and sensors (Figure 5) with the high-level control and synchronisation being provided by the 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. More details can be found in [1].

### *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

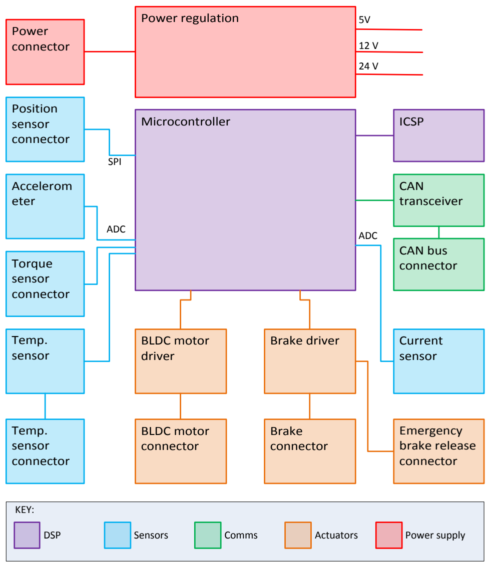


**Figure 5 - Architecture design for control electronics**

excess of +/- ~200° of motion. However, for practical reasons, the control of the joint limits it 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 for testing (e.g. rover/lander/spacecraft configuration).

***Databus***

Currently, CANbus has been selected and implemented 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 and combinations 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.

## 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). It fulfils a number of functions, including:

- 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.

In order to fulfil these function, the OBC currently provides data interfaces to the GCS through TCP/IP Ethernet, and the Joint Electronics modules, Force-Torque sensor (at the end of the arm), and the End-Effector through CAN bus. The OBC runs the On-board Software (OBSW), which hosts the On-board Control System (OCS) implementing the arm’s guidance, navigation and control.

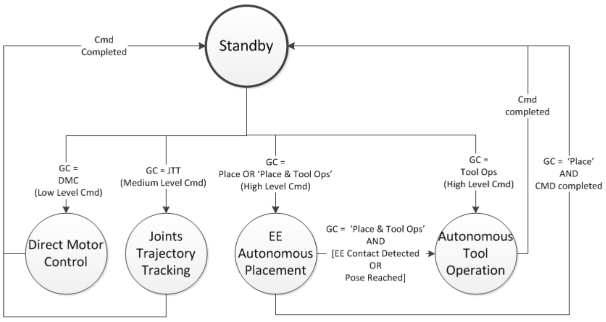


**Figure 6 – Onboard Control System state machine**

The LARAD On-board Software (LAROS) uses the Robot Operating System (ROS) middleware. However, LAROS has been split into a number of software modules (wrapped for use in ROS), implemented in C++ that can be evolved to comply with typical flight software developments processes.

***On-board Control System (OCS)***

Figure 6 illustrates the OCS top-level state machine where the following operation modes are implemented:

<u>Standby Mode</u> - In this mode the control algorithm is awaiting for a Ground Command (GC). Upon transition request to any other mode, the brakes are released.

<u>Direct Motor Control (DMC) Mode</u> - Used for both manual operation of the arm (e.g. for calibration) and for low level type of commanding. This mode currently accept six DMC command types: Position profile or target, Speed profile or target, Torque profile or target.

<u>Joint Trajectory Tracking (JTT) Mode</u> - JTT is used to demonstrate collision avoidance & path-planning capability of the Ground Control Software (GCS).

<u>End Effector (EE) Autonomous Placement Mode</u> - This high level command mode is used to place a tool in a pose just off its target i.e prior to contact with the environment or another system. The Autonomous Tool Operation mode together with the EE Autonomous Placement mode is used to demonstrate the use of contact tools like drilling and/or sample insertion. Both Joints Trajectory Tracking and EE Autonomous Placement modes can be used to demonstrate on-board collision detection capability.

To date, the overall OCS state-machine, Direct Motor Control and Joints Trajectory Tracking modes have been implemented. The other two modes have been designed and tested, however, their implementation will form part of future developments.

***Ground Control System (GCS)***

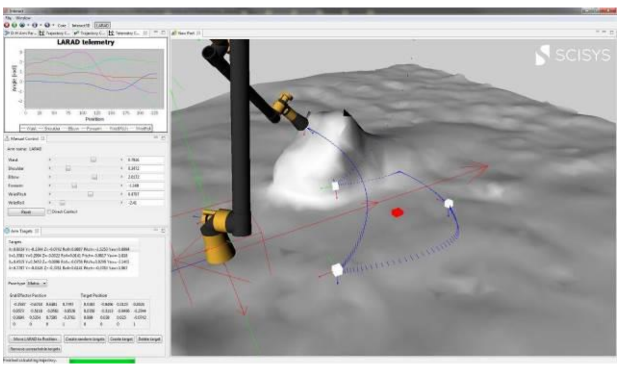


**Figure 7 – LARAD Ground Control System GUI**

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

By modelling the arm's environment for collision avoidance and implementing point click target selection, the planning of complex operations can be facilitated, including the placement of payload, or the acquisition of a surface sample. The Ground Control Software system was built upon SCISYS Overseer Interact framework [5], as illustrated in Figure 7. It provides a convenient interface to manipulate the arm joint by joint, plan specific trajectories to a target, calculate obstacle-free paths for the manipulator and monitors their execution. The GCS was successfully tested on a representative arm and was able to directly control the arm, dispatch trajectories and calibrate joints. Unfortunately, the full integration of the GCS with the OCS and the LARAD hardware was not possible in the timeframe of the original LARAD development and is considered as part of future work.

## 7. MANUFACTURING AND IMPLEMENTATION

### 7.1. Structure

The project provided a unique opportunity to bring together a range of novel materials and processes into a single product, some of which that had not been attempted yet in the field. The manufacturing stages proved to be challenging with each step of the design, manufacturing and integration providing its own unique set of challenges. However, ultimately, the experience gained throughout the process will see applications reaching far beyond LARAD, encompassing the design of ALM structures, their post processing, the understanding of the TiSiC structures and its bonding to Ti ALM.

***ALM Structures***

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 part.

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 (shown Figure 8). The parts were then post-processed through vibration grinding to improve the surface finish.

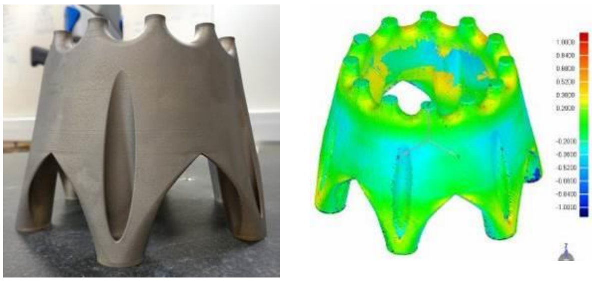

**Figure 8** – **ALM builds, left, and metrology investigation, right**

The ALM process is very similar to casting, where the volume is close to a net shape, but still needs further machining of the key interfaces. 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 9 shows all the ALM parts long the LARAD manipulator

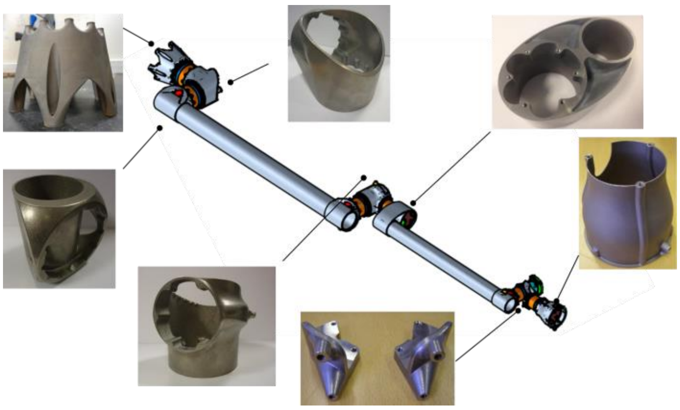

**Figure 9** – **ALM parts along the LARAD arm**

***TiSiCs Metallic Composite Limbs and ALM Diffusion bonding***

**Figure 10** – **Integrated structures of the first (left) and second limbs (right)**

The manufacture of the limbs (Figure 10) required the use of a range of processes to: produce the Titanium Matrix Composite (TMC) tube, 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 parts go through each of the manufacturing stages, the accuracy of the mechanical alignments of the various elements is critical to minimise any post machining of the interfaces. Similarly 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. New processes have been subsequently devised and successfully implemented, leading to the provision of these complex structures.

### 7.2. Motion Actuator Cores

The manufacturing and integration of the actuators was initiated with the early production of a prototype that enabled the verification of the key characteristics of the joint, while providing a test article for the development of the electronics firmware and the OBC control system. Once integrated, the MACs (Figure 11) 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 however be re-visited over the course of the forthcoming characterisation activities at joint and arm levels.

**Figure 11 - Integrated MACs (w/o electronics) with some ALM interfaces - Large (left), Medium (centre), small (right)**

Finally, the following table summarises the preliminary minimum and maximum joint rates in closed loop *rate control*:

**Table 2 - Preliminary Min/Max LARAD joint rates**

| | Min. rate [rad/s] | Max. rate [rad/s] |
|---|---|---|
| Link 1 | 0.010 | 0.05 |
| Link 2 | 0.015 | 0.04 |
| Link 3 | 0.030 | 0.12 |
| Link 4 | 0.015 | 0.11 |
| Link 5 | 0.015 | 0.11 |
| Link 6 | 0.015 | 0.11 |

### 7.3. Electronics

Beyond 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 an aluminium case to provide sealing from dust contamination, facilitate thermal conduction to the arm structure 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.

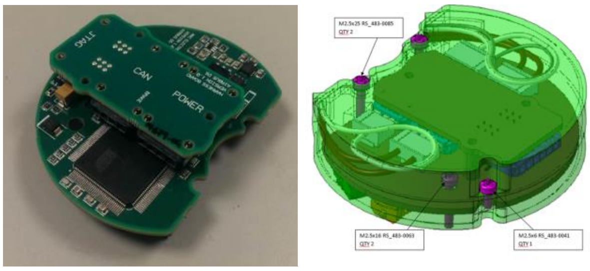

**Figure 12 - LARAD electronics boards**

### 7.4. Arm Integration and Cradle design

Upon integration of the various sub-systems, the arm was fitted on a cradle that provides a standard interface to any test carrier system, (e.g. mockup lander, rover, spacecraft), as well as a transport frame. The cradle, and the arm, have been sized to be accommodated horizontally or vertically to emulate different operational scenario. Four locking points are fitted along the arm designed as cup/cone interfaces that can be bolted down or fitted with Frangibolt NEAs to test and simulate the deployment sequences of the arm.

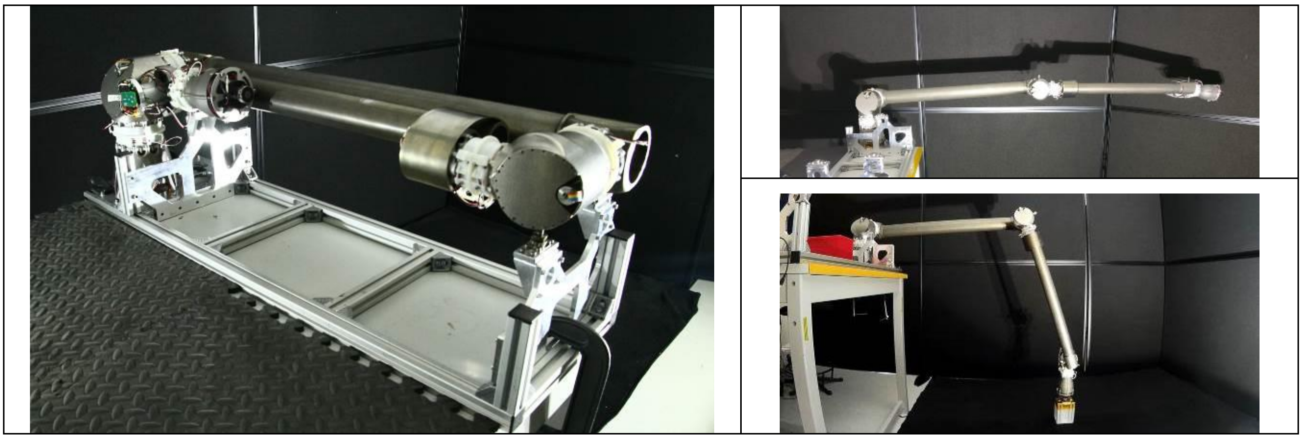

**Figure 13 - LARAD manipulator - Stowed (left), fully extended (top right), mock-up payload pick up (bottom right)**

## 8. FUTURE ACTIVITIES AND CONCLUSIONS

### 8.1. 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.

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 future missions.

### 8.2. Full Arm Characterisation and Future Activities

With the completion of the original CREST project, the manipulator is now fully integrated and low-level testing has been completed. The arm development is now entering a new phase that will see the arm characteristics being tested to assess its performance (accuracy, precision, repeatability) as well as its payload capacity in the arm workspace. Testing and final tuning is anticipated to be completed by Q3 2017. An evolution of the joints electronics has already been performed and TRL raising activities are being planned for the MACs hardware, electronics and software.

**Acknowledgements**

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