ROBOTIC ARCHITECTURES FOR THE ON-ORBIT ASSEMBLY OF LARGE SPACE TELESCOPES

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ABSTRACT

Space telescopes are our ‘eyes in the sky’ that enable unprecedented astronomy missions and also permit Earth observation integral to science and national security. On account of the increased spatial resolution, spectral coverage, and signal-to-noise ratio, there is a constant clamour for larger aperture telescopes by the science and surveillance communities. This paper addresses a 25 m modular telescope operating in the visible wavelengths of the electromagnetic spectrum; such a telescope located at geostationary Earth orbit would permit 1 m spatial resolution of a location on Earth. Specifically, it discusses the requirements and architectural options for a robotic assembly system, called Robotic Agent for Space Telescope Assembly (RASTA). Aspects of a first-order design and initial laboratory test-bed developments are also presented.

Key words: autonomous space robots; on-orbit assembly; large aperture telescopes.

1. INTRODUCTION

One of the main challenges associated with large aperture telescopes stems from the fact that their primary mirrors (PMs) cannot be monolithically manufactured, leading to the adoption of a segmented design. Correspondingly, the assembly and subsequent wavefront sensing/control for the telescope to meet the desired imaging requirements in the visible spectrum are highly challenging tasks [1]. Even if the PMs were monolithic at these sizes, another major hurdle is that it is impossible to stow them in the fairings of current and planned launch vehicles. Though deployment of a segmented telescope via a folded-wing design (as will be done with the 6.5 m James Webb Space Telescope) is one approach to overcoming the assembly challenge, it is currently considered infeasible for large apertures such as the 25 m telescope addressed in this paper. Thus, envisioning the need for future large segmented telescopes, Surrey Space Centre (SSC) is developing innovative solutions for autonomous robotic on-orbit assembly (OOA) in partnership with Airbus and Surrey Satellite Technology Limited (SSTL) [2, 3, 4]. Ongoing studies being conducted by NASA [5, 6] also indicate robotic OOA of smaller space observatories offers the possibility, in some circumstances, of reduced cost and risk at smaller sizes rather than deploying them from single launch vehicles. This further indicates a need for investigating robotic OOA and related technologies.

The scope of this paper is to propose five different robotic architectures and identify an appropriate architecture for assembling a Ritchey-Chretien style telescope system. The telescope design under consideration comprises a 25 m PM made from 342 hexagonal segments [7]. The user requirements of this Earth observation (EO) imaging system greatly facilitated the derivation of the telescope’s system/subsystem requirements, which will be presented in an upcoming paper [7] as it falls outside the scope of this paper. However, it is important to note the following: as no general user requirements exist in the literature for OOA, a set must be derived for the system requiring assembly (in this case, a telescope); this is the main challenge that should not be understated in the subsequent robotic system design. Simultaneously, it should be noted that this lack of engineering requirements is understandable for a variety of reasons: the precedence of robotic manipulator activities in orbit are limited; a fully commercial mission using space manipulators is without precedent but momentum in this area is picking up; and fully robotic OOA (autonomous or tele-operated) of any space structure lacks precedent at both space agency and commercial levels. These factors necessitate a consideration of various OOA robotic architectures; here, the discussion is limited to systems that necessarily use manipulators in the assembly process. Thus, free-flying systems (i.e., spacecraft without manipulators) that rendezvous and dock to form a telescope (e.g., AAReST [8]) are not explicitly considered within this study though there are considerable technological overlaps.

The layout of the paper is as follows. A brief discussion on the state-of-the-art of on-orbit assembly and its link to space telescopes is presented in Section 2. Then, robotic system requirements for the assembly of a 25 m are presented; based on this, five RASTA architectures are pre-
sented and an appropriate one identified. In Section 3, a first-order design of the robotic system is described and a brief description of a testbed under development at Surrey Space Centre (SSC) is included in Section 4. Concluding remarks on this feasibility study are stated in Section 5.

2. ON-ORBIT ASSEMBLY AND ROBOTICS

So far, there has been a strong reliance on deployment and human involvement in enabling the assembly and operation of large space structures. Large systems such as antennae have historically been deployable structures whereas, more recently, human astronauts have played a major role in the construction of the International Space Station (ISS), which has required over 200 spacewalks in the last 21 years for a number of assembly, repair, and servicing missions. The ISS’s large robotic arms have had an important yet limited role here; they have either served as teleoperated assistants in these missions or been used to perform crane-like operations to manoeuvre large objects (e.g., berthing cargo spacecraft (s/c) and transporting trusses). The current large robotic arms on the ISS [9] are the Mobile Servicing System (MSS), which comprises multiple element (including the Space Station Remote Manipulator System (SSRMS)), 2 Russian Strela cranes, and the Japanese Experimental Module-Remote Manipulator System (JEM-RMS). In 2008, a smaller dual-arm dexterous manipulator system was added to this team of manipulators; this robot, called Special Purpose Dexterous Manipulator (SPDM) completed its first mission in 2011 and is currently being used in the multi-phased Robotic Refueling Mission (RRM) [10]. While Dextre is reportedly capable of millimetre-level precision in manipulation with its 3.4 m arms [11], the Canadarm2 is capable of centimetre-level precision (impressive given its ~17.6 m span) which necessarily dictates the precision of assembly.

The only existing mission concept that explores and, to some extent, explains an autonomous robotic architecture for OOA of large space telescopes is the Robotically Assembled Modular Space Telescope (RAMST) architecture [5], its main focus is on the use of deployable systems that form the modular backbone. The RAMST architecture does not explicitly detail (at least in the open access literature discussed in [5]) the robotic system requirements that led to the investigators’ selection of a six-legged robot. However, the study mentions that a trade was performed between different robotic architectures for assembling a 100 m telescope, which drove the researchers’ decision on choosing a hexapod assembly robot. In keeping with the large robotic arms on the ISS, the RAMST [5] study assumes that robot manipulators are capable of centimetre-level precision in assembly and that a combination of connector interfaces and precision actuators will compensate for the inaccuracy resulting from the robot operations. Thus, an identical assumption is made in this paper; improving the accuracy of positioning of modular elements during the pick-and-place operations could be facilitated through a connector interface, such as Standardized Interface for Robotic Manipulation (SIROM) [12] or intelligent Building blocks for on-orbit satellite servicing and assembly (i-Boss) [13].

Given this brief background on orbital robotics and some appreciation of their impact on OOA of precision structures, the focus in the remainder of this section is on the identification of an appropriate architecture for robotic assembly. This is done by first laying down the requirements based on the telescope design; following this, a general set of architectures are discussed. These architectures are then evaluated against the requirements to identify the most appropriate baseline architecture for the assembly mission.

2.1. Robotic system requirements

In the telescope assembly architecture discussed here, the use of a single dexterous manipulator is adopted as a requirement, which is believed to be sufficient for several reasons. Firstly, it aligns with Surrey Satellite Technology Limited (SSTL)’s low-cost philosophy and mission requirements. Secondly, the chosen architecture is different to that proposed for RAMST, where dual-handed manipulation is necessary as the robot is responsible for deploying the truss and then placing it accordingly; in the assembly philosophy proposed in this paper, the use of an auto-deployable truss using a built-in motor driven nut makes dual-handed manipulation unnecessary [7]. Thus, by limiting the role of the manipulator to only pick-and-place actions, single handed manipulation shall be sufficient for assembling the proposed telescope.

The following are the set of requirements that have been identified for a s/c with single manipulator architecture to achieve telescope assembly:

1. The chosen robotics architecture shall be capable of performing the assembly of a 25 m space telescope with a single robotic manipulator. (Note that as the assembly sequence for the telescope assumes self-deployable trusses to create the PM assembly’s backplane, the robot’s responsibilities are pick-and-place of the backplane truss modules that are in their stowed configuration. Following the auto-deployment of a perimeter truss, the robot places a mirror module on it.)

2. The robotic agent in the architecture shall be able to service the assembled system. (This implies that the robot must be capable of reaching the farthest mirror segment in any module, should it need replacement.)

3. Once the telescope is operational, the robot shall not obstruct its field-of-view (FoV).

4. The preferred robotics architecture shall consume minimum on-board power, have low mass, and be low cost.
5. The robot shall possess the required capabilities (e.g., mobility around the base s/c) that facilitate assembly/servicing of the telescope.

6. During assembly, the chosen architecture must minimize overall complexity of the control systems.

7. Evidence of a robot design with space heritage shall be leveraged.

8. The robotics architecture selected shall pose the lowest risk to generating debris while effectively meeting primary mission objectives.

2.2. Robotic assembly architectures

A discussion of five RASTA architectures capable of meeting the above requirements is now presented.

i) Fixed-to-base self-assembly robot

This is the most fundamental type of robotic OOA system. As it serves as the baseline design from which the other assembly systems discussed in this section are derived, it is considered the simplest space robotic assembly architecture. It comprises one robotic arm, which is rigidly attached to a base satellite at one end while capable of manipulation with the other end (see Figure 1).

A pick-and-place method, as seen with six degrees-of-freedom (DoF) industrial robots, is used to move modules from their stored position to their final location on the base vehicle. Thus, it is evident that at every stage of the assembly process, the modules are always rigidly connected to either the s/c (inside or on it when stowed or at a predefined final location), or to the manipulator during the pick-and-place operation. This is shown in Figure 1.

While this is indeed the simplest approach for assembly, it is also less versatile than other proposed options, as its workspace is limited by its reachability. Assembling a large structure (such as a 25 m telescope) would require a robot with a significantly longer reach, which introduces a variety of complications, such as structural flexibility of the manipulator system or the addition of a greater number of links, which then increases control complexity. Spans greater than those currently used in space will be needed to assemble a 25 m telescope (e.g., the span of the Canadarm2 is 17.8 m), which further makes this less preferable.

ii) Tracked self-assembly robot

This architecture is one that extends the working volume of the robotic arm without increasing its span by placing it on a reciprocating slider; this results in an additional translational DoF, which is assumed to not overcomplicate the robot’s motion control. This mobility aid has space heritage and has been used on the ISS to relocate the Canadarm2, which can be transported along the length of the ISS on a carriage called the Mobile Base System (MBS). An issue with this architecture is that it significantly increases the cost and mass of the mission. Further, ambulation of the robot around the s/c to perform assembly requires additional grappling fixtures and tracks on the s/c to facilitate robot mobility (see Figure 2); such ports have further enhanced the mobility of the Canadarm2 and naturally leads to the next class of robotic architectures.

iii) End-over-end walking robot

This refers to a limbed-robotic system that can move along a s/c to different locations to perform assembly on it. The mobility of the robot along the s/c is facilitated via connectors placed at predefined points on the s/c. This introduces the possibility of a valuable design homogeneity that can solve the problems of robot mobility and assembly without vastly increasing mass and cost of the mission. This robot concept does increase control complexity and will adapt solutions developed for bipedal robotic locomotion.

A concept of such a walking robot is illustrated in Figure 3, which depicts the multi-stage process of transporting an assembly module to its final configuration.
that such transportation of a module is an idealization of what could be desired in an assembly process but not what might be practicable. For example, such a transfer would not be feasible nor recommended for mirror modules comprising multiple hexagonal mirror segments but may be possible for truss elements (which are highly rigid structures). However, the key takeaway should be that the end-over-end mobility would permit a lightweight and potentially low-cost option (in comparison to other mobility options) for a robot to locomote to different assembly areas on a s/c.

The current flight-proven state-of-the-art for such a mobile robotic system is the SSRMS, which can use either end of its two links to latch to the ISS thus allowing it to walk end-over-end. As is the case with fixed-to-base robots, the advantage here is that the robot is always physically attached to the base s/c while it is performing assembly. This eliminates the complexity during assembly and mitigates debris generation risks. Finally, the mobility of the robot via the standardized interface on the base s/c suggests that this robot’s workspace is limited only by the availability of attachment points and not the length of its links (in the case of a predefined assembly task); in other words, they can work over a volume much larger than their reachability.

iv) Free-flying assembly robots:

This architecture involves at least two free-flying agents at any given moment of the assembly process, one of which has one (or more) manipulators; a free-flying assembler with two arms is shown in Figure 4. The goal of the robotic agent is to perform assembly on another s/c separate from itself. Here, the assembly parts may be stowed within the space robot or the secondary s/c upon which assembly is to be carried out. The base for the robot is actively controlled in attitude and position; the base upon which assembly is being performed also requires its own stabilization, which increases power requirements for attitude control and mass expenditure for thruster-based position control (if needed). This increases mass and cost of the mission; also, the movement of modules from one point to another will again require the agent to move using thrusters, which influences the aforementioned aspects of cost and mass but will likely require a significantly more complex assembly architecture. For example, based on Figure 4, there are two possible assumptions to the assembly process, which highlight the complexity in the operations. The first assumed process could be that there is a third s/c (not shown) which carries all the stored material from which the mirrors and other assembly components are extracted by the robot which then performs the assembly on the base s/c, as shown in the figure. This would require station-keeping between all three s/c. Conversely, the second assumed approach could be that the base s/c carries its own assembly components, which are then extracted by the free-flying assembler to complete its objectives. In both assembly cases, the space robot must maintain its attitude and position actively to ensure safe extraction of modules, their transport, and placement at the goal location. Such an approach of having two or more free-flying robots in proximity while also maintaining rigid physical contact is unprecedented and poses a significant debris generation risk, given complicated station-keeping manoeuvres that could result in an uncontrolled collision between multiple s/c.

v) Docking-to-mobile-track free-flier robot:

To reduce the control complexity and increasing the safety of the free-flying external assembly robot (shown in Figure 4), a track with a mobile platform to host the assembler could be designed that is attached to the base s/c upon which assembly is being performed. It is thus an amalgamation of the free-flying architecture and the tracked-base robot architectures, which means it also carries with it a combination of the advantages and disadvantages of these architectures. This architecture, while offering a significant amount of flexibility, is still more complex and more expensive than the other non-propulsive options. Further, there is no precedent of such a tracked-base docking system in space yet and, as a result, poses significant development challenges that would drive up costs. This makes it infeasible for a near-term solution but one that could be explored in future.
2.3. Trade-off summary

From a weighted trade-off analysis performed in an internal study led by SSC, the end-over-end walker emerged as the most appropriate architecture for meeting the requirements of the assembly of a 25 m telescope. The free-flying assembly robot was the next best architecture and would likely be even more appropriate for structures larger than 25 m; this would need further requirements driven analysis to ascertain. These architectures are followed by the fixed-to-base self-assembly robot, the docking-to-mobile-track free-flyer robot robot, and the tracked self-assembly robot. Indeed, an amalgamation of each of these architectures would lead to newer ones; thus, this list of RASTA architecture should not be considered to be an exhaustive one. Nevertheless, the architectures presented in this paper meets the core requirements for the OOA of a 25 m PM. A conceptual rendering of the assembly of a 25 m PM by the end-over-end walker is illustrated in Figure 5.

![Figure 5. Concept art depicting the assembly of a segmented PM of a 25 m space telescope by a robotic manipulator; here, the robot is about to place the final mirror module to complete the segmented PM. The mirror modules are delivered by storage spacecraft, one of which is shown in a docked configuration to the base. As the robot builds around the base spacecraft, it may relocate to different points using grapple fixtures (shown in red).](image)

3. END-OVER-END WALKER: FIRST-ORDER SYSTEM DESIGN

Having chosen an appropriate robotic architecture along with the knowledge of the final layout of the assembled telescope, a preliminary (or first-order) set of requirements and sizing of the robot are now derived. As the robot has the ability to walk end-over-end to relocate itself, it is not required to have a robot that has a span that is equal to the aperture of the fully assembled PM. Thus, there are two foundational design requirements to enable a compact yet effective robot design:

1. The span of the robot must be as much as is necessary to assemble the inner and outer ring, when one of its ends is fixed to the base.
2. If a certain region of the assembly task is not within the current working volume of the robot, it shall relocate itself to continue/complete the assembly.

As the end-over-end walking robot is anchored to the base s/c during the assembly and/or servicing phases, it is believed that a robot with a full-length span of ~ 12 m shall suffice. This will enable it to perform assembly/servicing tasks in the outer ring to satisfy requirement 1. By design, the robot is an end-over-end walker so it satisfies requirement 2 regarding its capability to relocate to perform assembly at an initially unreachable location; however, this requirement will have to be revisited to assess the various servicing tasks that may be needed for the space telescope.

The proposed end-over-end walking robot will comprise two links, as seen on the Canadarm2 and European Robotic Arm (ERA) [9], with the possibility of enabling dexterous manipulation with the addition of a third shorter link. In other words, the fundamental robot design comprises two links; a third link is an extension to this two-link robot to improve the precision of placement. As either end of the two-link arm shall be capable of manipulation, the two-link manipulator will have seven-DoF: three at its shoulder and three at its wrist and one at the elbow joint connecting these two links. This two-link robot should be capable of placing the modular truss elements at the desired locations. Placement of the mirrors may also be performed with this two-link manipulator but a more precise smaller arm (the aforementioned third link) may be necessary to allow accurate positioning of the mirror modules as well as the ability to replace individual segments; the role of this smaller arm in placing deployable perimeter truss modules (DPTMs) would also need to be evaluated through design, simulation, and experiments. The span of this smaller precision arm is anticipated to be 1-2 m; this could be either a single link (with a three-DoF wrist) but could also be a two-link arm (six-DoF), such as the Japanese Small Fine Arm (SFA) on the ISS. Again, determining its final suitability for a mission will require a dedicated study to evaluate the capabilities of the robot to assemble/service the telescope and identifying limitations of the different designs. As a first order estimate, a 10-11 m span for the two-link arm might be sufficient for: its relocation to different locations on the base spacecraft; and the truss extraction/placements on the base s/c. Such a combination of a long arm and a smaller arm functioning as a precision end-effector is currently used in the ISS’s Japanese module’s JEM-RMS and SFA systems; the combined use of the Canadarm2 and Dextre provide similar functionality on the ISS.
The links of the ISS robotic arms make use of a variety of different materials: carbon fibre reinforced plastic (CFRP) is used on the JEM-RMS, aluminium is used on the SFA, and a more advanced thermoplastic carbon fibre, called polyether ether ketone (PEEK), is used on the Canadarm2; it is likely that this is the same material on the JEM-RMS based on estimations of mass using the material density of PEEK. Surveying systems that are currently under development to assess the state-of-the-art on materials for future space robots was also considered: the Next Generation Large Canadarm (NGLC) \[^1\], shown in Figure 6. The NGLC has telescopic booms for its links\[^2\], where each boom consists of an inner and outer segment with a lock mechanism, and a rail network to guide the segments’ relative translations. The pitch joints provide the actuation for extending and collapsing the telescoping booms. In the ground test-bed variant, each segment comprises a centre composite section bonded to aluminum end sections\[^3\] using a stepped-lap joint (see Figure 6). However, \[^4\] states that for “flight design, several material and geometric changes would be required. These changes may include the introduction of an ultra-high modulus carbon fibre with a cytanate ester matrix for increased stiffness, dimensional and thermal stability and general robustness in the space environment. Replacement of the aluminum sections with titanium for galvanic and coefficient of thermal expansion (CTE) matching is also recommended, in addition to creating a double-sided stepped-lap joint for improved load handling and durability”. This would indicate that the use of aluminium on long-reach space-qualified manipulators is likely not appropriate, which also appears to hold true for the current generation of ISS robots; the rationale for the use of aluminium on the Japanese SFA could not be found in the literature.

Based on the above discussion regarding materials selection for current and future space robots, PEEK is assumed to be the link material for the manipulators on account of its excellent thermal stability and stiffness while being lighter than aluminium. Assuming a three-link robotic assembly system (with a span of 12 m when fully extended) made of PEEK (mass density of 1320 kg/m\(^3\)) leads to an estimated mass of 677 kg; this is estimated assuming that each link is a hollow tube of length 5 m for the longer links and the shorter link is 2 m. The sensor package for this arm and drive mechanism are currently estimated at 40% of the total boom/link masses, giving the robotic system a total mass of 948 kg. This approach at mass estimation for the robot was also used to estimate the masses of the SSRMS and the JEM-RMS as a sanity check (as the link lengths and external diameters of the ISS’s arms are available online); an approximation was made regarding the arms’ internal diameters of the tubular links as this could not be found in any published literature. Note that this is a crude attempt at baselining a robotic arm specific to the orbital case; a more comprehensive attempt at sizing the arm will, in fact, require knowledge of the harnessing that run internal to the boom, for power and data as well as the mass of the multi-layer insulation used. Further, in the case of the RASTA manipulator, the mass estimations will also require refining based on the design of the payload interfaces (e.g., standardized connector) that enable manipulation.

Following the trend in recent space robotic arms, it is currently assumed that the joints will be actuated through DC brushless motors with a harmonic drive, which have been used on Experimental Test Satellite-VII (ETS-VII) \[^5\] and the Front-end Robotics Enabling Near-term Demonstration (FREND) arm \[^6\] that will be used for autonomous grappling of a non-cooperative target; in FREND, the joint actuators are based on a gearing architecture in which the motor torque is first increased using planetary gears and then stepped-up using harmonic gearing. This is done to harness the benefits of the high efficiency of planetary gears and excellent stiffness-to-weight ratio of the harmonic drives. A similar drive mechanism is envisioned for RASTA manipulator.

A systems-level block diagram of the RASTA system is shown below in Figure 7. Vision sensors will be located on each link of the arm to localize objects requiring manipulation, given that either end of the arm could be used in the assembly task. Further, they will assist the collision avoidance system that provides the situational awareness to prevent accidental collisions between the arm and the structural elements during manipulation. The end-effector will also come equipped with a sensor package, comprising cameras for visual servoing to autonomously grapple a co-operative object as well as force/torque sensors to aid with safe manipulation. At this point, it is believed believe that the design of the end-effector will be closely connected to the design of the connector interfaces, discussed in the next section, and also depends on the servicing abilities needed for the telescope during its operational life. The suite of sensors must operate across a broad range of viewing conditions (in variable lighting conditions, with clear space, and a cluttered Earth background). Evaluation of the appropriate sensor technologies is one of several future objectives of this research activity.

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\[^1\] NGLC is a large class manipulator with a 15 m reach (like the SS-RMS), which can be launched with a 3:1 packing ratio achieved by means of telescoping booms; thus it has a limited storage volume.

\[^2\] These metallic sections of both segments house the lock mechanisms, linear translation mechanisms, cabling, and provide the interface flange for connection to the rotary pitch joints of the manipulator.
4. TOWARDS A REPRESENTATIVE TESTBED

Based on the end-over-end walking robot architecture described above, a testbed development has been initiated at SSC to identify challenges associated with OOA. Currently, challenges associated with secure networking between different OOA modules is being explored using module prototypes, one of which is shown in Figure 8.

As physical connection is a consideration that been accounted for in this testbed, a universal androgynous connector, similar in philosophy to SIROM, has been designed to rigidly join two bodies that have free movement in two dimensions. Each module has three instances of this connector and the robotic arm has one at each end, so that it is possible to lock module-to-module and arm-to-module. The demonstration also includes instances of the connector at fixed points. On this basis, the robotic arm begins with one end connected to a fixed connector and the connector on the other end may connect to a module and relocate it to a new connector (which may either be at a fixed point or on another module). Each connector is actuated by a Futaba S3003 servo modified to give position feedback and a microswitch confirms whether another connector is in the berthing position. The combination of servo position and microswitch state determines the status of the connection.

Each module has a Teensy 3.2 development board, which hosts an ARM MK20DX256 microcontroller, and Espressif ESP8285 WiFi System-on-Chip to provide control logic and a data connection, respectively. The Teensy 3.2 actuates the servos and reads servo position feedback and microswitch state, whilst the ESP8285 relays UDP messages between the Teensy 3.2 and a WiFi network, where a Robot Operating System (ROS) network controls the system. A ROS node on the edge of the ROS network acts as intermediary between the Teensy 3.2 and the rest of the ROS network, as the messages sent to and received from the Teensy 3.2 are not directly compatible with ROS, so must be converted. Each module sends a status message at regular intervals, which reduce during execution of actuation commands. A planning algorithm on the ROS network generates action goals which the edge node formats as command messages and sends to the Teensy 3.2. The modules may be power cycled during operation to simulate the power supply reconnection that may occur when relocating modules in robotic OOA. Therefore, the ROS edge node maintains knowledge of the positions and states of each module.

The module-ROS edge communication uses a custom application-level protocol, which can be run over UDP or TCP socket connections. For OOA, the physical layer may be wired or optical rather than WiFi. The protocol has been designed to minimise the necessary data rate; it is estimated that for 255 modules this communication would require less than 200 kilobits per second.

The prototype aims to demonstrate secure networking, due to the value of assets dependent upon OOA. The ChaChaPoly1305 mechanism, which is a mechanism within the Authenticated Encryption with Associated Data class of security functions, was chosen for the prototype due to the availability of implementations on the ARM MK20DX256 microcontroller architecture. ChaChaPoly1305 is a combination of the ChaCha20 stream cipher for encryption and Poly1305 hash function for authentication. The overarching goal of this testbed is to demonstrate the reconfiguration of modules by a planar end-over-end walker (representative of the system shown in Figure 3); the planar robotic system is currently under development and will be used to demonstrate autonomous trajectory planning/execution and a prototype connector mechanism. This will be presented in a future paper.
5. CONCLUSION

In this paper, the robotic on-orbit assembly of a large space telescope with a 25 m primary mirror has been considered. One of the key challenges is in the identification of a robot design, which was tackled by identifying the requirements for a robotic system; these requirements were based on the payload’s requirements (to appear in a future paper [7]). A set of robotic architectures were proposed that could satisfy these requirements and one most appropriate for assembling a 25 m primary mirror was identified: the end-over-end walking robot. A first order design of the robot was then presented and a discussion on a test-bed initiated towards demonstrating challenges of assembly was conferred.

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