In-Space Robotic Assembly of Large Telescopes

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Abstract— **Advancements in our understanding of the universe have been enabled by ground and particularly by space-based telescopes (e..g. the Hubble), free of interferences from Earth's atmosphere. However, current astronomical challenges in areas such as exoplanets, interstellar medium and structure of the universe, require larger telescope apertures. Using deployable structures and a segmented primary mirror, such as in the James Webb telescope, allows an increase of the aperture, but the maximum size of the telescope is anyways limited mainly by the fairing size of the launch vehicle. Further increasing the size of the telescope requires a technological change, to move toward space-based assembly using autonomous robotic systems. This paper provides a survey of existing concepts for in-space assembly of telescopes, and introduces PULSAR (Prototype of an Ultra Large Structure Assembly Robot), the latest European effort toward proving feasibility of the technologies required for autonomous robotic assembly of a telescope or a large space-borne structure.**

I. INTRODUCTION

During the last few decades, astronomy has found an increasing interest upon the study of exoplanets. Finding new planets outside the solar system, understanding the physical properties of these planets and investigating the existence of an atmosphere (and its components) brings key elements for scientists towards the final goal of understanding life formation and conditions for life existence beyond the Earth [1], and this scientific goal has continuously pushed toward the development of larger telescopes. This research topic, together with more classical investigations such as the formation and structure of the universe, the interstellar medium, and the origins of the solar system, constitute hot topics in astronomy nowadays. Such astronomical studies have been mostly done from Earth, initially using telescopes with monolithic mirrors, and nowadays using segmented telescopes that enhance the diameter of the primary mirror, such as in the Thirty Meter Telescope (TMT)[1] or the 39 m European Extremely Large Telescope (EELT)[2]. However, these telescopes are fundamentally limited by the absorption and distortion created by the Earth's atmosphere, and by their fixed location on ground. Moreover, some studies require specific conditions that cannot be met with Earth-based telescopes, as part of the frequency spectrum is filtered by the atmosphere, hiding information that is essential for the advancement of astronomical knowledge.

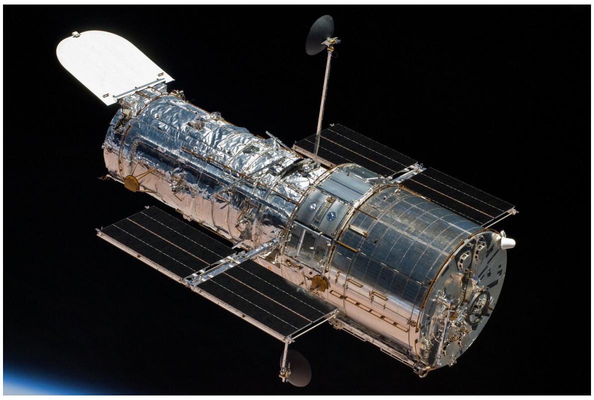

Fig. 1. Hubble Space Telescope (in service since 1990) (Courtesy of NASA).

Space-based telescopes complement the capabilities of large telescopes on Earth thanks to the larger range of the electromagnetic spectrum that the telescope is able to acquire [2], thus enabling observation without atmospheric disturbance. The main features of a telescope are its collecting capabilities (mostly represented by the surface or diameter of its primary mirror, although some other elements such as focal length are also important) and its pointing accuracy. The instrument collection area, or aperture diameter, determines the signal strength and the spatial resolution that can be achieved, while the pointing accuracy determines directly the quality of the obtained image. The most iconic example of space telescopes is the Hubble Telescope (HST, Fig. 2)[3], launched in 1990 and still operating after 29 years of service. The HST operates in Ultraviolet/optical/infrared (UVOIR) wavelengths, providing high quality images that have enabled important advances of the scientific community. It is also famous because of the various servicing missions it required, performed with the Space Shuttle and with astronaut labor. The successive missions to the HST constitute an example of servicing and on-orbit assembly (since several instruments

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[1] `https://www.tmt.org/`

[2] `https://www.eso.org/sci/facilities/eelt/`

[3] `https://hubble.nasa.gov`

were replaced and upgraded), which have allowed it to achieve a lifetime much longer than expected. HST has a 2.4m monolithic primary mirror. The largest space telescope using a single piece mirror up to now was the Herschel Space Observatory[4], an infrared telescope with an aperture of 3.5m. It was built and operated by ESA, and was active from 2009 till 2013.

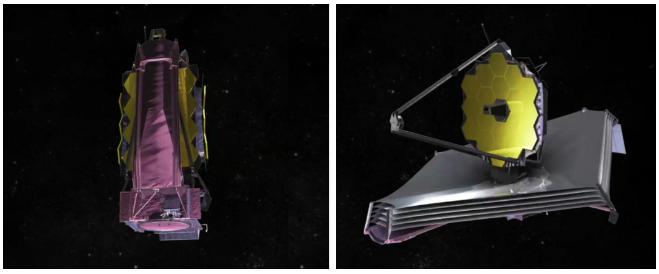

Fig. 2. Deployment of the James Webb Telescope (launch planned for 2021) (Courtesy of NASA).

Though an increase in diameter for space telescopes is desirable, the maximum aperture of the telescope is limited by the physical size of the launch vehicle fairing, mass of the payload that can be accommodated on the launch vehicle, and overall cost (though the overall cost of a telescope is mainly limited by the justification of its scientific return). There are also challenges in achieving a large aperture while keeping a high mirror surface precision and stability with a single-piece primary mirror. New developments try to overcome these limitations by using segmented mirrors supported by a deployable structure, such that the telescopes can fit into the launcher fairing. The closest example is NASA's James Webb Space Telescope (JWST, Fig. 2)[5], which has a primary mirror of 6.5m diameter composed by 18 hexagonal mirror segments [3]. The JWST is scheduled for launch in 2021 using an Ariane-5 rocket, which has a fairing diameter of 5.4m. The deployable structure increases the complexity of the mission, as the deployment relies on different mechanisms that must be actuated in the correct order without jamming (e.g. hinges, telescopic tubes). The next generation of space telescopes would need additional emerging technologies in order to continue escalating the size of the primary mirror, as it can be considered that JWST has reached the limit of what is feasible within a regular size launcher. For instance, LUVOIR-A is a planned space telescope with a segmented primary mirror of 15m diameter, significantly bigger than any previous development [4]. NASA is aiming to increase size of its next generation of space telescopes using the same concept developed for JWST, relying on the augmented capacity of new launchers such as Big Falcon Rocket, New Glenn and SLS. The fairing capacity of the Space Launch System (SLS), for instance, would increase to 8.4-10m, still low compared to the aperture demanded for current astronomical studies. Table I summarizes the main features of current and planned space telescopes.

A different path for improving size of space telescopes is its assembly in space using (mostly autonomous) robotics, which could bring additional versatility and mass and size optimization. In this case, the primary mirror would be assembled in orbit instead of being folded for launch and deployed when starting operation. Though in-space assembly could be carried out by astronauts, as shown previously in the repairing and servicing of the HST or the assembly of the ISS, the process would be very expensive and time-consuming due to the limited dexterity of the astronaut inside a space suit and the large number of working hours that would be required for such complex assembly operations. On the other hand, technologies for robotic ground assembly are currently under development, and initial demonstrations of fully autonomous assembly have already been provided [5].

Current space telescopes are built and tested at 1g conditions, while their operations are performed in micro gravity. Assembly of telescopes in space would alleviate the high constraints on design, manufacturing and testing required to fulfill operations in both environments at the same time. The telescopes could then be designed for in-service loads (0g) rather than for testing loads (1g). Also, launching the telescope components (in a single or in multiple launches) implies that less mass is required to package the components so that they survive the accelerations during the launch phase (vibration, noise, shock levels). In order to improve competitiveness of this alternative, the use of a conventional launcher is a key feature; otherwise the additional complexity introduced by the robotic manipulators required for assembly is hardly justified. Note that the same rationale for assembling space telescopes is valid for a starshade, a spacecraft that could fly in formation with the space telescope to block light from stars, thus allowing direct observation of exoplanets.

This paper focuses specifically in the survey of existing concepts for autonomous assembly of large telescopes in space. In general, the concepts include a modular deployable structure, satellites flying in a coordinated fashion, or a mission including a general purpose robot with advanced autonomous assembly capabilites. Finally, the project PULSAR (Prototype of an Ultra Large Structure Assembly Robot) is introduced as the latest European effort to develop and demonstrate the technology that will allow the on-orbit precise assembly of a very large primary mirror by an autonomous robotic system.

II. OVERVIEW OF PROPOSED IN-SPACE TELESCOPE ROBOTIC ASSEMBLY TECHNOLOGIES

Autonomous assembly of structures in space is a key challenge to implement future missions that will necessitate structures too large to be self-deployed as a single piece. Besides space telescopes, other foreseen applications in this area include solar arrays for power plants, light sails to reach outermost regions of the solar system, and heat shields to land on Mars.

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[4] `http://sci.esa.int/herschel/`

[5] `https://jwst.nasa.gov`

TABLE I

Characteristics of currently operational or planned space telescopes

Mission	Launch	Orbit	Spectral band	Primary mirror
HUBBLE	NASA, 1990	LEO, 547 km	Near-IR, Visible, UV	2.4m
HERSCHEL	ESA, 2009	Sun-Earth L2	Far-IR, sub-mm (55-672 m)	3.5m
JAMES WEBB	NASA, 2021*	Sun-Earth L2	Visible (orange) to mid-IR (0.26 28 m)	6.5m
EUCLID	ESA, 2022*	Sun-Earth L2	Near-IR, Visible	1.2m
PLATO	ESA, 2026*	Sun-Earth L2	Visible	**
LUVOIR-A	NASA, 2039*	Sun-Earth L2	100nm-2.5m	15m

* Expected launch date

** PLATO uses several small cameras instead of a large mirror

Assembling a large space structure implies putting together modular components in an ordered fashion, dictated by a high level master plan that indicates the relative positioning of each part. Common robotic systems in space applications have a small degree of autonomy. The execution of tasks usually relies on remote operations, which require an appropriate feedback channel for the operator, typically affected by substantial time delays. The concept of shared autonomy increases the dexterity of such systems and reduces the effort for the operators in difficult tasks. Nevertheless, remote operation approaches have limited use when it comes to the assembly of complex structures. Because of the fine granularity of assembly tasks, classical remote operation becomes unfeasible as it consumes substantial amounts of time for the synchronization of operator commands and manipulator actions. Therefore, a robotic assembly system should be capable of performing a sequence of operations or even the complete assembly task autonomously.

Autonomous operations in space are still very challenging and there have been a limited number of demonstrations on-orbit. The first successful demonstration of an unmanned spacecraft to conduct autonomous rendezvous and docking operations was done by NASDA in 1999 on ETS-VII. It was the first satellite equipped with a robotic arm that allowed ESA to conduct the VIABLE experiment demonstrating computer vision support for autonomous robot control. Several robotic arms are now present on board the ISS, including Canadarm, Dextre and Kibo, but for now they are all teleoperated. Autonomous robotic assembly of space systems has been demonstrated on ground for planar truss and beam structures, but their test in orbit and with more complex structures still remains a challenge. Among the missions under development, NASA's Restore-L and DARPA's RSGS are expected to demonstrate in the near future the autonomy and dexterity required for on-orbit assembly. An overview of current technologies for in-space assembly is provided in [6].

For space telescopes, current monolithic designs have reached the limits of the available cargo areas in launch vehicles. To push forward the size of space telescopes, current engineering approaches aim for a deployable structure, which can be packed inside the current cargo areas, or a modular design that can be deployed and assembled in space. For the latter, a tradeoff or risk vs. cost must be done between first time assembly and reassembly, i.e. either the telescope components are directly launched and assembled for the first time in space, or the telescope is assembled and tested on ground, then taken apart and launched to be reassembled in space. Other requirements for the new generation of space telescopes include serviceability to allow replacement and upgrading of instruments and subsystems as required, refueling and repairing on demand, and expandability, i.e. incremental enlargement of the aperture over time when the design allows it. The key question for this new approach is when does in-space assembly of telescopes represents an advantage (lower risk, lower price) with respect to building them on earth and sending them as a single piece.

The technology areas required for in-space assembly of telescopes have different levels of maturity:

- High maturity: launch vehicles, mirror segment fabrication
- Medium maturity: Segmented mirror wavefront and jitter control, robot hardware (arms)
- Low maturity: autonomous assembly, in-space assembly

The aspects with lower level of maturity are in-space assembly, i.e. technologies required to assemble a large diameter telescope in space and guarantee the same level of optical performance as a ground-assembled telescope, and autonomous assembly, i.e. assembly processes carried out by robots without intervention of astronauts or ground control. Different approaches have been proposed to achieve in-space assembly of telescopes, some based on high precision formation flying of satellites carrying individual mirror components, and some others for in-orbit assembly of the modular structure via a robotic servicer satellite carrying some sort of robotic manipulator. An overview is provided below.

A. Deployable structure

The James Webb Space Telescope likely represents the largest size of aperture that can be achieved using a deployable structure for a single-launch telescope. The JWST has a 6.5m mirror composed of 18 hexagonal segments, and its backplane truss is separated in three hinged sections such that the primary mirror fits into the Ariane 5 rocket fairing, with 5m diameter. The unfolding process must be carried out autonomously in space. For the JWST, a successful deployment depends on the correct performance of 40 deployment mechanisms and 178 release mechanisms. Testing these sequences on ground is difficult due to the presence of gravity loads, which do not actuate when the unfolding process occurs in orbit. JWST was not designed for servicing, mainly due to its location in the L2 point of the Sun-Earth orbit (SEL2).

As the HST approaches its predicted lifetime, different projects have looked at a post-HST UVOIR Telescope. For a single deployable structure, NASA's project ATLAST (Advanced Technology Large Aperture Space Telescope) is close to the upper limit of payload capacity for a fully filled aperture telescope. This study proposed a 8m monolithic telescope and two segmented telescopes with 9.2m and 16.8m aperture, which would still fit in the cargo area of heavy lift launchers [7].

For achieving a Large Ultraviolet Optical Infrared Telescope (LUVOIR), two architectures have been proposed: LUVOIR-A, a 15m segmented, on-axis telescope, and LUVOIR-B, a 8m segmented, off-axis telescope [4]. LUVOIR-B was designed for being deployed using a conventional, heavy-lift launch vehicle, while LUVOIR-A is designed to profit from the extended capabilities of the SLS Launcher. Both telescopes would be deployed in the SEL2 point, and are designed to be serviceable and upgradeable. If they are approved, their expected launch date would be in late 2030s.

B. Free-flying satellites

Satellites flying in a precise formation can mimic the behavior of a rigid structure, even without physical docking. For instance, ESA is preparing the Proba3 mission (PRoject for OnBoard Autonomy)[6], scheduled to launch in 2020, where two satellites will be autonomously flying in tandem formation. The two satellites, derived from the ESA's standard Proba platform, will form a 150m long coronograph to study the Sun; one satellite will carry the coronograph, while the other one will be the occulter.

Small satellites (e.g. up to 1000 kg) can play a significant role on in-space assembly operations due to their low cost and lead time [8]. For instance, AAResT is a mission led by the Surrey Space Center, consisting of two MirrorSats (3U nanosatellites) that carry an electrically actuated adapted mirror, and a central satellite, CoreSat (9U nanosatellite) carrying two fixed mirrors and a boom-deployed focal plane assembly camera [9]. The two MirrorSats can autonomously dock and undock from the CoreSat to create different configurations and guarantee a proper image at the focal plane. The three satellites are meant to be launched as a single package of about 30 kg, with foreseen launch date in 2020.

A swarm of satellites, each one representing a module of the structure, can also be used. In this case, each satellite can fly autonomously, and dock and undock from other modules. One example of such concepts is the GOAT mission (Giant Orbiting Astronomical Telescope), proposed by Surrey Space Center [10]. In these rendezvous and docking approaches the physical docking can take multiple forms, for instance using mechanical or electro-magnetic means. The risk and complexity of these formation-based approaches stems from the operation of several spacecraft in close proximity; collision avoidance techniques and precise navigation must be employed. In general, for free-flying based methods to be practical, the majority of elements involved in the process should be "dumb", i.e. not have propulsion capabilities, and only a few active spacecrafts would then be required to create the final assembly. While these proposals provide low risk technical demonstrations, they do not scale well for larger assemblies.

C. Assembly using robotic manipulators

A conceptually simple way to create large structures is using robotic manipulators mounted on top of an aircraft. The advantage of this approach is that the same robotic spacecraft can be reused to carry out multiple tasks including repairings, upgrades, or refueling, thus one single assembly mission would not have to pay for the full cost of the system, as it is reusable and mobile (can be used at different orbits).

For the case of assembling a telescope, the components of the structure can be taken to orbit in single or multiple launches. The selection of the size of the mirror tiles influences the number of assembly and alignment steps required to complete the full structure. Also, there must be a metrology system capable of measuring the pose of each individual tile to command possible corrections that reduce the pointing and wavefront errors. A separate vehicle can be used to to carry equipment for diagnosis and calibration of the primary mirror, providing also a third point of view for an accurate and cost-effective way to supervise the assembly process.

Different robotic systems have been proposed for these assembly processes, including:

- Single and dual arm manipulators rigidly attached to a spacecraft, which greatly limits their reachability
- Wheeled robots that move on rails on top of a satellite or on top of the structure being assembled, which extends the reachability of the arm
- Robots using some climbing (or walking) strategy that allows the robot to move on top of the spacecraft, attaching and detaching from the satellite as required.

Note that in the case of walking robots, their mobility should be enabled via standard connection interfaces, e.g. iSSI[7] or SIROM[8], conveniently located at different places on the spacecraft. In this way, the robot's working volume is not restricted to the reachability of the arm, but can be extended through the multiple attachment points.

Inspired by the segmented optics developed for the 10m Keck telescope in Hawaii, Boeing proposed AAST (Autonomously Assembled Space Telescope), a 10m aperture Cassegrain optical telescope consisting of hexagonal rings of segmented mirror tiles (SMTs), and assembled with robotic manipulator arms [11]. The focus of this proposal was on the minimimzation of the number of segments for the telescope while optimizing the segment size and layout to ensure the best optical performance of the primary mirror.

Building upon heritage from the JWST, a modular design with mirror segments for a 20m aperture UV-Optical

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[6] `http://www.esa.int/Our_Activities/Space_Engineering_Technology/Proba_Missions`

[7] `http://www.iboss-satellites.com/material`

[8] `http://www.h2020-sirom.eu`

telescope was proposed [12]. Two different mirror panel configurations are considered, with either 12 and 16 mirrors. These mirror panels would be assembled on ground, so that the installation of mirrors on the backplane panels and the optical verification can be carried on Earth. Then, the panels would be launched to be assembled into the primary mirror in space, using both robot and astronaut workforce.

A concept for assembly of a large reflector in GEO orbit was presented in [13]. Several elements are launched into MEO (Medium Earth Orbit) and assembled using multiple robotic arms. The structure then spirals up to GEO (Geosynchronous Earth Orbit) using solar sails as a propulsion system. For performing the assembly in GEO, a new technique called Equilibrium Shaping was proposed, to find a final configuration using autonomous planning based only on sensing the state of the other agents involved in the process.

To reduce the running cost of a space telescope mission, Northrop Grumman Aerospace Systems proposed the concept of an Evolvable Space Telescope (EST), where the construction and launch of the telescope is conducted in several stages, each one providing a complete functional telescope whose capabilities can be extended over time [14], with an expected total lifetime of over 40 years. The original proposal included a first stage to produce a 4x12 meter telescope using mirror tiles with 4m diameter, which would be extended in two stages to create a 12 and 20m aperture telescope. The advantage of such scaled approach is the staged budget, and reduced risk for schedule slip and descoping due to budget restrictions.

The concept and architecture for a robotically assembled, modular space telescope (RAMST) was presented in [15]. The exemplary application is the assembly of a 100m aperture telescope assembled in earth orbit and operated at SEL2. The approach uses four independent aircrafts carrying the primary mirror, the optics and instrumentation unit (OIU), the metrology unit, and a sunshade. The primary mirror consists of hexagonal truss modules that are first deployed and attached, and then the mirror modules are attached to the underlying truss structure. The assembly is carried out by a six-limb robotic manipulator with supervised autonomy, which can travel over the truss structure to perform the required tasks.

An initial hardware-in-the-loop test of assembly of a telescope under micro gravity conditions has been proposed by MIT and NASA Goddard with the program ALMOST (Assembly of a Large Modular Optical Telescope) [16]. The concept uses the SPHERES[9], a floating robotic platform deployed inside the ISS since 2006. The proposed experiment uses 3 SPHERES to assemble a floating telescope with 0.76m aperture inside the ISS; ech SPHERE would act as a vehicle that carries out one part of the assembly (central module, mirror panels and camera to provide supervision of the process). The experiment would test the full assembly sequence in a realistic free-floating environment, with actuator and sensing constraints coming from using multiple autonomous agents. Several steps have been already validated onboard the ISS and on a ground-based testbed called SWARM.

III. PULSAR:Prototype of an Ultra Large Structure Assembly Robot

The European Commission has set up the Space Robotics Technologies Strategic Research Cluster (SRC) in the Horizon 2020 program, with the goal of enabling major advances in strategic key points of this domain. To fulfill this objective, an European roadmap composed of three successive calls (2016, 2018 and 2020) has been defined by the PERASPERA[10] consortium, composed by the main European space agencies. The first activities in the 2016 call have addressed the design, manufacturing and testing of reliable and high performance common robotic building blocks for operation in space environments. The specific objective of the second call in 2018 was to integrate these building blocks into ground-based demonstrators, towards applications of space robotics in the field of both orbital and planetary use.

The PULSAR (Prototype of an Ultra Large Structure Assembly Robot) project is related to OG8 (Operational Grant 8) (Fig. 3). It aims at developing and demonstrating the technology that will allow the on-orbit precise assembly of a large primary mirror by an autonomous robotic system. As discussed above, the new generation of space telescopes requires multiple mirror tiles (individually adjustable) and multiple interfaces, and therefore a meticulous process for autonomous assembly. This is fulfilled by perception and planning algorithms that make use of extended mobility for very large structures. The latter requires a controlled, stable spacecraft during operations and a spacecraft structure that provides attachment and housing for the robotic arm and mirror tiles. The approach in PULSAR involves two physical demonstrators (one focused on assembling a fully functional section of a telescope mirror on Earth conditions, and the other one on assembling a very large structure in low gravity conditions - underwater) and one simulator (evaluation of the PULSAR technology in space conditions).

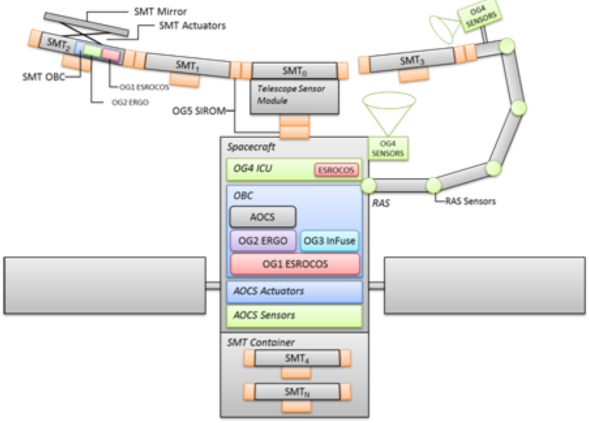

Fig. 3. PULSAR architecture, based on previous components (OGs).

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[9] `https://www.nasa.gov/spheres`

[10] `https://www.h2020-peraspera.eu`

A. Requirements for a future PULSAR-like mission

A PULSAR mission would use an Ariane 6 launcher. This launcher will provide a maximum payload of 8 Tn for injection on a transfer orbit to SEL2 [17]. The choice of SEL2 is motivated by two main aspects: first, the apparent steady position of the spacecraft with respect to the Sun and Earth, thus ensuring constant sun incidence without eclipse, and second, the lower gravitational forces, minimizing effect of disturbances and enabling more accurate and stable pointing of the telescope. The JWST mission is also planned to exploit these benefits. HST, on the other hand, operated in LEO orbit, mainly because the spacecraft was specifically conceived for receiving in-orbit servicing. With various servicing missions, repairing and refueling the spacecraft, the telescope has maintained its mission for almost 30 years. Nevertheless, future space telescopes are less suitable for this approach: as they are bigger and heavier, and with more demanding pointing specifications, the environment of LEO orbits makes the mission a hardly solvable technical problem for the Attitude Orbit and Control System (AOCS). Moreover, complexity of operations is added to manage eclipses and occultation of targets by the Earth or the Sun. Summarizing, the following preliminary requirements could be highlighted for a future European Space Telescope:

- Orbit: SEL2, enabling observation of space and distant celestial bodies without interference of Sun or Earth.
- Launcher: Ariane 6, limiting the mass of the telescope to 8 Tn.
- Launch date: between 2030 and 2035. A launch before 2030 is not realistic due to the significant developments needed, and after 2035 the interest on a PULSAR-like mission might be limited, if LUVOIR-A is already operational.
- Primary mirror: 8 to 10m diameter.

B. Requirements for in-orbit assembly of the primary mirror

A mission of this type requires that the basic modules (including supporting structures, mirrors, mirror mountings and control interfaces) are designed, stacked and packaged for the required launch vehicle fairing. After the modules are placed in orbit, they could be assembled anywhere in space. The assembly platform requires robotic dexterous manipulation for retrieving the tiles, deploying and joining the basic components. After the telescope modules are retrieved, they must be positioned and aligned using suitable standard interfaces for latching structural elements and providing power, thermal and data connectivity.

Given the size of the mirror envisaged for a space-based telescope, the robotic arm would need some kind of mobility in order to reduce its required length. A very long robotic manipulator would make very difficult to meet the accurate position and orientation requirements needed for assembly; a preferred solution is using a smaller robotic manipulator (typically 1 to 2m length) but with the ability to move within the structure. Two main alternatives have been analyzed for providing the required mobility: a walking manipulator, and mobility within a rail. The lower complexity of the second option makes it preferable at this stage of the study (Fig. 4). Although no space applications are known so far implementing this kind of technology, it is common on ground applications. On the other hand, different walking manipulators have been implemented for space applications, including ERA and SSRMS [18]. A proof of concept of a walking manipulator for a space-based assembly application is currently under development in OG9-MOSAR [19]. Adaptable perception, localization and mapping techniques are required to guide the assembly process. After the telescope is assembled, a metrology system needs to be employed for verifying the location and orientation of each mirror tile, so that adjustments can be made to achieve the required accuracy and precision.

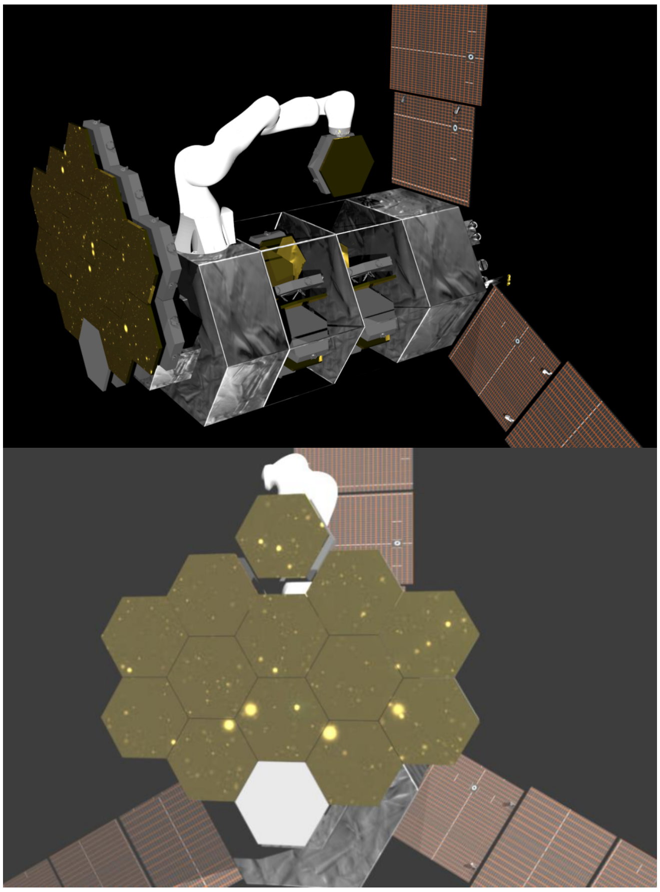

Fig. 4. Concept for precise assembly of mirror tiles in PULSAR.

C. Demonstrator of precise assembly of mirror tiles (dPAMT)

The demonstrator for precision assembly of mirror tiles will show the capabilities to autonomously assemble several mirror tiles following specifications from a Master plan. This demonstrator will be implemented with a combination of adaptable perception, integrated assembly and grasp planning, and compliant control of the manipulators. The assembly demonstrator will rely on an assembly planner, which integrates a grasp planner and a motion planner, for autonomously creating a master plan for the overall process starting with the specification of the desired assembly. The system automatically decomposes a given assembly into a task sequence, which is then mapped to a sequence of appropriate robotic skills. The skills exploit the capabilities of a lightweight and highly sensitive robotic manipulator, the KUKA iiwa, for achieving compliant operations that guarantee successful execution of the robotic skills even in the case of positional or sensorial uncertainties. Standard interfaces will be used both at the end point of the robotic arm and at the mirror tiles, to facilitate the retrieval and repositioning of the SMTs. The main limitations of the demonstrator will be gravity and the robotic arm's payload limit, which restricts the achievable size of the assembled structure.

Visual servoing will be an important component for verifying the execution according to the nominal plan. Additional external sensors are required to provide a ground truth measurement for robot positioning and motion, and for measuring the success of the assembly process for the space telescope. An external measuring device will be used to verify the pose of each individual mirror tile in order to validate the geometry and configuration of the primary mirror, and to define the adjustments required to perform an optical alignment to a given focal point (Fig. 5).

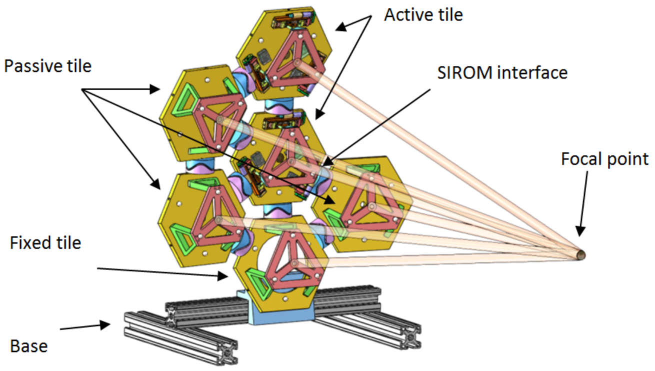

Fig. 5. Validation of the mirror adjustment in PULSAR.

D. Demonstrator of large structure assembly in free floating environment (dLSAFFE)

To simulate on-orbit conditions, in particular the effects of micro-gravity, the autonomous assembly of a large segmented mirror in underwater conditions will be demonstrated. This needs advanced mobility to overcome the limits of robotic arm adaptability to the accumulated assembly errors, and an optimal Attitude and Orbit Control System (AOCS) to stay in the required pose. An underwater platform endowed with a robotic manipulator will be used, and thrusters in the platform will help to control the effects of impulsive forces created during the assembly operation. The extended mobility of the arm will show the feasibility of assembly operations of a large structure. For this demonstrator, all the technical sub-systems have to be adapted for underwater operation, including the connectors and the mirror tiles.

E. Demonstrator of In-Space Assembly in Simulation (dISAS)

This last demonstrator will address the challenge of autonomously deploying a large structure in space while ensuring the stability and safety of the spacecraft. To compensate the limitations of the fidelity of low-gravity facilities (such as time-delay for the robotic platform and water-drag instead of neutral buoyancy), simulation means are retained as the third demonstrator. This includes accurate physical models of spacecraft, robotic assembly system, and segmented mirror tiles, to estimate torque disturbances involved in the deployment as well as robust controllers to manage them. Software coming from the previous OGs will be embedded, including the European Space Robotics Control Operating System (ESROCOS)[11], European Robotic Goal-Oriented autonomous controller (ERGO)[12] and data Fusion for Space robotics (InFuse)[13]. The objective is to demonstrate that the deployment of large structures and active tessellated mirror control can be carried out on-board a spacecraft respecting the AOCS requirements.

The AOCS must be designed to support all mission's needs from launch and early orbit phase (LEOP) to satellite disposal. The satellite must implement at least the following operational phases: launch phase, transfer phase, deployment phase, mission phase, deorbit phase. Each phase is supported by one or more AOCS modes [20]. In the context of PULSAR, our main concern will be to design efficient controllers for the deployment phase and mission phases. The deployment phase is normally entered when the satellite has finally reached the target orbit and all the satellites appendages (i.e. solar arrays, antennas, instruments) are deployed. The mission phase begins after the deployment and it is maintained up to the end of mission before satellite disposal.

The deployment phase is certainly the most challenging as far as the control design problem is concerned. During this time period indeed, as already observed in the early work with ETS-VII [21], it is important to stabilize the attitude with a reasonable accuracy to keep communication link despite the torque perturbations that are generated by the robotic arm. Moreover, the robotic arm is used to build the primary mirror from tiles that are progressively deployed from the main body. As a result, the inertia of the total satellite varies rather slowly but significantly during this deployment phase. Many different strategies have been developed in the literature over the past thirty years to handle attitude control problems in the presence of time varying inertia, for instance Adaptive Control Techniques for Linear Time Varying systems [22], [23], linear parameter varying models [24], or robust control techniques that consider the

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[11] `https://www.h2020-esrocos.eu/`
[12] `https://www.h2020-ergo.eu/`
[13] `https://www.h2020-infuse.eu/`

variations in the inertia matrix as time-varying uncertainties [25].

During the observation phase, the inertia matrix does not change significantly. However, pointing stability is the driving requirement for high-quality imaging in a space telescope [26]. The full primary mirror tends to generate badly damped and rather low frequency torque perturbations. The main control design issue will then consist of enhanced weighting functions tuning to optimize the compromise between a reasonable pointing accuracy and disturbance rejection. The general structure of the AOCS during deployment will be kept in order to facilitate control switching from the deployment phase to the observation phase.

IV. Final discussion

This paper provided an overview of different robotic technologies proposed for the assembly in space of a large telescope. While the paper primarily focused on the assembly of the telescope structure and primary mirror and the optical verification of the telescope, the full assembly process of the telescope requires several additional steps, including assembling the metering structure, secondary mirror, other telescope components (optical train, cameras, sensors, reference units), and providing power, thermal and data connectivity for all the components.

The European project PULSAR was finally introduced, which aims to provide a first experimental verification for low-level technologies that need to be further developed for in-space autonomous assembly of complex structures such as telescopes. This goal will be achieved through three different demonstrators, based on a mobile robotic manipulator (for testing autonomous assembly and optical verification of the telescope), an underwater platform (for testing assembly in a low gravity environment), and a simulation-based approach for testing a full mission. The final demonstrations will be performed in 2021.

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