PULSAR: TESTING THE TECHNOLOGIES FOR IN-ORBIT ASSEMBLY OF A LARGE TELESCOPE

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Abstract— **The EU project PULSAR (Prototype of an Ultra Large Structure Assembly Robot) carried out a feasibility analysis for a potential mission that could demonstrate robotic technology for autonomous assembly of a large space telescope. The project performed the analysis using two hardware demonstrators, one devoted to show the assembly of five segmented mirror tiles using a robotic manipulator, and another one showing extended mobility for assembling a large structure in low gravity conditions. The hardware demonstrators were complemented with a simulation analysis to demonstrate the operation of a fully integrated system and to address the challenges especially in the field of attitude and orbital control. The techniques developed in the project support the path toward In-Space Servicing, Assembly and Manufacturing (ISAM).**

Keywords: In-orbit assembly; orbital robotics; space robotics; space telescope

I. INTRODUCTION

Space Industry is attiring unprecedented levels of attention in the last few years. Favored by the progressive reduction of the traditional entry barriers (technology complexity, high investments) and stimulated by an ever increasing demand of new, more performing services, a proliferation of innovative ideas is emerging [1]. One of the key aspects enabling the current golden era is the improvement of launch capabilities: today's launchers allow a drastic reduction of the cost per launched kilogram, mostly thanks to the introduction of reusable rockets [2]. While some of the new launchers multiply the payload capacity (in mass) compared to its predecessors, still size and accommodation limitations impose severe constraints in the design of the space vehicles. These constraints become important limiting factors in some particular missions and space vehicles requiring very large structures. Indeed, the need of enhanced services of space infrastructure combined with the renewed interest in science and space exploration allows to identify a number of use cases requiring big size structures and/or appendages [3]. Potential applications include large space telescopes (Fig. 1), large antenna reflectors, orbital platforms, very large solar arrays, deployable radiators, and thermal shields [4].

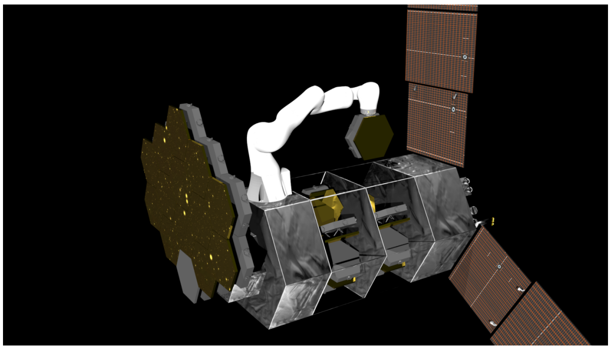

Fig. 1. Artistic concept of the PULSAR project.

These large space structures do not easily fit inside a launcher fairing, and usually require some kind of mechanism for deployment, or a specific design allowing unfolding when the structure shape allows for it. This was the approach taken with the James Web Space Telescope (Fig. 2), launched in 2022, which used a deployable primary mirror splitted in three segments [5]. However, novel assembly technologies are required for substantially increasing the size of structures to be deployed in space. In order to make the solutions scalable and able to cope with complex geometries and high performance requirements, the use of robotic manipulators to perform assembly in-orbit is a subject of increasing interest among governments and industrial institutions [6].

In this context, prominent industrial actors in the

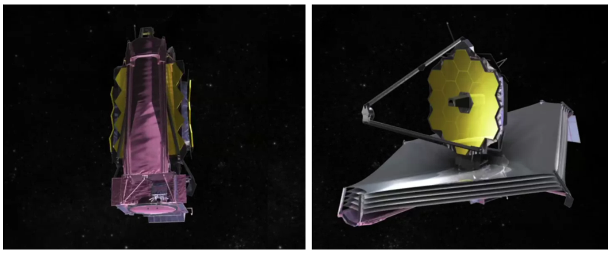

Fig. 2. Deployment of the James Webb Space Telescope. Left: folded configuration, for transportation in the cargo area. Right: fully deployed configuration in space (Courtesy of NASA).

European Union have identified the need of fostering Europe's capabilities in space robotics and in-orbit assembly. The European Union funded, through the Space Robotic Technologies program within Horizon 2020[1], the project PULSAR (Prototype of an Ultra Large Structure Assembly Robot)[2]. This project aimed to develop and demonstrate the technologies that will allow the in-orbit precise assembly of a segmented mirror using an autonomous robotic system. PULSAR was organized in three demonstration tracks to address the major challenges of in-space autonomous assembly of telescopes:

- dPAMT, demonstrator of Precise Assembly of Mirror Tiles: addressed the challenge of assembling a mirror composed by multiple hexagonal segmented mirror tiles. This requires a robotic system that provides high assembly accuracy and adaptability to cope with the accumulated assembly errors.
- dLSAFFE, demonstrator of Large Structure Assembly in Free Floating Environment: addressed the challenge of assembling a large structure in a free-floating environment, in this case, underwater. This requires advanced mobility to overcome the limits of robotic arm range, adaptability to cope with accumulated assembly errors, and optimal attitude and position control systems.
- dISAS, demonstrator of In-Space Assembly in Simulation, addressed the challenge of simulating in the most realistic conditions possible the autonomous deployment of a large structure in space while ensuring the stability and the safety of the spacecraft. It was used to simulate a fully representative scenario with respect to the spacecraft Attitude and Orbit Control System (AOCS) considerations, including for instance the effect of the arm motion on the spacecraft attitude.

This paper summarizes the main results achieved within the project PULSAR based on the three demonstrators above described.

II. Demonstrator of Precise Assembly of Mirror Tiles (dPAMT)

The main objectives of the dPAMT demonstrator were to prove the feasibility of performing autonomous assembly of Segmented Mirror Tiles (SMTs) for a space telescope using standard connection interfaces and a suitable Robotic Assembly System (RAS), and to verify the assembly precision using an external measurement device, and command calibration motions of the optical surfaces to correct alignment errors induced by the assembly process.

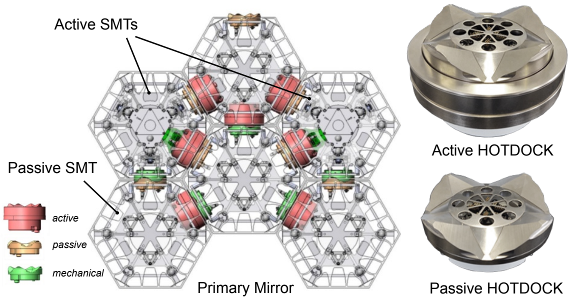

Fig. 3. Primary mirror in the dPAMT demonstrator. Left: components of the assembly. Right: HOTDOCK standard interconnect, passive and active version.

The primary mirror to be assembled consisted of a fixed, central tile, and five SMTs that had to be properly placed by the robotic system in an appropriate assembly sequence (Fig. 3). Two of the SMTs were active, in the sense that they had a mobile stage with a positioning mechanism that could adjust a circular mirror mounted at the center of the tile [7] (Fig. 4). The adjustment range was ± 3mm in position, with 1μm resolution and 5μm repeatability, and $\pm 1^\circ$ in tip/tilt angle, with 4μrad resolution and 20μrad repeatability. The mirror was representative of the telescope optical surface, and it was used as metrological target for the demonstration. The SMTs also contain the supporting structure for several Standard Interconnects (SIs), HOTDOCK in this case (Fig. 3). The HOTDOCKs provided mechanical, electrical and data connection between the tiles, and also served as means for manipulating the SMTs with the robotic system [8].

The demonstrator was implemented using a *KUKA KMR iiwa* robotic system. Its main components are a mobile platform and a robotic manipulator mounted on top of it. The mobile platform provided the robot navigation capabilities, and carried the SMT container and the on-board control computer. Furthermore, it carries a camera mounted on a pole, with a pan-tilt unit, to acquire the required visual information from the assembly (Fig. 5). The robotic manipulator is a *KUKA LBR iiwa 14*, which is a seven degrees-of-freedom (DoF) lightweight robot that can be controlled in position or impedance mode, as required to fulfill the delicate

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[1] `www.h2020-peraspera.eu/the-strategic-research-cluster-and-operational-grants/`

[2] `https://www.h2020-pulsar.eu/`

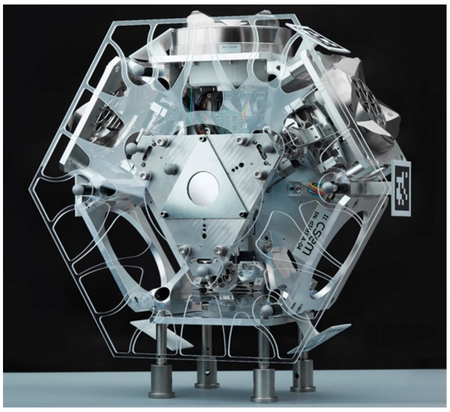

Fig. 4. Active segmented mirror tile of dPAMT.

assembly tasks performed during the demonstration. The robot was endowed with an active HOTDOCK as end effector, to retrieve and manipulate the SMTs.

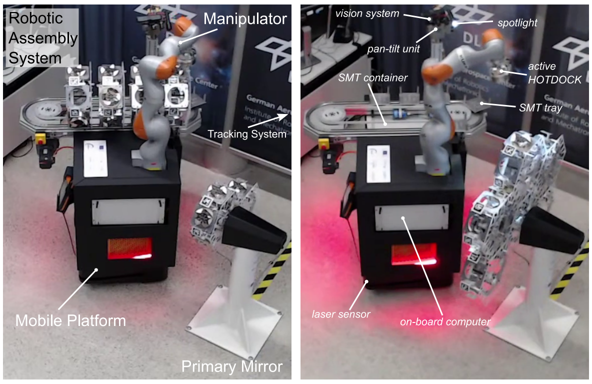

Fig. 5. Components of the dPAMT demonstrator.

The sequence of steps to assemble the structure was determined using a hybrid planning framework [9]. This planner is structured in two main parts, a physical layer and a logical layer (Fig. 6). The main objective is to generate the best possible assembly sequence using as cost function the torque demands on the robot manipulator due to the weight of the SMTs under ground conditions. The physical layer computes the trajectories to place each tile minimizing the joint torques; this optimization is achieved using Stochastic Trajectory Optimization for Motion Planning (STOMP) [10]. In the logical layer, the assembly sequence is represented as a graph, where the nodes are sub-assemblies in the process, and the edges contain the information given by the physical layer on the largest required joint torques to assemble the corresponding tile. Once the graph is generated, the planner searches for the sequence that minimizes the overall cost. Furthermore, the search takes into account the connectivity between the tiles in order to ensure mechanical stability of the assembled structure and to guarantee control access to all active SMTs.

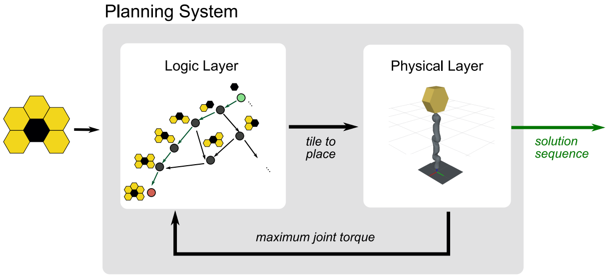

Fig. 6. Planning of the assembly sequence for dPAMT using a hybrid planning framework.

Suitable robotic manipulation skills are assigned to each assembly step. These skills include different compliant assembly strategies, depending on the degree of uncertainty in the estimated pose of the HOTDOCK interface. For navigation, the robot base was localized relative to the primary mirror using two laser sensors located on the mobile platform. Additionally, a perception module implemented the localization of the tiles using AprilTags as visual markers (Fig. 7).

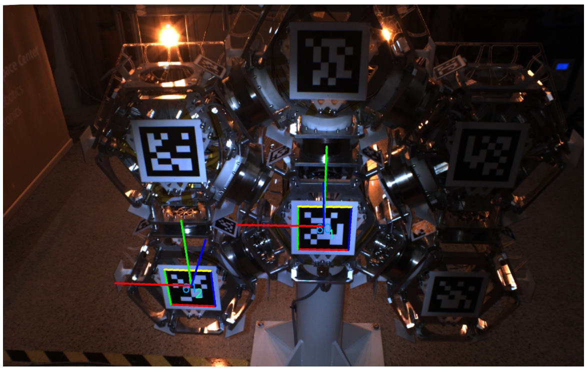

Fig. 7. Visual reconstruction of the assembly using AprilTags.

The demonstrator successfully showed the assembly of five SMTs. The HOTDOCK connectors allowed single, double and triple matings during the assembly process thanks to their form fitting and passive guidance features, which allowed deviations up to 15mm in position, and up to 10° in orientation (Fig. 8). The visual localization successfully reconstructed the relative location of the tiles during the assembly process. Also, using an external VICON tracking system for verification, the relative position of the active SMTs could be reconstructed, and suitable adjustment commands were successfully transmitted and executed by the active tiles. The demo was successful, even though it had a primary limitation: gravity, as the structural capacity of the robotic arm limited the achievable size of the assembled structure. The tiles had a diameter of 30cm, while the tiles on the real scenario would have a diameter of 1.3m. The next demonstrator, dLSAFFE, worked with 1:1 tiles in low gravity conditions.

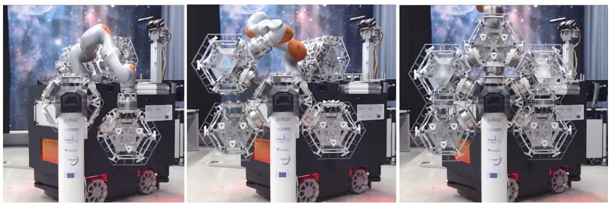

Fig. 8. Single, double and triple mating connections during the dPAMT demonstration.

III. DEMONSTRATOR OF LARGE STRUCTURE ASSEMBLY IN FREE FLOATING ENVIRONMENT (DLSAFFE)

The main objective of dLSAFFE was to demonstrate the extended mobility required to assemble very large structures that exceed the workspace of the robotic manipulator, focusing mainly on motion planning and control. The demonstration was set in an underwater zero-buoyancy environment to lift size and weight constraints, as well as to partially simulate the free-floating dynamics. Using components adapted towards underwater deployment, the robotic assembly system and segmented mirror tiles were represented at near one-to-one scale, with realistic proportions and workspace [11].

The robotic assembly system consists of a manipulator arm with six DoF situated on a linear rail system acting as prismatic joint. The rail increases the workspace of the manipulator and allows traversing the distance between storage compartment and assembly target. However, even with the rail in place, the large mirror structure to be assembled exceeds the workspace of the robotic assembly system. To overcome the workspace limit and facilitate the assembly of much larger structures, an extended mobility concept was introduced. Instead of assembling the mirror tile by tile (individually), several tiles are pre-assembled, forming a subassembly. This subassembly can be manipulated as a unit and assembled to its final position on the mirror structure (Fig. 9).

For dLSAFFE, the robotic assembly system and mirror tiles were designed at a near one-to-one scale to accurately represent the workspace: the hexagonal mirror tiles measure approximately 1.3m in diameter with a thickness of 0.4m; the lightweight manipulator arm has a reach of 2m while weighing only 20kg in air. As required by the extended mobility concept, multiple mirror tiles are manipulated simultaneously. Weight constraints were lifted by setting the demonstration in a zero-buoyancy underwater test environment. The assembly system, mirror tiles and standard interconnects were adapted towards underwater usage (Fig. 10).

The robotic assembly system consists of a six DoF manipulator arm mounted on a linear rail. The linear rail allows vertical movement of 1.2m, and it uses a spindle drive mechanism for actuation. The *GraalTech Underwater Modular Arm* was used as baseline to create the customized manipulator for dLSAFFE. The manipulator can be controlled in joint position and velocity mode. The segmented mirror tiles were designed considering weight and drag minimization, to reduce undesired effects on the demo. Instead of a solid body, the tiles consist of a hexagonal frame of carbon fiber beams. Weight and buoyancy of the tiles are carefully calibrated such that the tiles are very slightly positively buoyant, with as little restoring torque as possible.

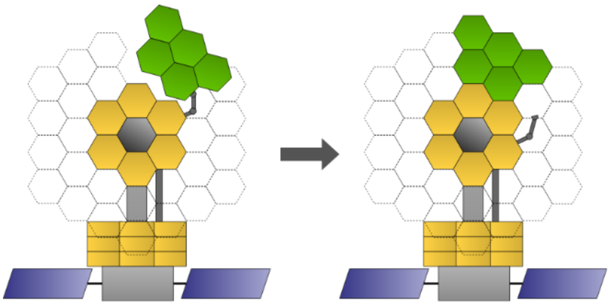

Fig. 9. The outermost ring of the mirror structure lies outside the workspace of the robotic assembly system. To overcome this limit and facilitate the assembly, a unit consisting of five mirror tiles (green) is pre-assembled before being mounted to its final position on the outer ring.

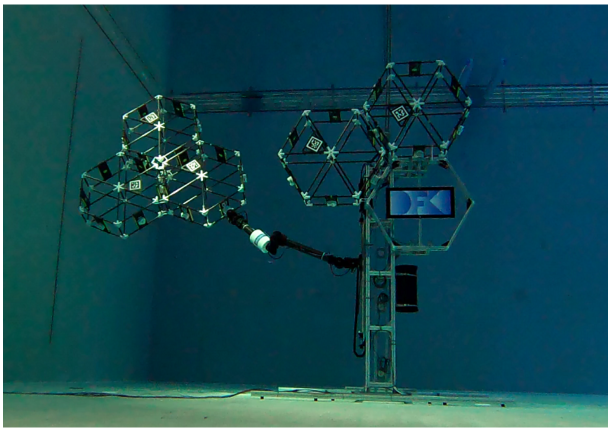

Fig. 10. dLSAFFE underwater spacecraft mock-up in the test facility. The robotic assembly system manipulates a *subassembly* consisting of three mirror tiles. Two tiles of the inner ring of the mirror structure are already assembled to the stationary central tile. Without mirror tiles, the mock-up is 3.5m tall.

The mirror tiles are connected to each other via standard interconnects based on HOTDOCK, adapted for underwater usage. The interfaces are simplified and only provide mechanical connection, while power and data transmission were omitted. To avoid movable components, the mechanical connection is provided using permanent magnets. An active standard interconnect is also used for grasping the tiles by means of an electro-magnetic version used as end-effector on the manipulator.

To a large extent, the software was shared between

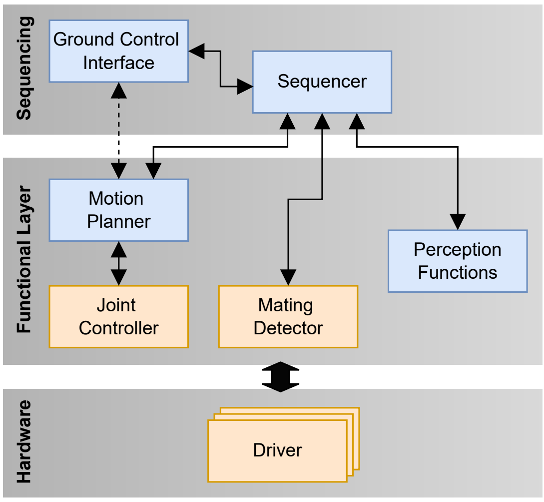

Fig. 11. Simplified software architecture for dLSAFFE. Components in blue are shared among demonstrators, while yellow components are specific to dLSAFFE.

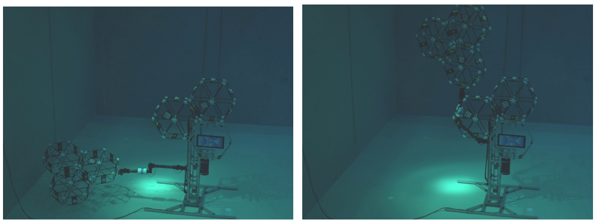

Fig. 12. dLSAFFE demonstrating the manipulation of a subassembly with three mirror tiles.

PULSAR demonstrators. In the context of dLSAFFE, motion planning and control software were implemented, while higher level execution functions were developed and tested with dPAMT and dISAS. A simplified view of the software architecture is given in Fig. 11. In particular, the motion planning component generates trajectories for the robotic assembly system to accomplish a desired task, e.g., to reach a target position, while satisfying constraints such as joint limits and collision avoidance. This was based on a C++ library targeted towards the ROCK framework[3]. The library provides interfaces to different state-of-the-art planning [12], [13], [14], kinematics [15], [16] and collision detection algorithms [17]. In PULSAR, the library and the dLSAFFE software were adapted and integrated within the ESROCOS framework [18].

dLSAFFE successfully demonstrated planning and execution of constrained manipulation of mirror tiles. The demo showed the assembly of the outer ring, i.e., the extended mobility function, where multiple mirror tiles were manipulated simultaneously, as shown in Fig. 12.

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

The dISAS demonstrator was conceived for testing the complete assembly of the primary mirror with the highest accuracy possible via simulation, and to provide a set of tools for the specification, execution and visualization of large structures assembly via simulation, in order to validate their feasibility.

The complete spacecraft is modeled and simulated accurately using a combination of the Webots simulator[4], which uses ODE[5] (Open Dynamics Engine) as physics engine, and dedicated controllers to deal with flexible elements such as the sunshields. Taking into account the physics of the flexible elements required dedicated development, to be able to realistically simulate the effect of the flexible appendages on the whole spacecraft. Resulting forces and torques are then computed and applied at each simulation time step on the different spacecraft anchor points. The simulated system has twenty-two flexible modes: the first four modes of each of the two solar panels and the first three modes of the four support beams of the sun shield.

Thanks to its modularity, the simulated system complexity can be easily adjusted in order to isolate the influence of different system properties on the correct execution of the mission. Thus, the robustness of the spacecraft controller to inertia variation and to the external disturbance generated by the robotic arm have first been tested on a model without flexibility nor sensor noise. In that context, H_∞ synthesis [3] has been proven to be an efficient tool to design controllers that handle the system dynamic evolution (inertia and flexibility) and sensor noise. The simulator integrated assembly planning, motion planning and AOCS controller to consider the full system perspective.

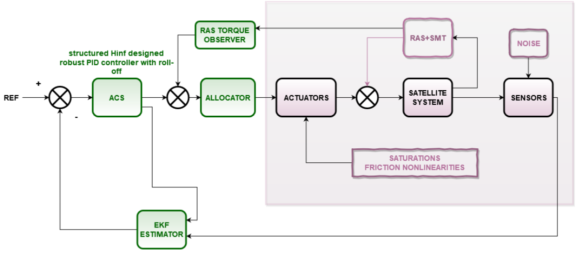

Fig. 13. dISAS Final implementation of the attitude controllers.

In order to increase the robustness of the controller to the RAS motions, the contributions made by an observer of the perturbation torques of the RAS in the controller structure were also studied (Fig. 13). Two sets of reference trajectories for the Robotic Arm System were tested to achieve the full deployment scenario: (a) a first

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[3] https://www.rock-robotics.org/

[4] https://cyberbotics.com/

[5] https://www.ode.org/

set of trajectories minimizing the torques generated by the arm accelerations, and (b) a second set minimizing the derivative of the angular momentum of the arm. We noted that minimizing the angular momentum derivative is the most relevant criterion to consider in the path planning process in order not to exceed the capabilities of the spacecraft actuators (Fig. 14).

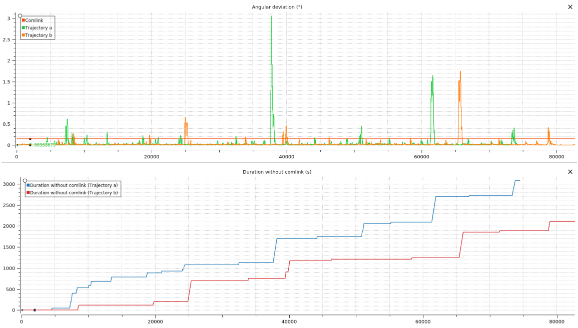

Fig. 14. Attitude deviation (deg) of the spacecraft and duration (s) without comlink during the full deployment with two sets of trajectories.

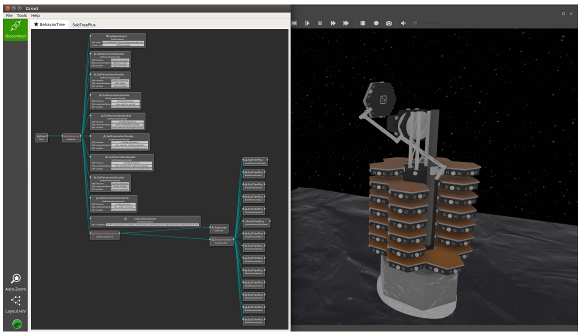

Fig. 15. Behaviour tree (simplified representation) for the primary mirror assembly (left); current assembly state in Webots (right).

A behavior tree (BT) representation [19] is used to describe the required sequence of actions to perform the complete mirror assembly. Complex actions are decomposed into simpler ones, until atomic operations are described, which allows better reusability and composability. Fig. 15 shows a simplified BT representation of the current scenario, together with the corresponding simulation state in Webots. The BT formalism allows to easily define the different sets of actions to achieve the full assembly sequence, with possible recovery cases if needed. It is similar to finite state machines, but with better maintainability (nodes can be designed independent from each other in BT, allowing adding or removing new nodes without the necessity to change other parts of the model), scalability (possibility to decompose BT into small subtrees) and reusability (since nodes are independent in BT, the subtrees are also independent).

A perception capability using fiducial marker detection and object pose estimation was also implemented and tested. For the implementation in simulation and the real execution in hardware in the dPAMT demonstrator, each tile has the same fiducial marker configuration (one big marker at the back, and two small markers around each SI), but with different marker patterns in order to uniquely identify and localize the different tiles. Fig. 16 shows an example of successful identification and pose estimation by the perception module. The small fiducial markers located near the SI are used to precisely localize the tile in the camera frame for picking tasks, when the robotic arm is close to it. Such a perception approach allows to use vision to autonomously perform tasks such as tile picking or tile assembly. With an embedded camera on the robot end-effector (eye-in-hand camera), tile grasping operation has been successfully tested in simulation. At the beginning of the operation (Fig. 17), the two markers can be simultaneously detected. From their precise corners coordinates extraction and the model of the markers, it is possible with a calibrated camera to accurately compute the pose of the tile with respect to the camera. A visual servoing implementation then takes care of commanding the robot in order to reach the desired end-effector pose. This can be visualized with the yellow frames in Fig. 17, which represent the pose of the tile in the camera frame at the desired pose. Thus, converging toward the goal pose brings the current tile frame closer to the yellow frame. At convergence of the visual servoing control, the robot end-effector reaches the desired pose with SIs correctly mated. This desired end-effector pose corresponds to a specific pose of the tile with respect to the camera frame (Fig. 18).

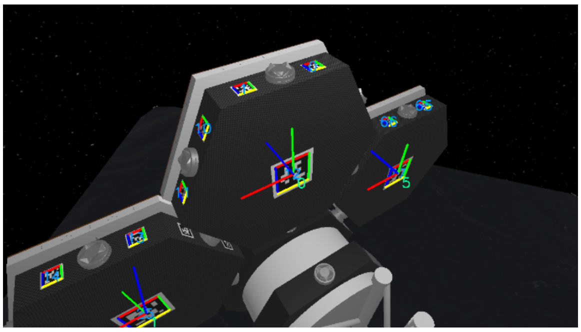

Fig. 16. Tiles identification and localization using AprilTag fiducial marker detection

dISAS can be used to model realistic sensors and actuators. It demonstrates that core components (AOCS, RAS motion planner, perception functionalities) are able to interface seamlessly with real and simulated hardware. The simulator also allows the modeling of component flexibility and related disturbances. Multiple tests have been performed to assess the validity of the different modeled sensors. Custom sensor models are implemented in order to output realistic values from

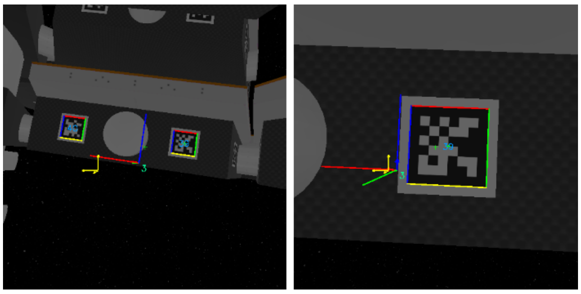

Fig. 17. Tile pose estimation at the beginning of the operation (left), and close to convergence (right).

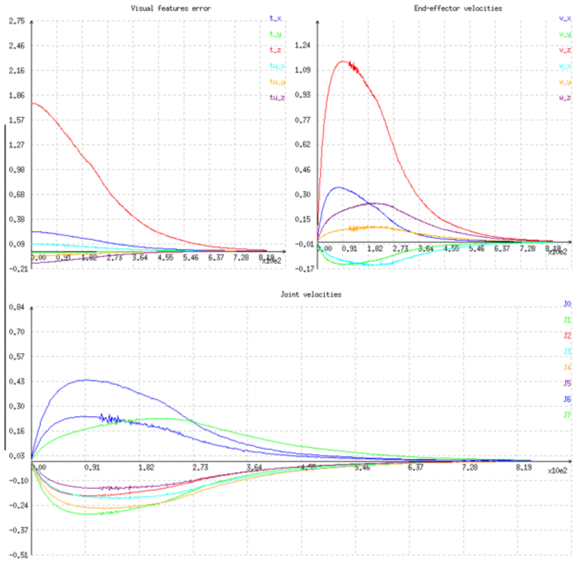

Fig. 18. Visual features errors and velocity commands (right).

perfect data, including also the possibility to use custom sensor noise models. The repeatability of the different implemented instruments (gyroscope, star tracker, reaction wheel) has been validated with this demonstrator.

The simulation has been an invaluable tool to prototype an implementation of perception functions for assembly tasks [20]. It enabled rapid testing of, for example, different sensor specifications, sensor positioning, or illumination conditions, at various assembly steps. It allowed to simulate the full assembly process for a large telescope, including effects of the arm motion on the AOCS of the spacecraft (Fig. 19). It also allowed us to gain interesting insights on the limitations of such functions in an operational context, as well as give clues towards the trade-offs to be made in order to use these types of capabilities in a real mission.

V. FINAL DISCUSSION

The European project PULSAR was introduced, which aimed 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 was 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 were successfully performed in 2021 (links to videos of the demonstrations are provided in the Appendix).

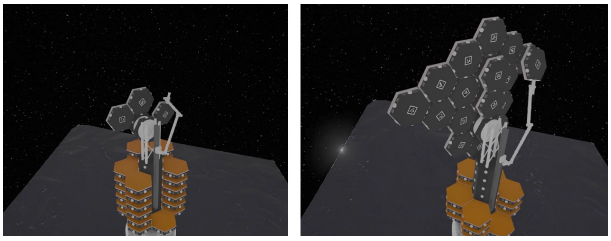

Fig. 19. Telescope assembly using the dISAS demonstrator.

The dPAMT demonstrator proved the feasibility of autonomous assembly of the primary mirror, using a combination of adaptable perception, integrated assembly and motion planning, and compliant control of the manipulators. HOTDOCK was effectively employed as standard interconnect that enabled the assembly of multiple components. The SMTs provided a modular approach for constructing a large mirror, facilitating the manipulation and providing high motion accuracy and adjustment as required for a space telescope. The knowledge gained in this demonstrator has strong synergies with other ground-based applications, where collaborative robots are used for assembling different structures, for instance, using modular construction kits [21].

The dLSAFFE demonstrator used a zero-buoyancy facility, and used an underwater robotic manipulator of representative size mounted on a linear guide. This partially lifted the constraints on the robotic arm workspace, and provided the required mobility to simulate retrieval and assembly of real-size segmented mirror tiles, considering partially the free-floating dynamics and focusing on motion planning and control. The demonstrator was limited by the water drag, which damps structural flexibility effects, and only considered the mobility of the robot but not the integration with the AOCS. However, the strategy to work with sub assemblies was verified as a promising venue to work with large size structures.

The dISAS demonstrator was based in simulation, and used accurate physical models of spacecraft and its components to estimate torque disturbances involved by the deployment, as well as robust controllers to manage them. It included an initial study of the influence of the root arm motion on the spacecraft attitude control, which is a phenomenon to study in further detail, considering that a continuous attitude adjustment will negatively influence the length of the mission due to excessive energy consumption. This is a topic of current work [22].

PULSAR tested the feasibility of key technologies for performing in-space assembly of a large structure, but the same technologies are generally applicable to ISAM (In-space Servicing, Assembly and Manufacturing). Several of the technologies, e.g. torque-controlled robots, visual perception, assembly and task planning, originated from ground applications, where they have proven to be effective to solve challenging problems especially in manufacturing and logistic contexts. Now these automation technologies are proving their feasibility for ISAM, both at the hardware and the software level. Current developments in this direction are considered in the EU project EROSS+ (European Robotic Orbital Support Services[6]) and successive projects, which will strengthen the European competitiveness in space robotics within the global landscape.

APPENDIX

The following links contain videos of the results in the PULSAR project.

General overview of the PULSAR project:

`https://www.youtube.com/watch?v=X5PLVNdIm3o`

dPAMT demonstrator:

`https://www.youtube.com/watch?v=1kyrO8k5rj0`

dLSAFFE demonstrator:

`https://www.youtube.com/watch?v=o0R-1gai6Ps`

dISAS demonstrator:

`https://www.youtube.com/watch?v=SaoC67rYp0g`

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