Designing a Software Architecture for the Precision Assembly of Space Structures

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As NASA's space exploration and science missions expand in complexity, longevity, and distance beyond earth's orbit, Orbital Servicing, Assembly and Manufacturing (OSAM) technologies and concepts have become a critical area of ongoing research and innovation. Artemis' Moon-to-Mars goals of building sustainable elements on and around the Moon and Mars that allow our robots and astronauts to explore and conduct more scientific research will demand in situ resource utilization, construction, and maintenance to succeed. In-space Assembly (ISA), as a sub-component of OSAM, focuses on the on-orbit building or fabrication of mission infrastructure and payloads. One such ISA application is highlighted by the recent NASA In-Space Assembled Telescope (iSAT) study, which stated that the next generation of space observatories will exceed the fairing size of existing or even planned launch vehicles and ISA has emerged as a viable approach for observatory assembly. Research efforts at NASA Langley Research Center have led to the design of a novel TriTruss structural concept for the modular construction of large complex persistent platforms. The TriTruss design and other developing OSAM technologies enable larger and persistent space missions that would not be possible with single-launch-sized structures. For example, 20 meter or larger telescopes or orbital platform applications. However, the increased complexity will require autonomous operations for the construction and maintenance of long-term infrastructure to achieve mission success. NASA's Precision Assembly of Space Structures (PASS) project is focused on the structural and autonomy capabilities required to construct an iSAT in deep space. PASS research efforts will develop and validate critical technologies needed for effective efficient on-orbit assembly that can be confidently adopted for future systems. PASS will utilize the TriTruss modules to demonstrate the autonomous modular assembly of a 20m-class iSAT mirror backbone structure including simulated mirrors and wiring harness. In this paper, we address the software and hardware design considerations, technologies, and challenges of designing a robust robotics framework for assembling modular space structures in support of In Space Assembly missions in general as well as for PASS specifically.

I. Introduction

On-orbit servicing, assembly, and manufacturing (OSAM) is set to revolutionize the space ecosystem. Many proposed missions rely on large structures such as habitats, lunar towers for power and communications, space telescopes, refueling stations, and human transit spacecraft. The current practice for missions involving large space structures is to develop complex deployment mechanisms to allow for packaging within a limited launch vehicle volume.

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Such mechanisms require additional mass that can result in undesirable dynamic modes. OSAM would mitigate these undesirable effects by using simple joining methods such as the electron beam welding methods developed at LaRC [1]. The extra degrees of freedom required for deployment are shifted from the structure itself to an assembly tool that can be reused. This paradigm introduces advantages over the conventional deployment approach including serviceability, expandability, packing efficiency, and modularity. The use of upgradeable and repairable assembly architectures will enable rapid updates, greatly extending the typical 5 to 15-year mission life for in-space structures. For example, components that have degraded due to radiation or micro-meteoroid impacts could be replaced on an as-needed basis. Furthermore, space structure mass and volume will be liberated from the constraints imposed by a single launch vehicle.

A practical assembly system will be able to autonomously and robustly manipulate, assemble, and service objects with limited supervision. However, the ability for a human operator to override actions will be maintained at all levels of operation. This architecture constitutes a robust assembly system that can perform its nominal mission with minimal human interaction and still allow an operator to manually handle scenarios that lie far outside expected uncertainty levels.

In the near term, OSAM can enable or simplify many missions and technologies, including large communications antennae, large shields for radiation protection, megawatt solar arrays, large lightweight structures for artificial gravity [2], and telescopes such as the Large UV-Optical-IR Surveyor or the one detailed in the NASA in-Space Assembled Telescope Study [3].

The in-Space Assembled Telescope (iSAT) study examined when Supervised Autonomous Assembly (SAA) for in-space structure provide clear benefits over traditional tele-operated methods. The study's findings conclude that SAA provide benefits to telescope system construction of all sizes, but when the telescope had a 10 m or larger primary mirror the benefits of SAA are particularly clear.

This paper presents a current overview of the software and hardware design considerations for the autonomous assembly of TriTruss[4] based 20m iSAT by the Precision Assembly of Space Structures (PASS) project in the Space Technology Mission Directorate Game Changing Development Program. Section II provides further detail of the design reference mission (DRM) and targeted TriTruss hardware. Section III discusses the identified autonomous capabilities for such a system and the current tools, design considerations, and approaches being used to realize those capabilities. Section IV discusses the hardware considerations being used to execute the planned assembly demonstration. Finally, section V concludes the paper with a discussion on future work of PASS.

II. Design Reference Mission

The iSAT study noted a particular concern during the assembly of large telescope systems is the difficultly of achieving the required level of precision for the mirror backing structure. The PASS project seeks to address this concern[5]. PASS is furthering the design and development of SAA approaches by focusing on a DRM of the assembly of the primary mirror backing structure of a 20 m iSAT telescope as shown in Figure 1.

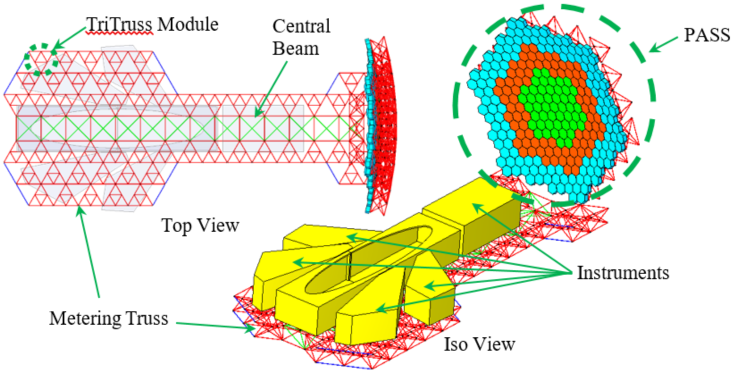
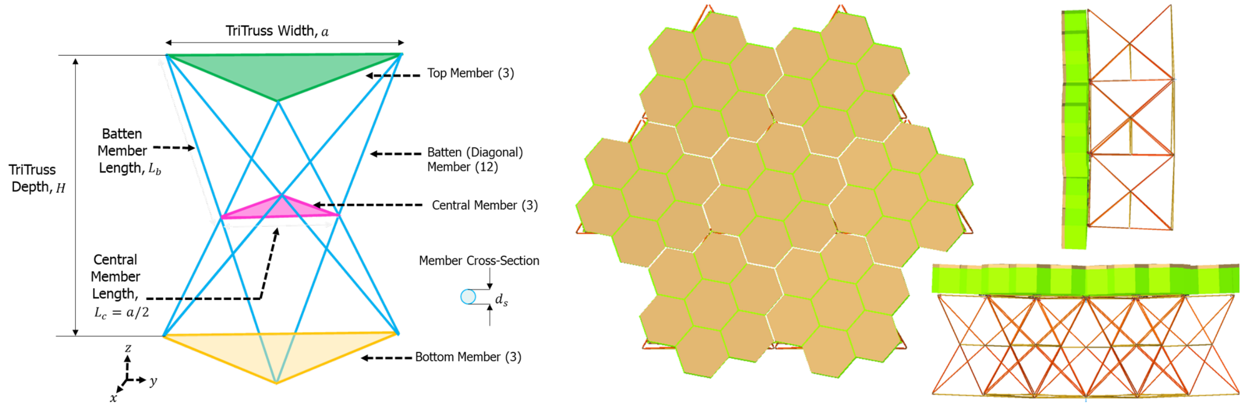


Fig. 1 In-Space Assembled Telescope 20-m operational instrument configuration.

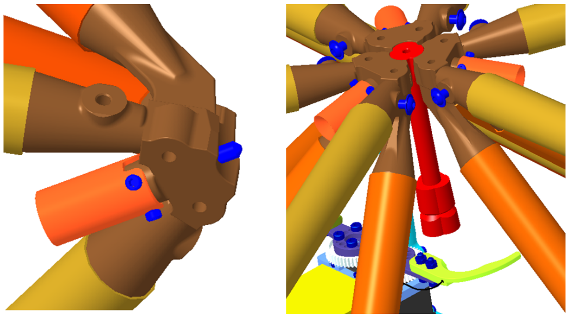
PASS will be assembling the structure using a modular approach by utilizing TriTruss modules. Mirror rafts is an effective strategy allowing larger mirror modules to be efficiently comprised of smaller integrated mirror segments. Rafts can either be pre-attached or attached during assembly. Figure 2a shows the structure of a TriTruss module and

Fig. 2b shows how a single ring of seven TriTruss modules can be assembled together to begin forming the optical bench for an iSAT installation. TriTruss modules are joined together at a three point multi-nut as shown in Fig. 2c.



(a) Overview of TriTruss module.

(b) One ring iSAT optical mirror built using seven TriTruss modules with attached mirror rafts.



(c) TriTruss modules are joined together using a multi-nut.

Fig. 2 TriTruss and ring assembly overview.

PASS will demonstrate the assembly of such a structure using two large robotic manipulator systems with a custom designed TriTruss grapple mechanism end-effector shown in Fig. 6b. The process for placing a TriTruss consists of two phase: a coarse alignment, and a fine alignment and fastening. The grapple mechanism, discussed in further detail in Section IV, is an intelligent mechanism within the multi-agent autonomous system with its own onboard sensors, communication, and computational capabilities that coordinates with the robot manipulators to place the TriTrusses in the appropriate positions and uses onboard actuators to securely fasten the module into place.

III. Autonomous Capabilities and Architecture

A key objective for the PASS project is the design and development of a software architecture suitable for the autonomous operations necessary for the assembly of space structures. An effective system design will be capable of multi-agent task planning and coordination, trajectory generation in dynamic and cluttered environments, and advanced sensing and perception for both local metrology and fault detection. A system built around a distributed communication paradigm will also achieve high flexibility in both development and deployment by allowing researcher to easily swap software modules, algorithms, hardware and other system components as the system requirements evolve. Lastly, a robust simulation environment for this system is required for testing, evaluation, verification and validation of software components and algorithms because the autonomous physical assembly operation will be consuming, expensive in the event of hardware failure, and potentially dangerous to bystanders.

A. Distributed Communication

The majority of the software architecture for PASS is built using the AEON (Autonomous Entity Operational Network) framework [6]. The AEON framework is an extensible collection of libraries and plug-and-play nodes facilitated by the Data Distribution Service (DDS)[7] communication protocol standard. DDS is a publish/subscribe messaging middleware that provides the flexibility for AEON to be modular and easily extensible. DDS provides dynamic endpoint discovery, allowing for the easy expansion of the multi-agent distributed system. As new system components are developed or hardware changes are made, they can easily be integrated into AEON modules, thus abstracting the interfacing logic from the larger AEON network. This allows the developer to focus on the data relationship between the necessary nodes required by the autonomous system. The data transmitted via DDS can also be easily recorded and playback for real-time or post processing data analysis.

Another advantage of utilizing a framework such as AEON that is built around the open DDS standard is the ease of integration with other software frameworks, modules and tools. A key component of DDS-based software is if the DDS implementation used is faithful to the open standard, the end-point communication will language, platform, and vendor agnostic. This enabling technology is increasingly being embraced by the robotics community, as evident by the transition to DDS-based communication in the development and release of Robot Operating System 2 (ROS2) framework[8]. This has allowed us to take advantage of existing software packages within the ROS2 ecosystem. Enabling ROS2 modules we are integrating include MoveIt[9][10] for scene management and manipulator trajectory generation using OMPL's RRT* implementation[11], and the ROS2 robotic manipulator controller packages for our hardware manipulators. Utilizing these existing ROS2 modules has allowed us to focus on the novel software components for successfully executing our DRM.

B. Software Architecture

Figure 3 shows a high level overview of the current PASS software design. The architecture is broken into two major areas: the robotic manipulator and the grapple mechanism. Nominally, the software modules in the upper reside on the robotic manipulation system(s) and the lower modules on the grapple mechanism. However, since DDS enables distributed communication, run-time deployment is flexible with the only requirement being modules that required serial communication with hardware components to be executed from onboard devices attached to the respective hardware.

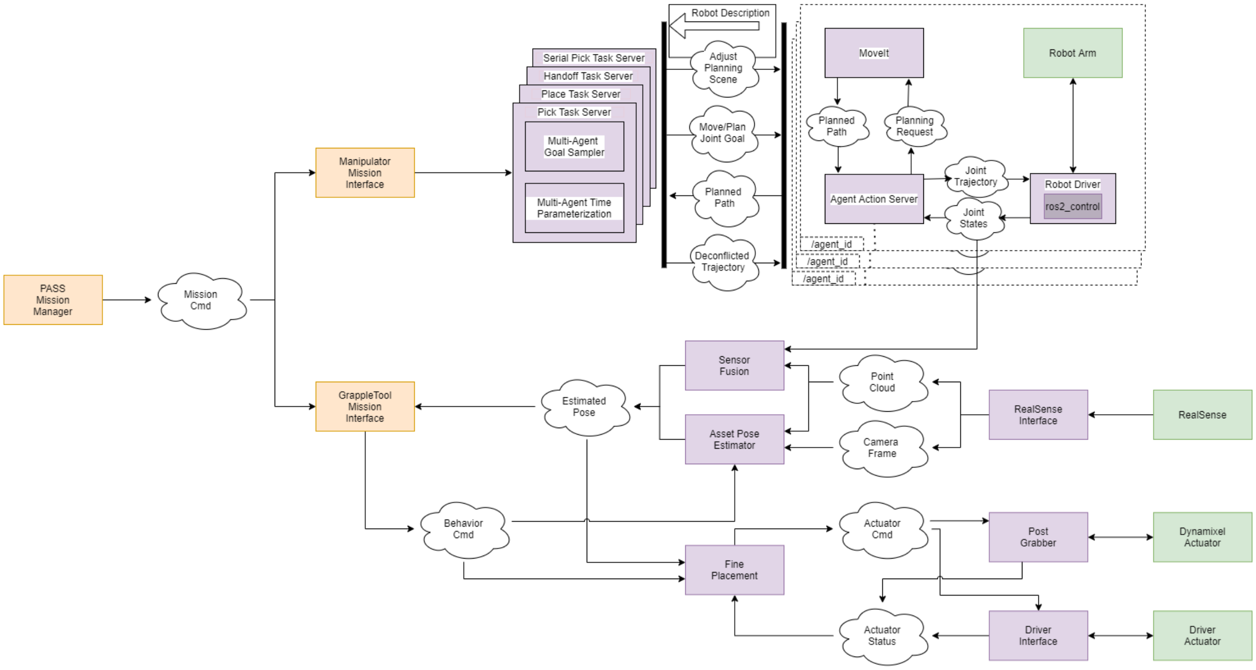
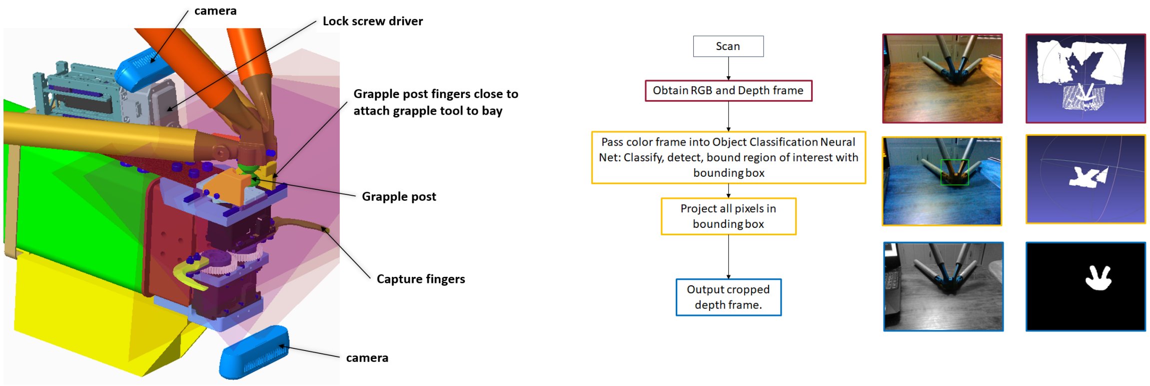


Fig. 3 PASS Software Architecture

The robotic manipulator(s) are responsible for the scene management, trajectory planning, and execution with provided input from the grapple mechanism's sensing and state estimation. The robotic manipulator(s) are the primary executor during the coarse alignment phase by the using knowledge of the observed scene and inverse kinematics to generate and execute a safe trajectory to place the TriTruss within 1 inch of the designated assembly location. A class diagram of the trajectory planner being used is provided in Fig. 11 in the appendix.

C. Metrology

Metrology, the science of measurement and application, is paramount for fine placement and fastening phases to achieve the precision needed for the assembled structure. Once the coarse placement phase has been successfully executed, the grapple mechanism takes over primary control. High precision metrology is achieved using the several sensor systems at the edge of each spoke, shown in Fig. 4a. Camera systems provide both RGB image and infrared-based depth data as the primary sensors used for local metrology, object detection and pose estimation.



(a) The Grapple mechanism spokes are outfitted with several sensor and actuation systems.

(b) Object detection and pose estimation pipeline.

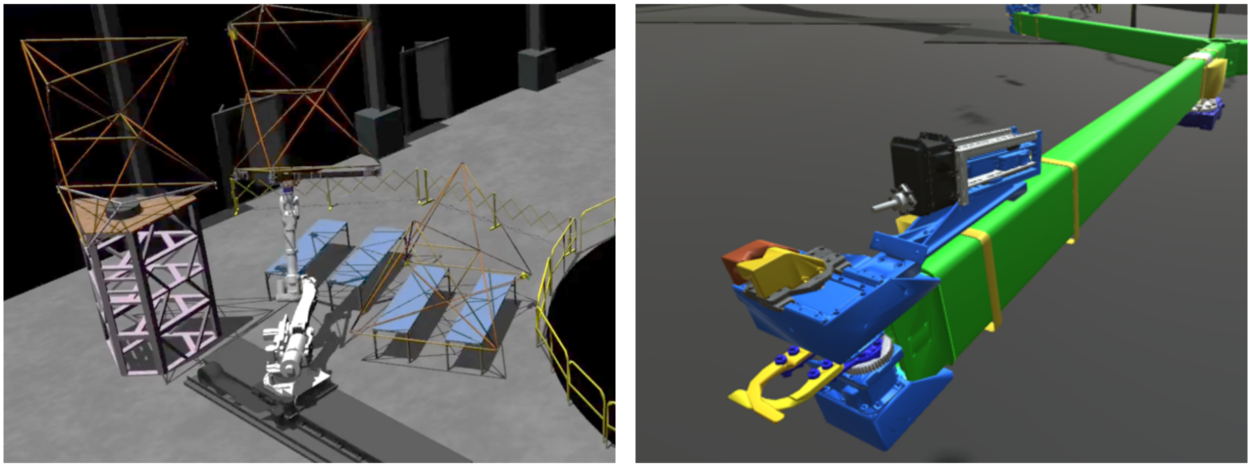
Fig. 4 Grapple mechanism metrology systems.

Once within operational range of the grapple mechanism end spokes, the metrology systems provide feedback to the fine placement behavior by identifying the in-place TriTruss modules and estimating their pose to request fine position and orientation adjustments from the robotic manipulator to ensure proper alignment before the linear actuators drive the fasteners into the multi-nuts. As with the overall software architecture, the metrology systems is designed to be modular, allowing for quick changes to classification and pose estimation techniques with little impact to the rest of the distributed system. For example, we have successfully integrated custom trained Mask-RCNN and YOLOv4 networks classify the TriTruss modules and can integrate other classification networks into the pipeline if the need arises while the PASS project progresses. The object classification and segmentation pipeline is shown in Fig. 4b.

Once the classification network has identified the TriTruss module(s) in the RGB frame, the bounding box and segmentation data from the object classification can be used to crop the point cloud data from the depth frame to provide a tightly cropped 3D scan of the object of interest to preform pose estimation. Like the classification stage, the pose estimation software is designed to the modular. This allows for the ability to easily test and evaluate various pose estimation techniques and algorithms. We have successfully integrated an Iterative Closest Point (ICP) algorithm implementation for point cloud registration to generate pose estimation into the pipeline and have begun to explore TEASER [12] for more robust pose estimation.

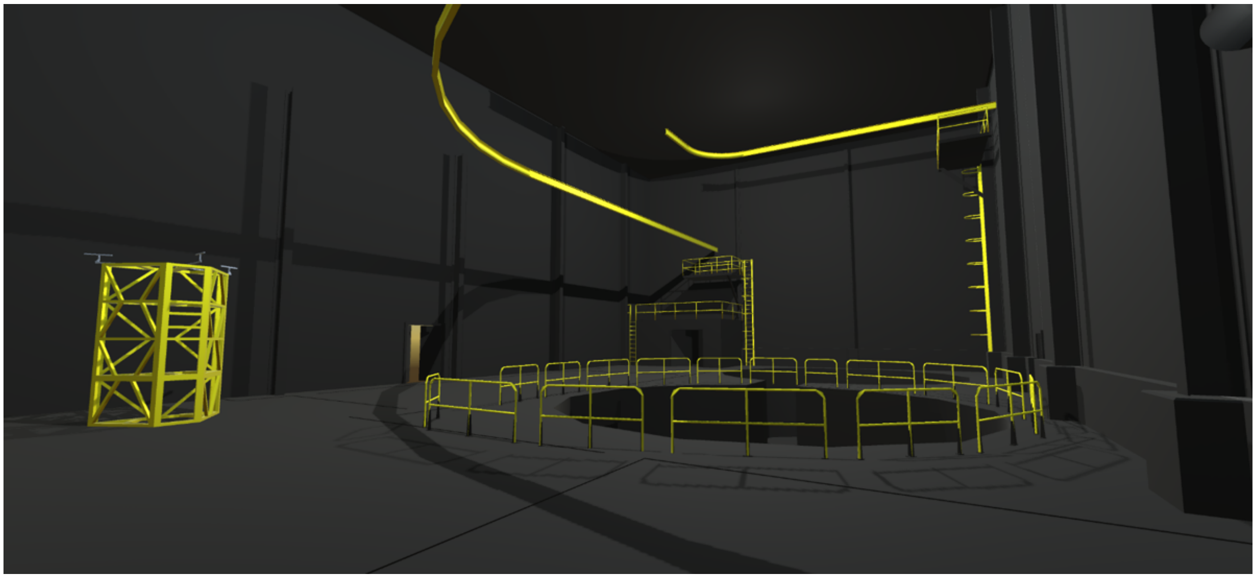
D. Simulation Environments

To support the research and development efforts of designing and developing a software architecture for PASS, robust simulations tools have also been integrated to enable test and evaluation of software modules and operational changes to support evolving con-ops. Two simulation tools are currently being utilized: the ROS2-based Gazebo simulation [13] and the NASA Langley developed Unity-based Baseline Environment for Autonomous Modeling (BEAM)[6][14]. Both are DDS-based simulation tools which allows for easy integration with the software architecture. By using DDS-based simulation environments, the same code used to control the physical hardware is exercised by the simulation, thus enabling verification and validation before execution on the physical system.



(a) Three TriTruss assembly in simulation.

(b) Simulated grapple mechanism.



(c) Simulated environment for Bldg 1268 OSAM Laboratory at NASA Langley.

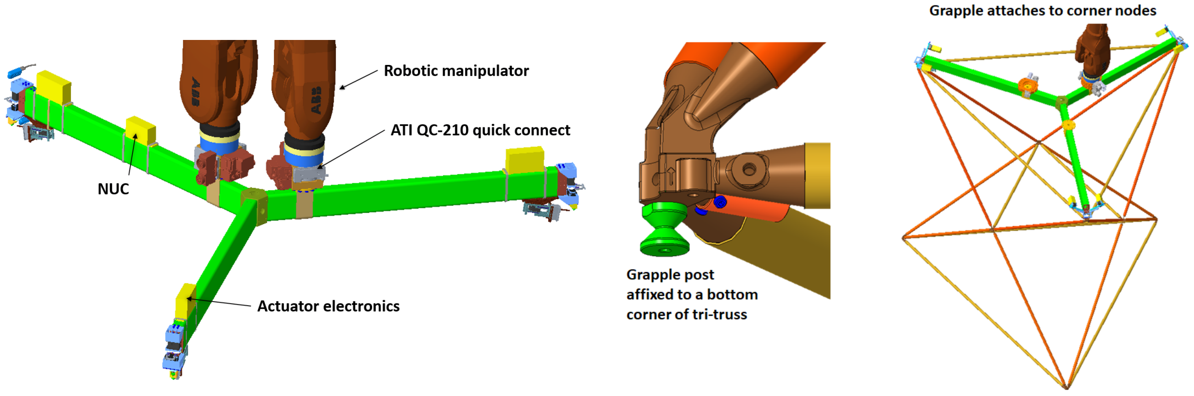
Fig. 5 TriTruss, grapple mechanism and robotic manipulators in simulation.

IV. Hardware Capabilities

As discussed previously, PASS will be conducting a physical assembly demonstration of an iSAT mirror backing structure to test, evaluate and advance the autonomous system technologies required for such a mission. This section will provide more detail into the hardware design considerations of the grapple mechanism and the proposed assembly demonstration process.

A. Grapple Mechanism

The grapple mechanism is an end-effector uniquely designed to grasp and manipulate TriTrusses for the purpose of in-space assembly with a triangular pattern with three spokes emanating from the center structure housing a 'quick-change system'. Linear actuators are located at the end of the spokes that are used to clasp specifically designed protrusions at the bottom of TriTrusses called 'grapple posts' as shown in Fig. 6. Combined with on-board sensors, actuator drivers, and a single board computer enables the end-effector to participate as an intelligent agent with mobility provided only by capable manipulators.



(a) Grapple mechanism components.

(b) Custom grapple mechanism attaching to TriTruss modules.

Fig. 6 Grapple mechanism overview.

The central quick change system provides the means for the end-effector to be swapped or 'handed-off' to another manipulator as shown in Fig. 7. Although electric systems are preferred for space environments, a pneumatic system was selected as a result of a trade study to satisfy testing of in-space operations in Earth's gravity. The quick change system is composed of two halves identified as base and tool sides where each manipulator is outfitted with the base side and the tool side for the end-effector. Additional pass-through modules to provide the end-effector with power and communications.

Supporting the complicated hand-off of the grapple mechanism are an array of exteroceptive sensors with sensor fusion for run-time pose estimations to reduce uncertainties in the workspace. Initially this will be provided using a stationary VICON motion capture system that will later serve as a performance evaluation system. A combination of passive and active sensors such as cameras and LiDARs will replace the VICON system in a later study. The published pose-estimations will feed the dexterous position control of the grapple mechanism and a multi-manipulator workspace analyzer to determine optimal positioning of both manipulators. The multi-agent motion planning and trajectory generation systems subsequently use all available information to determine optimal collision-free, temporally de-conflicted, and dexterous trajectories to execute. Since the grapple mechanism is treated as an individual intelligent agent, it will be able to influence PASS operations by providing additional information to run-time planners, controllers, and task managers.

B. System Evaluation Experiment Approach

Three configurations have been determined to evaluate the hardware and research algorithms in incremental stages to ensure safety and proof of concepts.

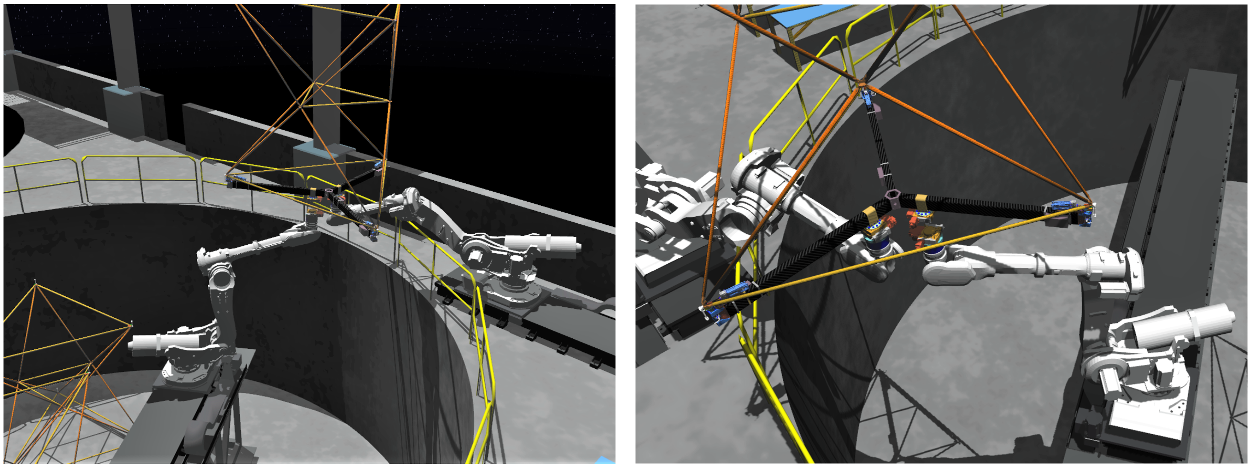
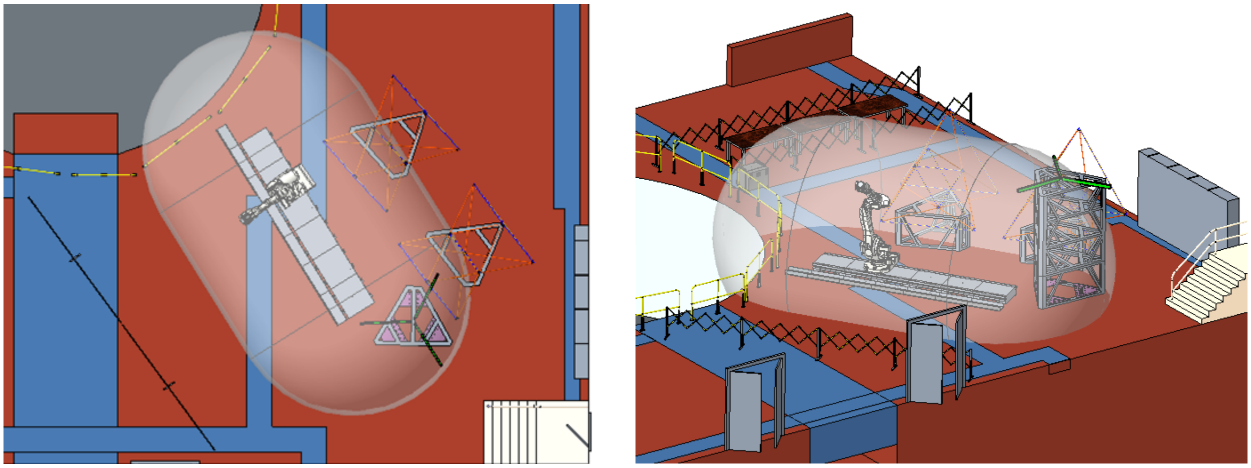


Fig. 7 Coordinated hand-off of grapple mechanism from two viewpoints.

Phase I

A single linear track and serial manipulator with grapple mechanism positioned in close proximity to a small rigid structure with a single truss mounted on top as shown in Fig. 8. In this configuration the manipulator system will perform the assembly of a three TriTruss structure by acquiring and fastening two additional TriTruss modules to mounted TriTruss module on the raised platform. The system will be evaluated for its dexterous manipulation of a TriTruss in close proximity to a rigid structure.



(a) Top View with Workspace Visual **(b) Side View**

Fig. 8 Phase I Experiment Configuration with Initial Truss Support Structure.

Phase II

The second experimental configuration substitutes the rigid structure holding the initial TriTruss for a turn-table allowing for the assembly structure to rotate and greatly increasing the system's workspace. Again the system will be evaluated for dexterous manipulation performance but will include an uncertainty analysis, collision avoidance, and temporal de-confliction of trajectories. Using a turn-table will also enable the system to assemble multiple TriTrusses to complete up to two complete rings of a mirror backing structure furthering the initial proof of concept.

Phase III

Lastly, the third experimental configuration relaxes initial assumptions and restrictions to examine pragmatic concerns of ISA such as acquiring TriTrusses from storage, increasing system workspace incorporating new tools, techniques, and approaches. This will involve a second robotic manipulation system positioned in the pit and the first moved to a different location where both manipulation systems overlap as shown in Fig. 9. The outer manipulator system would pick up TriTrusses, stored safely away from assembly operations, and bring them into the workspace of the manipulator system in the pit that will assemble TriTrusses underneath the rotating turntable. Handing-off the grapple mechanism is an efficient method compared to other approaches as TriTrusses are only designed to be handled by a single end-effectors and forces/torques need to be minimized for safe operation. Several technologies would need to be researched and developed to include optimal workspace analysis for manipulator placement for grapple mechanism hand-offs, implement force/torque control using the wrist 6 axis force/torque sensor, robust sensor fusion and reduction of uncertainty for collaborative dexterous coordination.

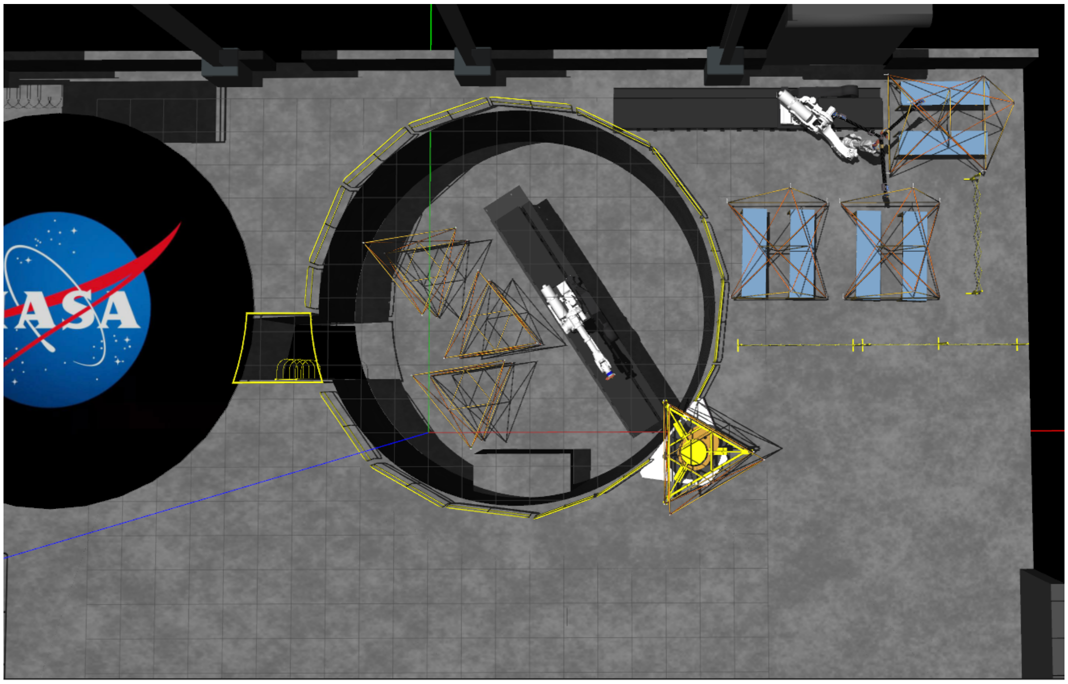
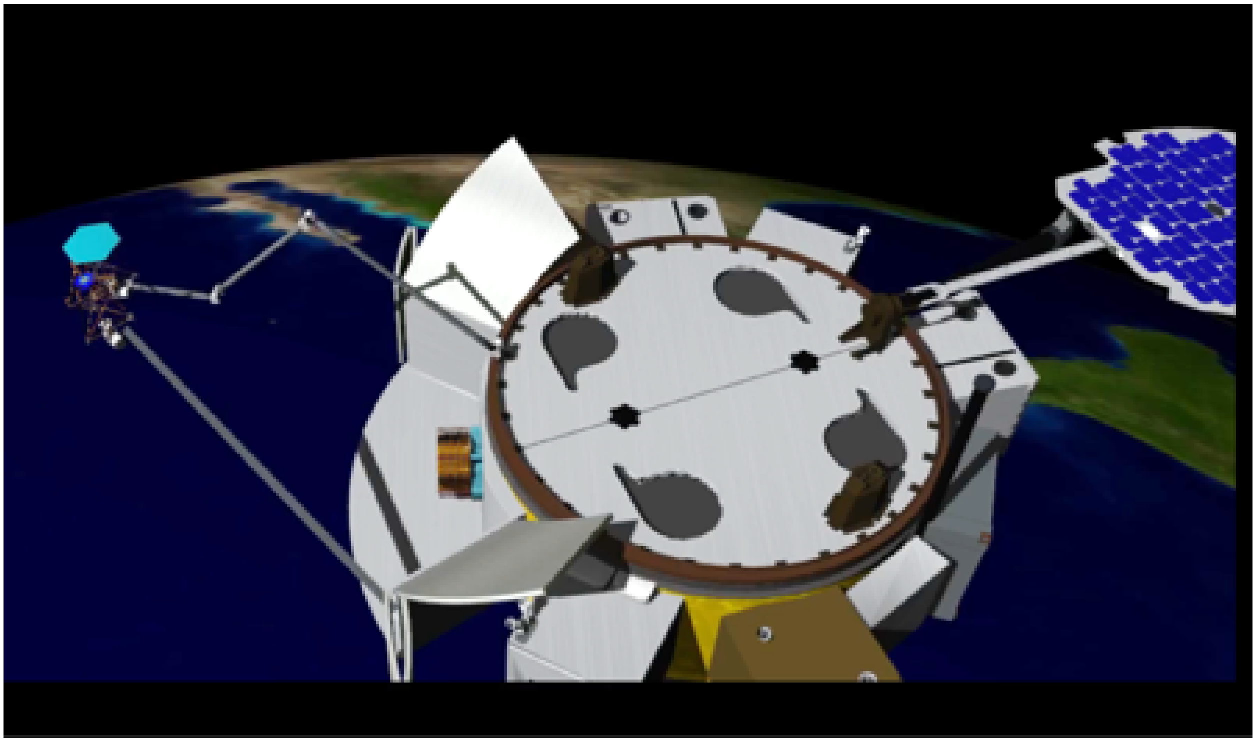


Fig. 9 Phase I experiment configuration with two robotic manipulation systems.

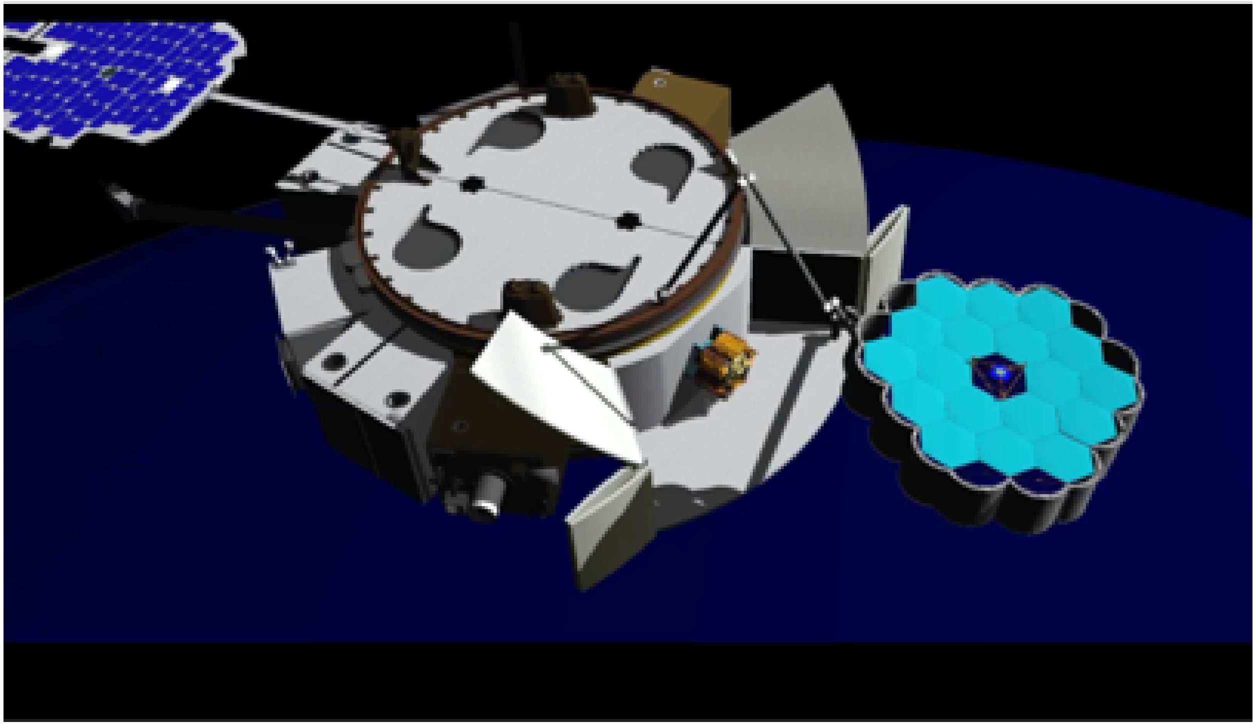
V. Conclusion

The proposed software architecture for the PASS project has already proven to be a valuable approach. The distributed communication and modular design has enabled the early integration of simulation environments as an integral part of the development and testing cycle. The modularity of the system has allowed researchers to easily swap various algorithms and software modules with minimal impact on the rest of system. These design features have allowed the project to not only easily experiment with different software component approaches and implementations, but also to effectively experiment with various con-op considerations.

This has enabled the use of simulations to begin looking beyond the terrestrial demonstration of the iSAT DRM. One proposed con-ops is to validate the autonomous in-space assembly paradigm with the use of an evolved expendable launch vehicle (EELV) secondary payload adapter (ESPA) class experiment[15]. This concept is shown in Fig. 10. Scaled TriTruss modules, robotic manipulators and grapple mechanisms can be integrated and housed in an ESPA payload module and Fig. 10a shows this module beginning deployment. A telescoping manipulator extends to act as a temporary turntable from which a highly actuated manipulator proceeds with an assembly process similar to the PASS terrestrial DRM. This completed two ring assembly is show in Fig. 10b.



(a) ESPA payload assembly con-ops in simulation.



(b) Complete ESPA assembly.

Fig. 10 ESPA ring assembly concept.

Appendix

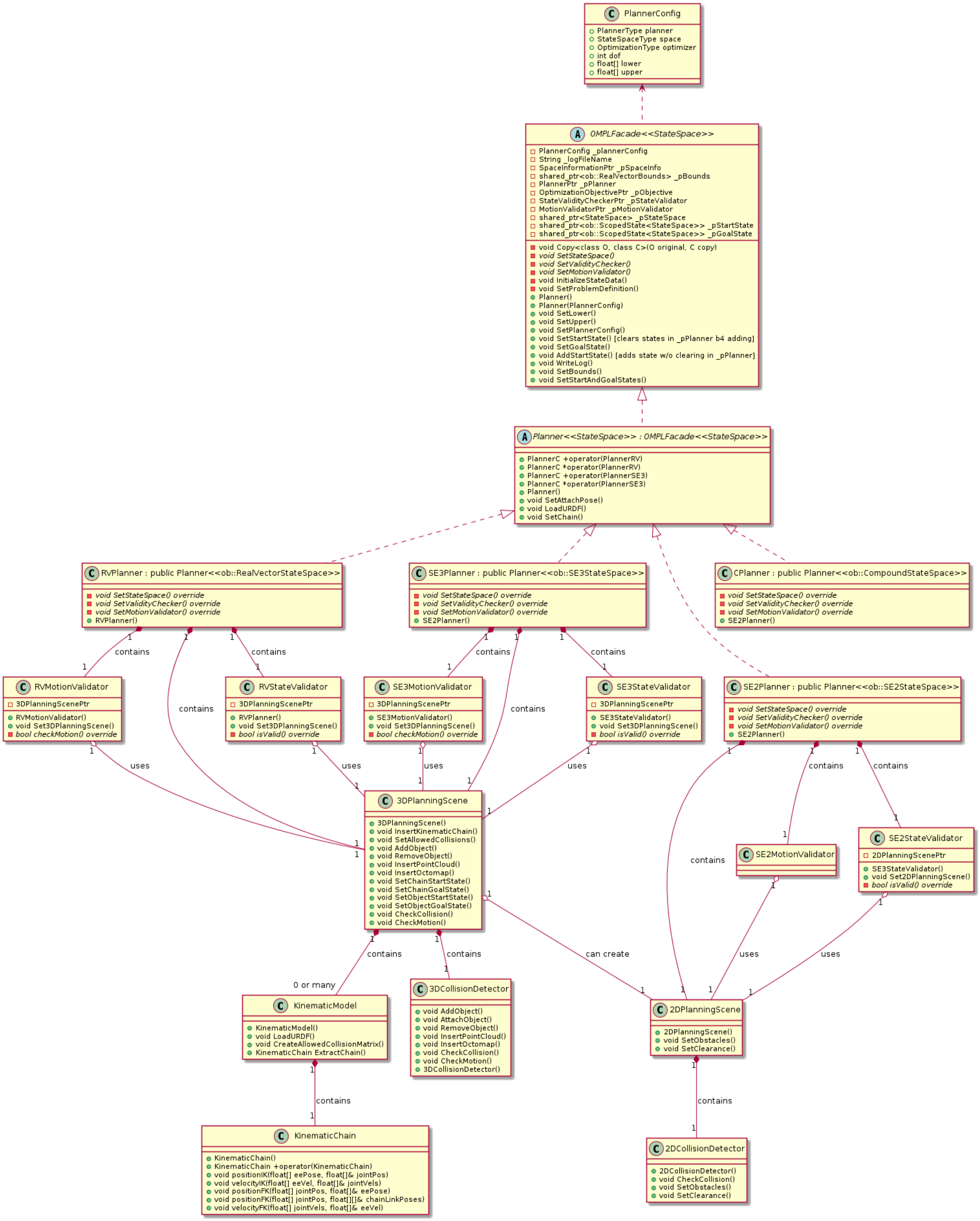


Fig. 11 Class Diagram of Trajectory Planner.

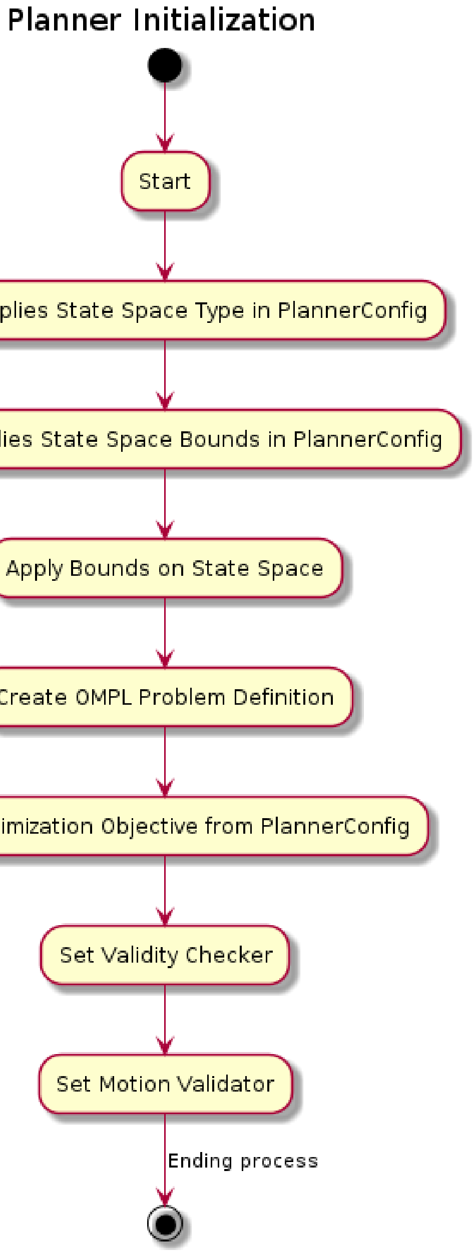


Fig. 12 Trajectory Planner Execution Sequence.

Acknowledgments

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