

Test Results for Autonomous Assembly of Modular Space Structures

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This paper presents test results for autonomous assembly of a modular space structure. A Universal Robots UR10e manipulator with a custom end-effector, known as the Grapple Tool, was used to join TriTruss structural modules. The TriTrusses and their assembly configuration were developed for an in-space assembled telescope conceptual design. The tests presented here were performed with a 1:2.8 dimensionally scaled version of the Tri-Trusses. Robot trajectories were generated autonomously using a sample-based motion planner and an a-priori worksite model. The test results verify the assembly concept of operations as well as the software requirements for the Grapple Tool. While the Grapple Tool used in the tests was designed for the 1:2.8 scale Tri-Trusses, it has the same actuators, software, and computation architecture as the version designed for the full scale structure. The test operations consist of picking up two TriTrusses from their stowed locations and joining them to a third TriTruss mounted on a test stand and joining them to each other. This constitutes the first three modules of the in-space assembled telescope conceptual design. The paper presents the robot behavioral architecture, the generated trajectories commanded, the actual trajectories of the robot, and actuator performance of the Grapple Tool.

I. Introduction

THE contribution of this paper is a concept of operations for autonomous assembly of a modular space structure validated through hardware tests. In-space servicing, assembly, and manufacturing technologies have the potential to revolutionize the space ecosystem. NASA's On-orbit Servicing, Assembly, and Manufacturing 1 mission will demonstrate servicing of an existing spacecraft via teleoperated robotics [1]. The introduction of modular structural design and autonomous systems can greatly enhance reparability as well as enable new types of spacecraft. This paper represents a proof of concept for such an architecture. In the hardware tests presented herein, a Universal Robots UR10e manipulator was used to position structural modules to be joined. A custom robotic end-effector, known as the Grapple Tool, was used to both grasp modules at their stowed locations and attach them to other modules in the existing structure. Once attached, the robot applied a test load to verify the connection was successfully made. Results are presented for an assembly of three modules. Figure 1 shows the configuration in the Subscale In-Space Assembly Laboratory at NASA Langley Research Center, and figure 2 shows the final state after three modules have been joined.

The testing was performed as part of NASA's Precision Assembled Space Structure (PASS) project. The design reference mission of the project is construction of an in-space assembled telescope based on the concept proposed in the NASA in-Space Assembled Telescope (iSAT) Study [2]. The study concludes that in-space assembly is likely the only means to achieve a space telescope with aperture greater than 15 m. The design concept has a backbone truss structure composed of structural modules, dubbed TriTrusses [3, 4]. A mirror segment would be attached to each TriTruss. Figure 3 shows the iSAT design concept. The iSAT mirror is 20 m in diameter. The PASS project will perform a full scale ground demonstration of the assembly of the backbone truss structure for the mirror. The results presented in this paper represent the first steps in the buildup to this demonstration.

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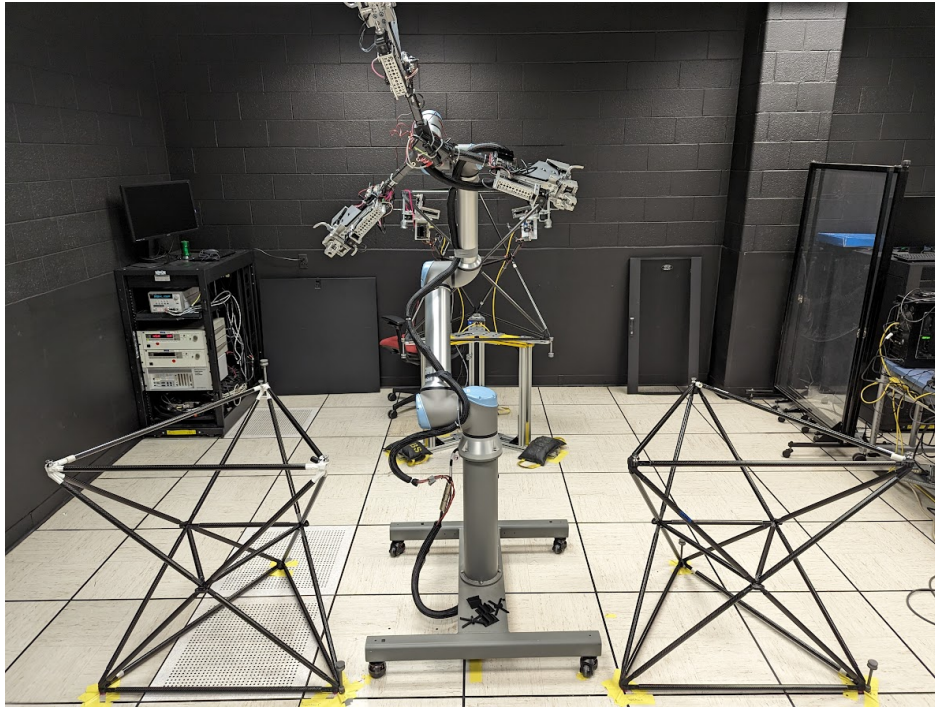


Fig. 1 Starting state for TriTruss assembly test in the Subscale In-Space Assembly Laboratory at NASA Langley Research Center

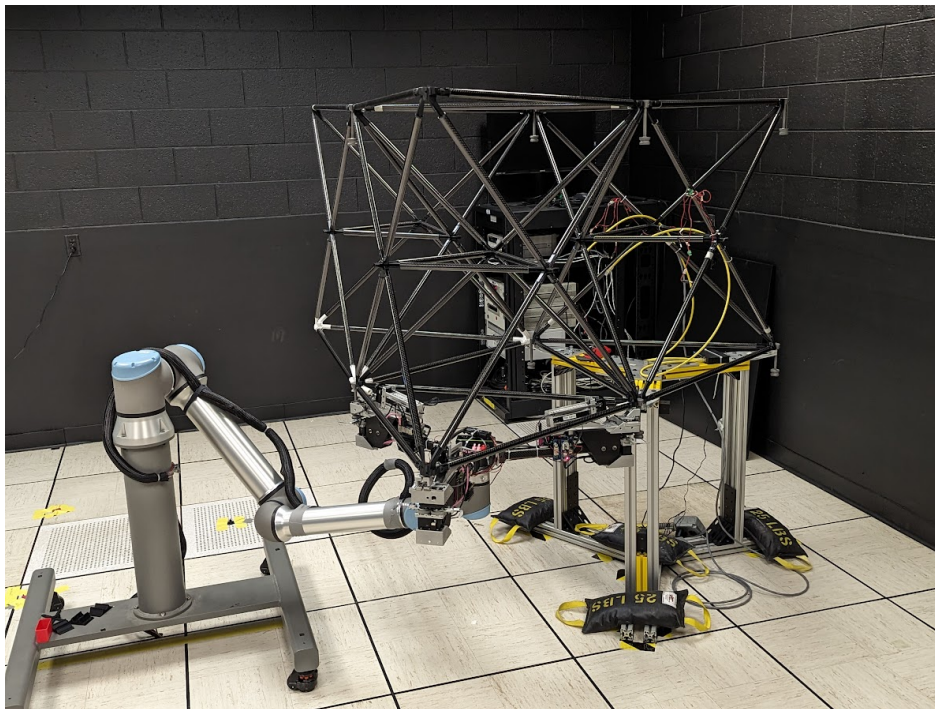


Fig. 2 Fully assembled three-TriTruss system

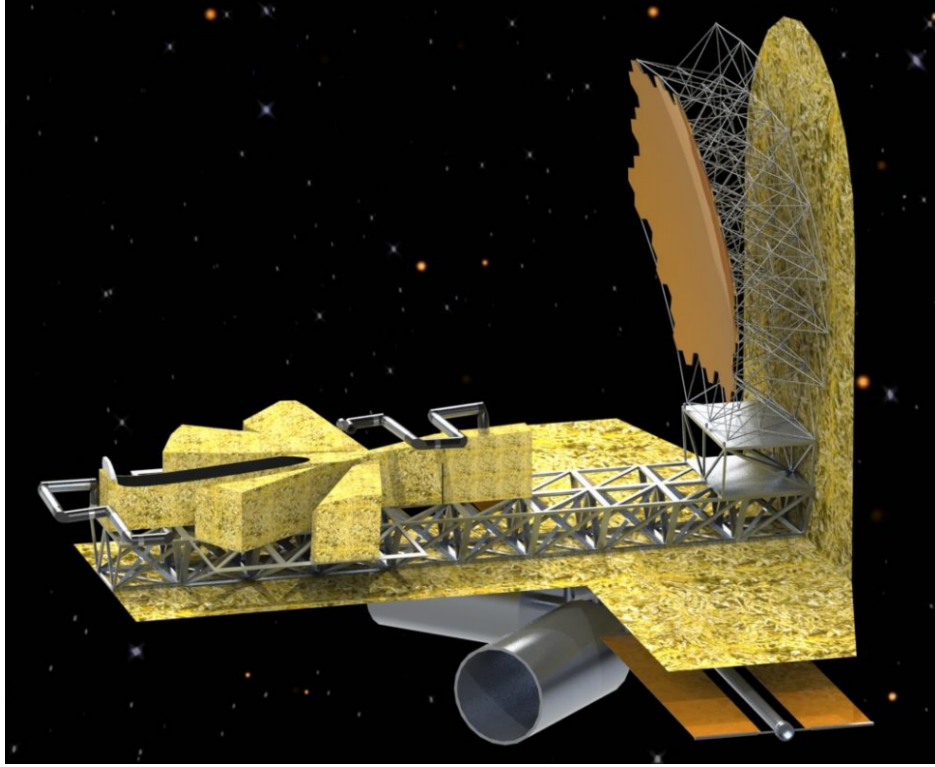


Fig. 3 In-Space Assembled Telescope design concept

The test results presented here use a 1:2.8 scale version of the TriTruss also referred to as the 1 m TriTruss since 1 m is the length of each side on the triangular face. A single 1 m TriTruss is shown in figure 4. The test results presented herein validate the robot trajectory generation pipeline and the Grapple Tool software. The Grapple Tool uses the same actuators, electronics, and software as the full scale version.

The remainder of the paper is organized as follows: section II details the methods used for robot trajectory generation, section III describes the Grapple Tool design, section IV presents the test procedure for assembling three TriTruss modules, section V provides test results and data, and finally conclusions are drawn in section VI.

II. Trajectory Generation

The Robot Operating System (ROS2) ecosystem is leveraged for trajectory generation and control of the manipulator [5]. The MoveIt motion planning software [6] is used to interface to the Open Motion Planning Library (OMPL) [7]. Trajectory generation is performed using a model of the robot's workspace with mesh representations of obstacles.

A six degree of freedom end-effector goal state is provided. This corresponds either to the grasping pose for picking up a TriTruss or the insertion pose to connect the TriTruss to the rest of the structure. First, the robot inverse kinematics are used to find a robot joint state that satisfies the end-effector goal state. If the resulting joint state is valid, i.e. no constraints are violated (joint limits, collision constraints), a Cartesian motion planner finds a motion from the goal state to an approach point. This Cartesian motion is executed in reverse to bring the end-effector from the approach point to the goal state with the desired payload orientation. This step ensures that the goal state is reachable from the approach point. Next, the Rapidly-Exploring Random Trees (RRT) algorithm [8] is used to plan the gross motion from the starting state to the approach point. At each step of this pipeline, constraints are checked using a planning scene which represents all objects in the robot workspace.

III. Grapple Tool

The Grapple Tool is used to grasp and attach TriTrusses and was first presented in [9]. The version of the Grapple Tool used in the tests presented here is designed for the 1:2.8 scale TriTrusses but retains all actuators and electronics,



Fig. 4 1 meter TriTruss

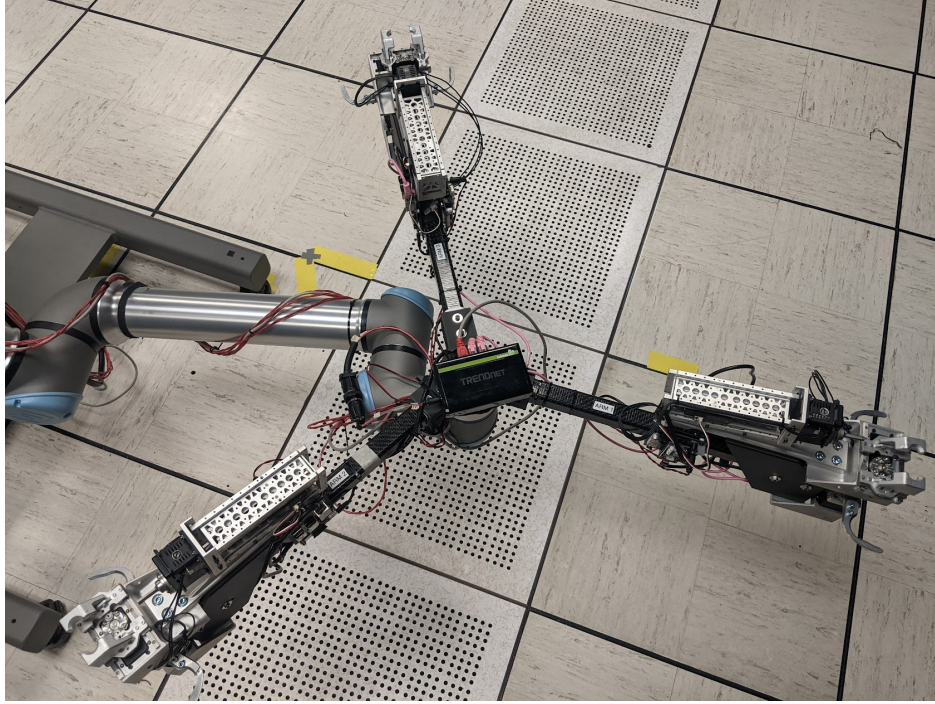


Fig. 5 Grapple Tool

and software of the full scale version. Therefore, these test results validate the Grapple Tool software requirements.

Figure 5 shows the Grapple Tool used for the tests. It has three prongs for grasping each corner of the triangular face of the TriTruss. Each prong has an identical set of actuators: three Dynamixel MX-106 rotary servos and one MightyZAP 12Lf-78PT-53 linear actuator. Figure 6 shows the configuration of the actuators at each end of the Grapple Tool. One rotary servo controls the Post Fingers which are used for grasping the TriTruss. Another rotary servo controls the Capture Fingers which grasp a Capture Post attached to the TriTruss that is to be joined with on the existing structure. This ensures fine alignment between the two TriTrusses. The final rotary servo is used to rotate the Lock Screwdriver while the linear actuator pushes it forward. This mechanism drives a bolt which joins the two TriTrusses.

IV. Test Procedure

The initial conditions for the test consist of one TriTruss attached to a test stand and the robot and two other TriTrusses in predefined starting poses as shown in figures 1. The test was carried out as follows. Note that in future work, manual fine alignment steps will be replaced by a visual servoing algorithm discussed in [9].

- 1) The robot plans a trajectory to pick up the first TriTruss using the trajectory generation algorithm of section II.
- 2) Fine alignment is performed manually using the UR10e teach pendant.
- 3) After fine alignment, the Post Fingers close on the TriTruss Grapple Post. At this point, the robot's payload information is updated using a mass model of the TriTruss.
- 4) The trajectory generation algorithm is used to plan a trajectory to the insertion point for the first TriTruss.
- 5) Again, manual fine alignment is performed.
- 6) The robot switches into a compliance control mode and the Capture Fingers close on the Capture Post attached to the TriTruss that is being joined. Compliance control allows the Capture Fingers to pull the robot into a final position such that the Lock Screwdriver can drive a bolt to join the two TriTrusses.
- 7) The Lock Screwdriver tightens the bolt to 8.4 Nm using torque feedback from the rotary servo. Once the bolt is tightened, the Lock Screwdriver backs out and the Capture Fingers open.
- 8) The robot applies a 100 N test load in the axial direction of the bolt. This ensures the connection was successful.
- 9) The robot payload information is updated to remove the previously held TriTruss.
- 10) Cartesian motion planner is used to drive the robot along a retreat path.
- 11) Steps 1-10 are repeated with the second TriTruss to complete a three-truss assembly.

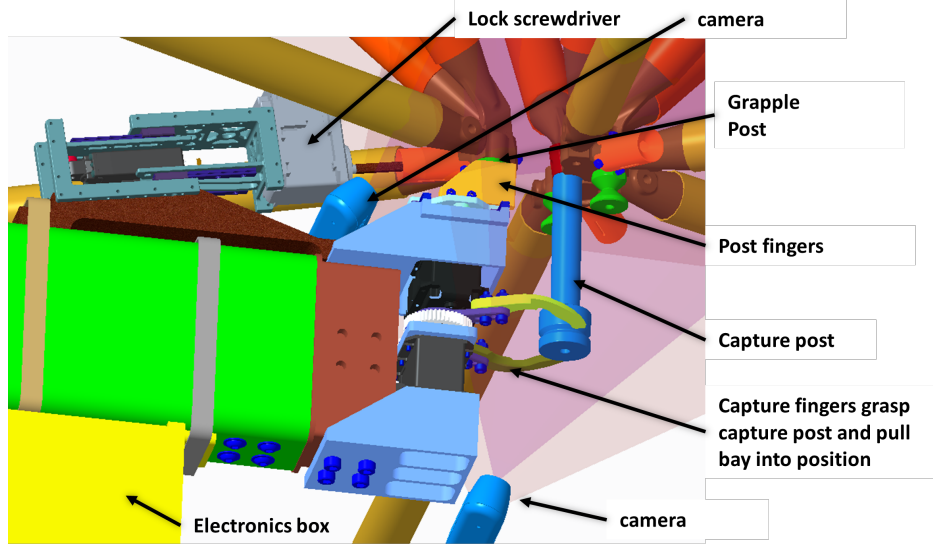


Fig. 6 Grapple Tool components

V. Results

A. Robot Trajectories

The joint positions and end-effector state of the robot during the assembly operation are shown in the following figures. Figure 7 shows the joint positions for the first trial, figure 8 shows the end-effector states for the first trial, figure 9 shows the joint positions for the second trial, and figure 10 shows the end-effector states for the second trial.

In both trials the sensed joint positions tracked the desired positions. Slight tracking errors occur when the payload changes (TriTruss grabbed or let go) as the robot's mechanical brakes are engaged during this step.

The end-effector state is represented in a fixed frame attached to the robot base. x , y , and z represent the Cartesian position, and ϕ , θ , and ψ represent x , y , and z Euler angles respectively. Note the high frequency oscillations in ϕ are a result of angle wrapping between π and $-\pi$, and this signal is not used for feedback.

B. Actuator Data

Positions and currents are plotted for each Grapple Tool actuator during three trials of TriTruss attachment. Figure 11 shows these data for the rotary servo that drives the Capture Fingers as they close around the Capture Post.

Figure 12 shows the position and current of the rotary servo of the Lock Screwdriver as the bolt is being tightened, and figure 13 shows the same for the linear actuator of the Lock Screwdriver. Note figure 13 includes the linear actuator backing out after successfully driving the bolt.

Figure 14 shows the position and current for the rotary servo that drives the Capture Fingers as they open after the Lock Screwdriver successfully drives the bolt.

Finally, figures 15 and 16 show the position and current of the Lock Screwdriver rotary and linear actuators respectively as the bolt is being removed.

C. Test Load Data

After joining the TriTrusses, the robot was used to apply a 100 N test load in the direction of the bolt axis. This ensures that the connection was successful. A force/torque sensor built in to the UR10e was used to verify this load. Figure 17 shows the force data in this direction while the test load was applied during the three TriTruss attachment trials.

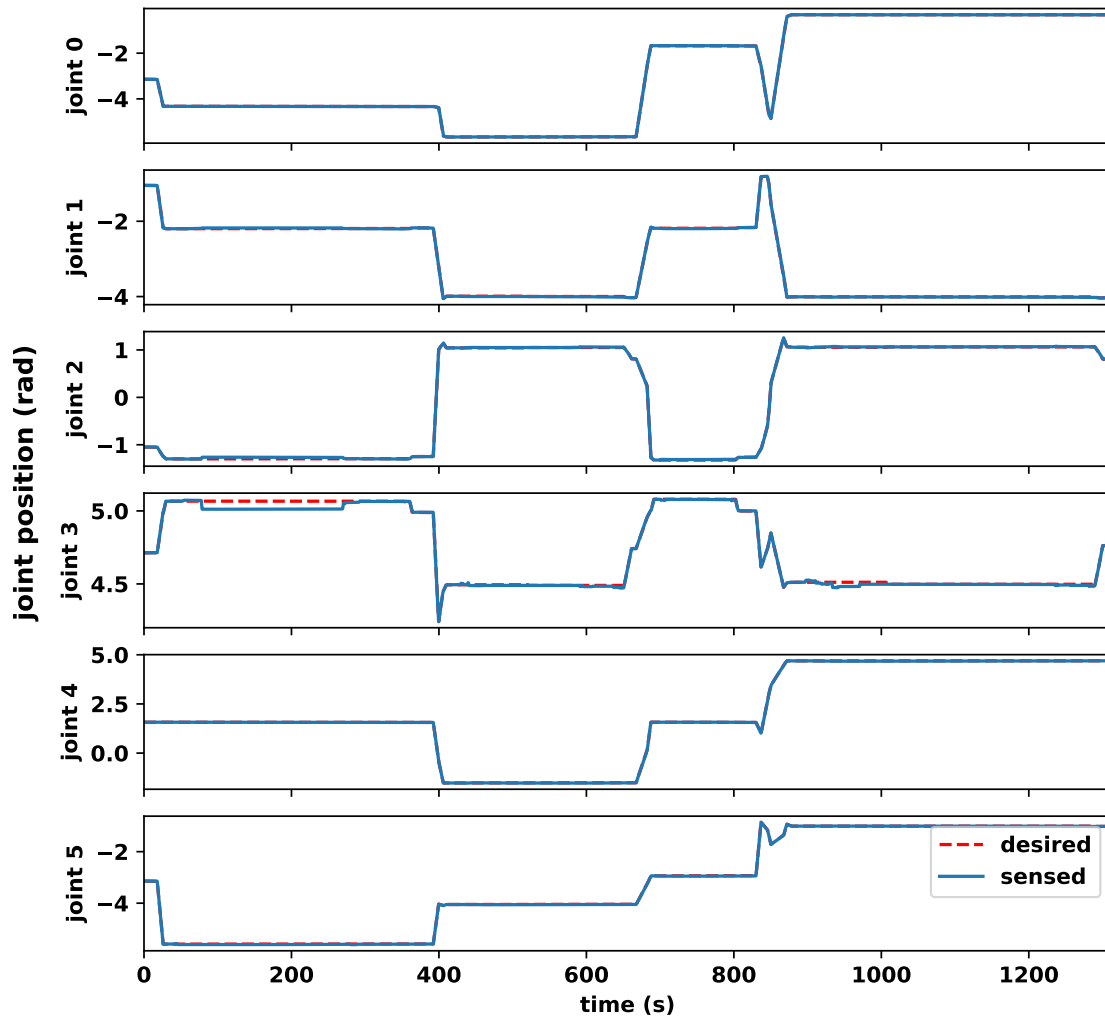


Fig. 7 Robot joint angles commanded and measured during trial 1

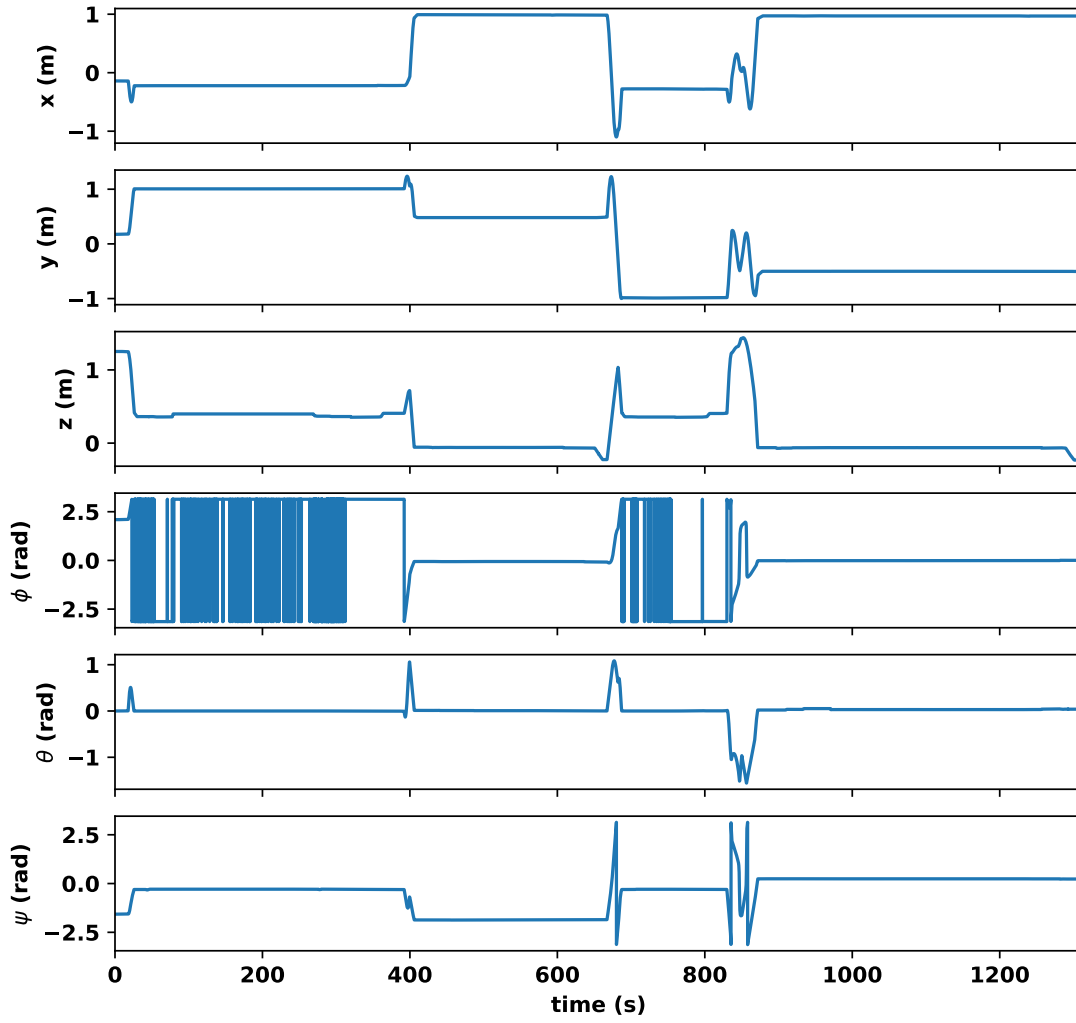


Fig. 8 End-effector state during trial 1

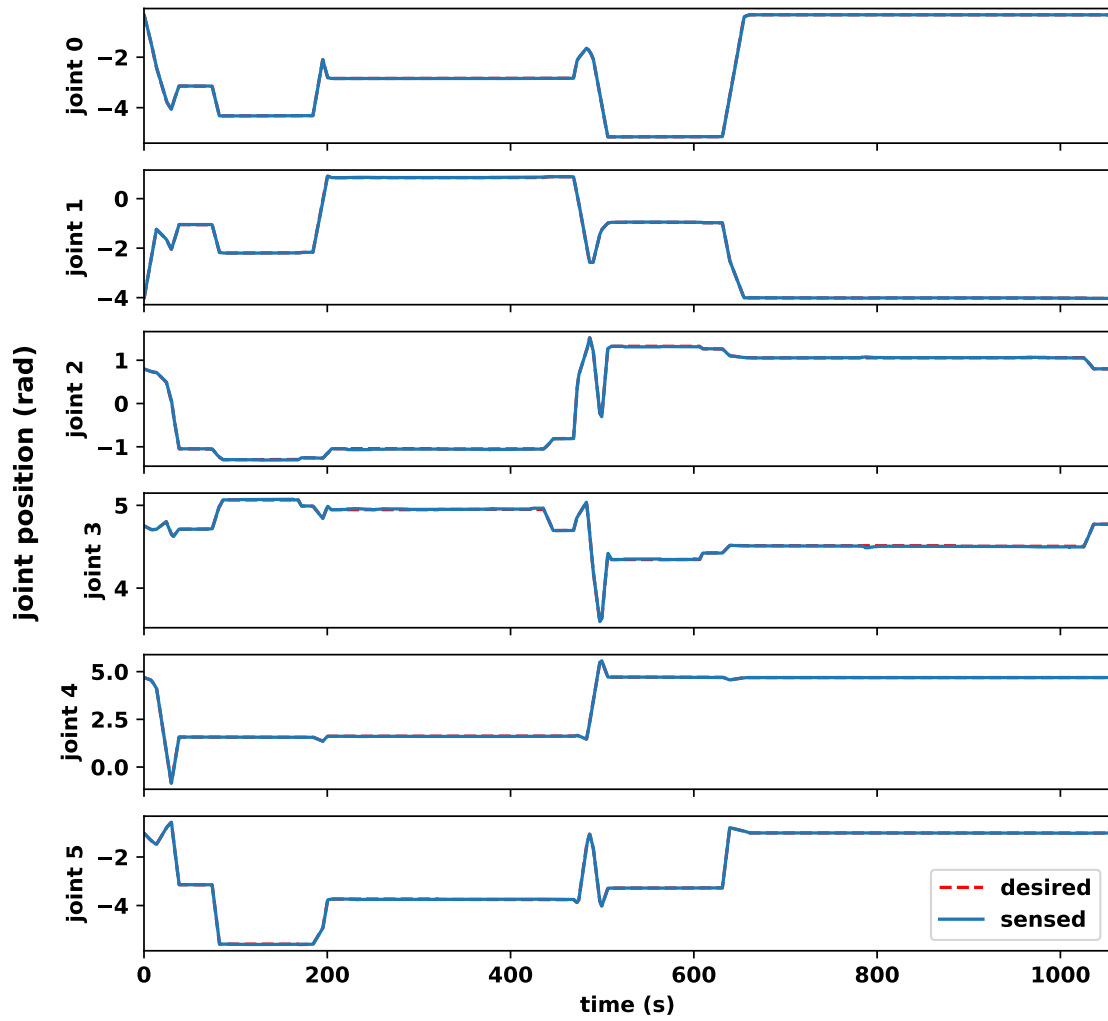


Fig. 9 Robot joint angles commanded and measured during trial 2

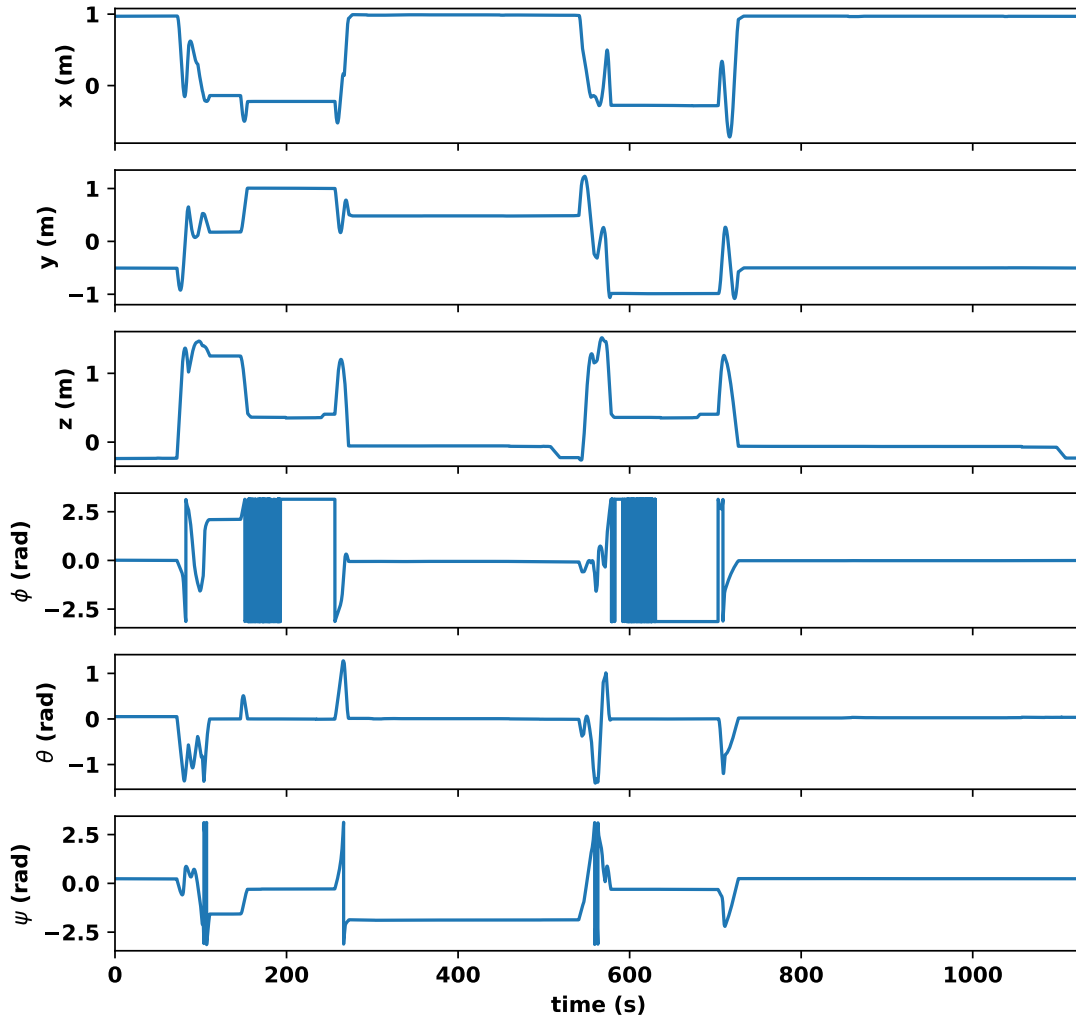


Fig. 10 End-effector state during trial 2

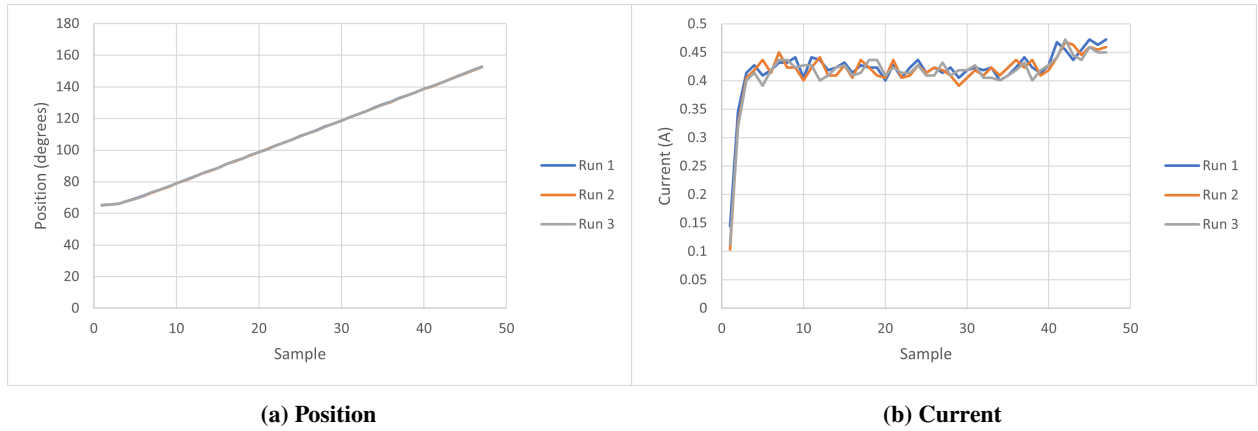


Fig. 11 Position and current for the Capture Fingers actuator as the Capture Fingers closed around the Capture Post

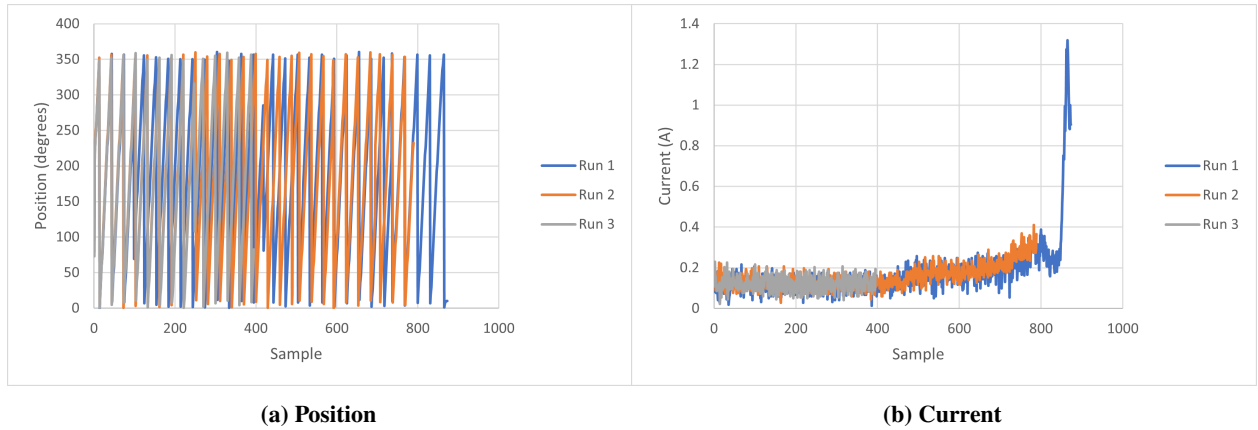


Fig. 12 Position and current for the rotary servo of the Lock Screwdriver as the bolt is being tightened

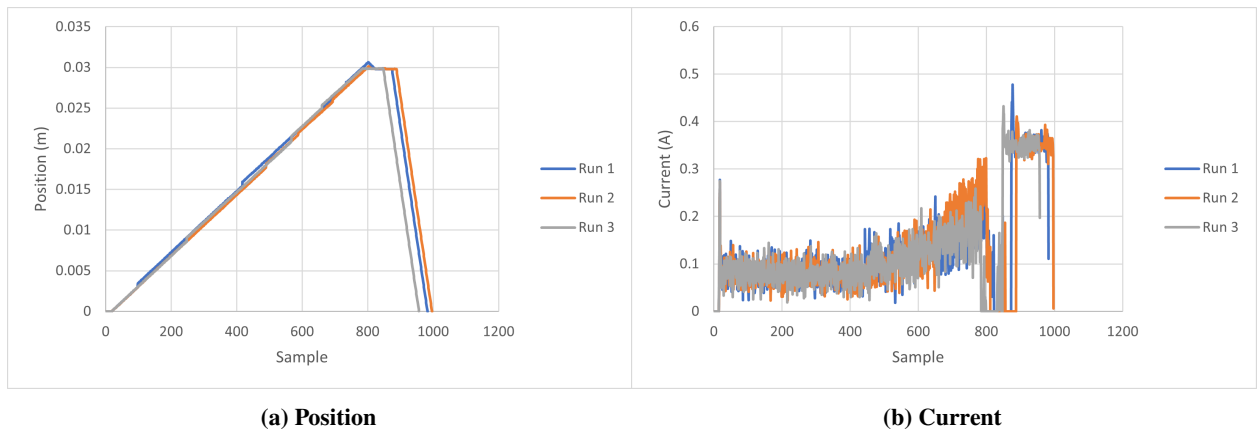


Fig. 13 Position and current for the linear actuator of the Lock Screwdriver as the bolt is being tightened

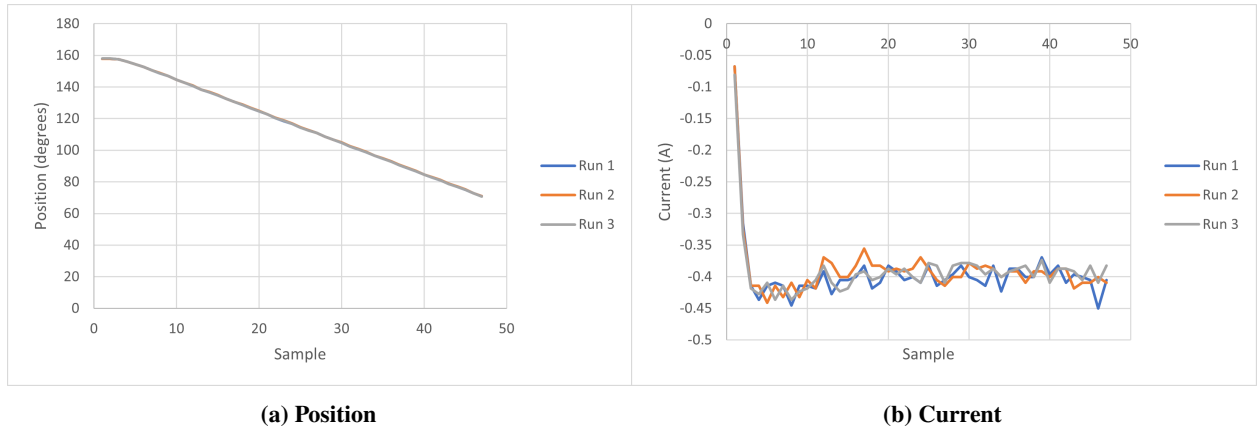


Fig. 14 Position and current for the Capture Fingers actuator as the Capture Fingers open after the Lock Screwdriver successfully screws the bolt

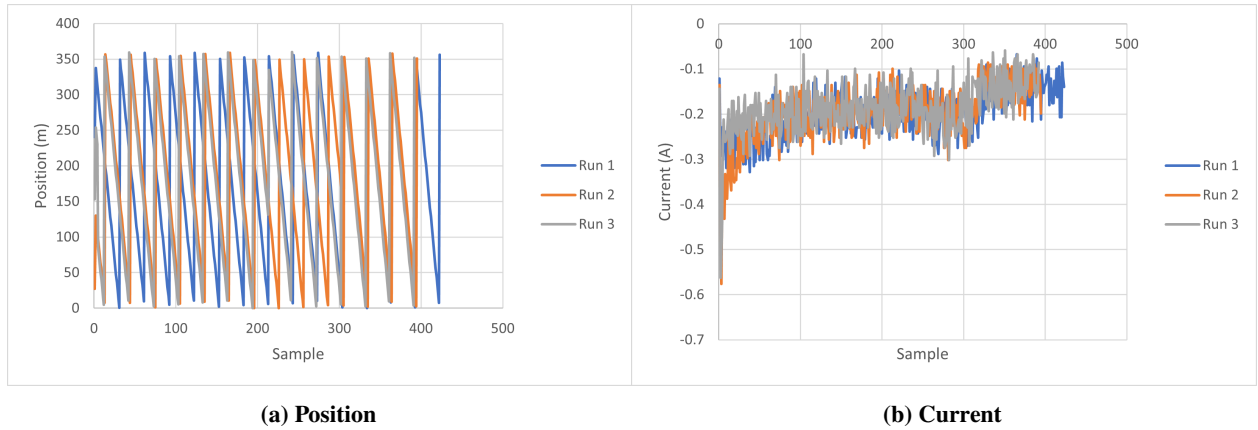


Fig. 15 Position and current for the rotary servo of the Lock Screwdriver as the bolt is being removed

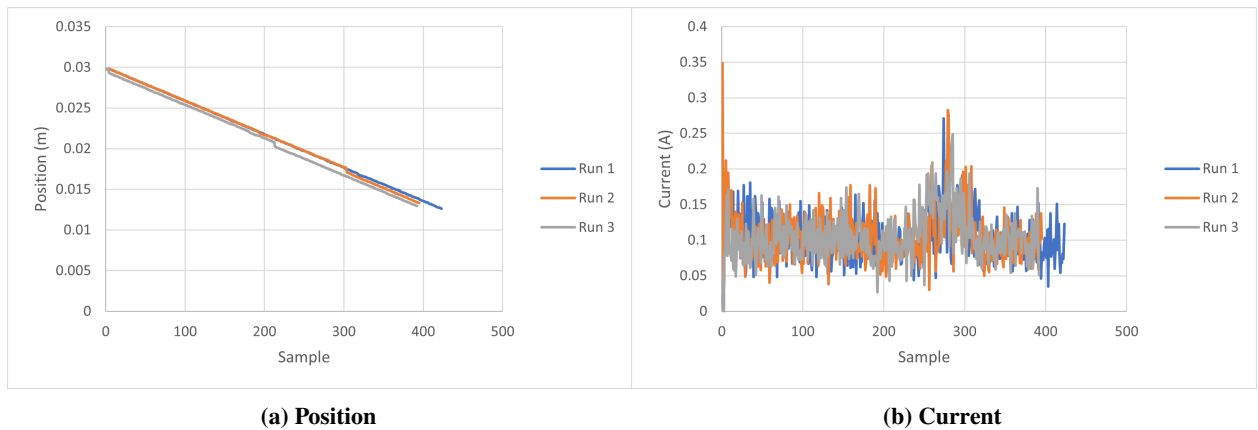


Fig. 16 Position and current for the linear actuator of the Lock Screwdriver as the bolt is being removed

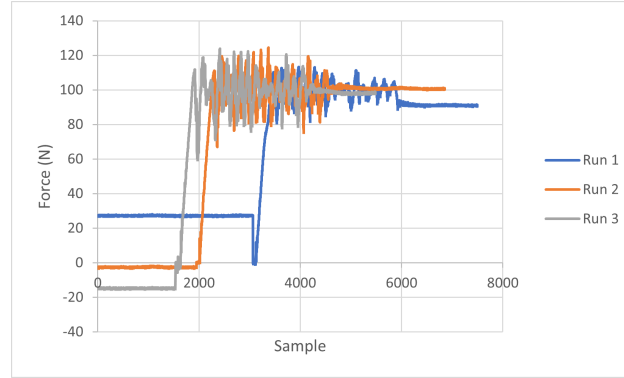


Fig. 17 Force applied during test load

VI. Conclusion

The test results presented here verify the feasibility and repeatability of the autonomous assembly concept of operations. This basic concept can be used to enable new types of spacecraft that can be easily repaired, extended, and evolved. The remaining gap is how to integrate visual servoing for fine alignment. Future work will explore this concept. Additionally, future tests will further enhance the reliability of the autonomous systems by demonstrating larger assemblies with more TriTrusses, and testing with the full scale, 2.8 m TriTrusses and Grapple Tool.

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