A Collaborative Manipulation Strategy for the Assembly of Space Trusses

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Abstract—This submission describes a method for a team of collaborating robots to construct truss structures in which each truss element is a free component. The work presented here is a prototype for a method to assemble a solar array backbone truss, in which a team of robots with distinct capabilities collaborate to assemble, position, and join the truss elements. To mitigate the risks associated with close collaborative contact, this method uses mechanical means such as capture volumes and passive compliance, and algorithmic means such as an application of the EKF-SLAM algorithm for mapping the structure, localizing the robots, and improving assembly accuracy. This submission also presents the results and analysis of an initial hardware experiment with limited autonomy\(^\text{1}\), along with descriptions of the ongoing and upcoming experiments with added autonomy.

I. INTRODUCTION

Autonomous in-space assembly (ISA) in orbit and on the surfaces of other worlds is a major interest of both NASA and the space industry. Practical ISA would decouple spacecraft size from launch vehicle size, enabling larger solar arrays for solar electric propulsion vehicles, higher bandwidth communications satellites, larger scientific instruments, and habitats, to name a few things\(^\text{2}\). Ambitious ideas currently seen as too distant, such as telescopes that can image exoplanets, and sustainable long-term colonies, would be within reach. On Earth, the technology required for practical ISA would transfer well. Assembly is required for objects of all purposes and scales. In specific cases, this is done by scripted robots in tightly controlled environments, streamlining manufacturing to the great benefit of society. For everything else, manual assembly remains the state of the art. Autonomous assembly systems would make assembly safer and more efficient, but they require improved perception, estimation, motion planning, and decision making capabilities before they can supplant manual methods.

Autonomous assembly is a challenging problem whose solutions have wide applicability to field robotics. Construction is a collaborative activity by necessity. Assembly tasks extend beyond snapping parts together, and include cutting and shaping parts, overcoming manufacturing errors, reusing or repurposing parts, making ad-hoc corrections to propagated errors, and inducing stresses to align parts. Often, the attachment of a subassembly requires several agents coordinating to complete the task. In the field, assembly robots are expected to operate with added mobility and versatility, and must handle uncertainties in both sensor inputs and events in a dynamic environment.

In recent years, Langley Research Center has developed an assembly approach in which tasks are distributed between specialized agents, including a type of robot called an Intelligent Precision Jigging Robot (IPJR)\(^\text{3}\), whose primary purpose is to position and hold objects that are later joined by other robots; and a long reach arm for performing gross manipulation tasks. The assembly system employs optimal state estimation in the assembly workspace to maintain a map of the evolving structure and assembly agents, uses sequencing algorithms, and detects and corrects errors. In one telescope assembly scenario, an IPJR and a long reach arm assembled and welded a titanium telescope truss to 3 mm

\(^1\)Accompanying video can be found here\(^1\)

\(^2\)Accompanying video can be found here\(^2\)

\(^3\)Accompanying video can be found here\(^3\)
accuracy\cite{4}. In \cite{5}, a team of IPJRs collaborated in assembling a curved truss structure utilizing MLE-SLAM with only local measurements to position parts and to guide corrections to geometrical placement errors, reducing nodal positional error growth from $O(n^3)$ in the number of parts, to approximately constant nodal errors dominated by per-step process noise. In one solar array assembly scenario, a Stewart platform IPJR and a long reach arm collaboratively manipulated, assembled, joined, and deployed solar array modules on a backbone truss. This system employed EKF-SLAM, a general assembly sequencing algorithm, and strategies to prevent induced stresses in collaborative manipulation scenarios\cite{6}. This IPJR was later used in a related scenario using two different long reach arms\cite{7} to deploy a backbone truss and demonstrate tool repositioning.

Related research also explores the theme of distributed manipulation and assembly; a team of three robots collaborated to join a part to a structure \cite{8}, a pair of robots precisely assembled beams using rigid motions \cite{9}, and an arm assembled and disassembled a telescope truss with reflector segments \cite{10}. Industry also has a strong interest in this area, leading to competitions such as the Airbus Shopfloor Challenge \cite{11}, which builds on peg-in-hole assembly \cite{12}. The assembly of furniture \cite{13} \cite{14} serves as a testbed for approaches that have widespread applicability.

II. Motivation

A common feature in the design and implementation of space structures is the backbone truss, which serves as a rigid and lightweight platform linking the modular elements of a spacecraft. One such truss forms the backbone of the International Space Station, for example, and individual backbones support the solar arrays. The current paradigm for launching backbone trusses is to design them to be compactly stowed for launch, and to self-deploy once in orbit. The mechanisms that enable these operations add parasitic mass and reduce the stiffness and precision when compared to a similar welded truss.

Trusses can be made stiffer and lighter by eliminating deployment mechanisms and self-aligning mechanical interfaces, but doing so requires assembly agents (astronauts and/or robots) capable of substituting for these tasks. In a flight scenario, the backbone truss components will be launched in a densely packed configuration. The steps required to build a truss from this configuration can be categorized as:

- Remove the components from storage.
- Transport the components to the assembly site.
- Transfer the components between robots.
- Position the components to the accuracy required by the structure.
- Join the components to the growing structure.

Each of these steps requires manipulation, which combines motion planning and control with an estimate of the workspace state accurate enough to ensure correct operations. Depending on the tools used, any of these steps could require multiple robots collaborating to manipulate individual components. This, in turn, requires agents to work in close range and in contact with other agents. If closed kinematic chains are formed, residual stress must be handled or damage will occur. Positioning and holding truss elements prior to, and during, the joining operations is an exercise in motion planning in confined spaces where collisions must be avoided.

III. Truss Assembly Strategy

Instead of using a single type of robot engineered to perform every task, the strategy presented here uses a team of simpler robots with distinct capabilities to achieve the same tasks. For truss assembly, these tasks include high-precision element alignment ("jigging"), dexterous element manipulation, and long reach manipulation. The robots that perform these tasks are shown in Figure \ref{fig:robots} and are respectively the NASA Intelligent Jigging and Assembly Robot (NINJAR), the Lightweight Surface Manipulation System (LSMS), and the Strut Attachment, Manipulation, and Utility Robotic Aide (SAMURAI). These three robots collaborate to assemble and join square bay trusses in which the truss elements have wide tolerances while loosely connected, permitting the mitigation of error growth. Following joining, backlash is eliminated and the joints are rigid.

A. Truss Design for Assembly

The truss was designed with features to facilitate assembly by distributed robots. Figure \ref{fig:truss} highlights the relevant features. A semi-circle bracket joint is located at each node, and each side of the bracket has a flat surface to enable fillet welds to be formed against the flat edge of the struts that meet at the bracket. The interior of the bracket has a metallic plate that attaches to Electro-Permanent Magnet (EPM) grippers on the NINJAR. The bracket has holes that allow the loose mechanical connection of struts to the joints with flexible tabs, which prevent the struts from detaching prior to being welded. The center of the bracket is hollowed out and has a spherical feature enabling the SAMURAI to grasp it from a range of positions for strut insertion. A special end-effector called an Electron-Beam Welder (EBW) welds the joints by grasping the joint, and moves the welding head on a radial line away from the node centers while it welds both edges of a strut end to the joint. The EBW only works in a vacuum, so for the ground experiments presented here, welding was simulated by hot melt adhesive deposited along the interfaces.

To simplify the on-orbit assembly process, some assembly can be done in advance. In this experiment, each pair of joints are pre-joined to a single strut; this object is called a Strut Joint Pair (SJP), and is treated as a single rigid body object for state estimation. An SJP is shown in Figure \ref{fig:truss}A-C.

B. NINJAR: Precise Positioning and Jigging

The NINJAR is a Stewart platform parallel manipulator with high precision and stiffness relative to serial manipulators. Its key role is to position and hold components relative to one another during the joining process using end-effectors attached to both end plates. The Stewart platform controls the relative
position and orientation of the objects held by both end plates. The end-effectors in use depend on the task. For the square bay truss assembly task, an entire bay of struts and joints must be held in place prior to joining. To achieve this, the NINJAR holds the components of each bay while on the inside of the bay. A single square bay consists of 8 joints and 16 struts, requiring each plate to grasp 4 of the joints, which it does using EPMs. The loose mechanical connections linking the struts to the joints eliminates the need for the NINJAR to grasp the struts independently prior to welding.

Starting with a base plate containing a pre-assembled “batten” frame, the NINJAR holds and positions the 4 new joints relative to the 4 previously welded joints. Each new bay builds on the batten frame made in the previous step. In this experiment, the NINJAR rests on a turntable, so the truss must be repositioned each time a bay is added. During the repositioning process, the NINJAR retracts its 8 joint grippers to mitigate the possibility of collision. Then the NINJAR positions its end plate to grasp the 4 joints on the batten frame once the truss is within grasping range.

C. LSMS: Compliant Long Reach Manipulation

The LSMS is a general purpose long reach manipulator that performs several roles in the truss assembly process. The LSMS:

- Transports SJP s and free struts from storage to the assembly site via the SAMURAI end-effector,
- Enables the SAMURAI to hand off the SJP s to the NINJAR, and to insert struts into joints,
- Repositions the truss after each bay is built, enabling the construction of a new bay, and
- Is designed to position the Electron-Beam Welding tool, enabling welding.

The LSMS is a tendon-actuated arm with passive compliance — this enables it to deform under stress if a contact event occurs, without damaging the rest of the assembly system. It is fixed to the floor resting on a turntable which rotates about the vertical axis, and possesses three arm joints providing planar mobility. Used in concert with NINJAR’s turntable, the LSMS possesses sufficient range of motion to access both the NINJAR and the truss storage. The LSMS was designed with versatility in mind, and can be attached to a mobile base; or, with special end-effectors, it could locomote in an inchworm fashion.

D. SAMURAI: Dexterous Strut Manipulation

The SAMURAI is an end-effector on the LSMS designed to be a swappable tool. Unlike the general purpose LSMS, the SAMURAI is tailored to the truss assembly task. The SAMURAI:

- Grasps SJP s and struts from storage, and can change the distance between its grippers to accommodate various strut lengths,
- Grasps the node spheres located at the center of the joint brackets to both force a specific position relative to the joints, and react against the mechanical insertion force, and
• While holding a strut and grasping the joint centers, inserts the strut flexible tabs into the joint brackets, creating a loose mechanical connection prior to welding.

The design of the grippers for both the struts and the joint centers had capture alignment features that enabled accurate grasping starting from a position on the order of 1 mm of error. The compliance in the LSMS prevented excessive loads and damage to the SAMURAI and the truss during capture.

E. Measurement, Estimation, and Control

Metrology for the assembly demonstration was provided by a fourteen-camera Vicon motion capture system. The cameras were arranged in a semicircle around NINJAR to provide the best coverage of the assembly workspace. Tracked objects made of retroreflective markers were attached to the SJPs, NINJAR end plates, SAMURAI arms, LSMS wrist, and strut storage. The positions of each Vicon tracked object were provided to the assembly control system, which applied the Extended Kalman Filter with a stationary state transition model to generate a complete state estimate. While simple to implement, the stationary state transition model causes a notable lag in the filter if objects are moving. This was mitigated by slow robot motion.

A dedicated computer called the Langley Control System (LCS) controlled all of the robots, and updated the state estimate based on the inputs from the Vicon system. LCS ran a control loop which iterated over several steps in sequence:

1) The LCS collected the most recent camera measurements.
2) The LCS applied the EKF to the measurements to update the robot and truss state estimates.
3) The LCS evaluated the current step, and if the goal was met, started the next step or exited the loop if assembly was complete.
4) The LCS generated commands for all robots to advance to the positions required by the current step.
5) The LCS could relinquish control to a human operator using a joystick if deemed necessary.

A more detailed explanation of the algorithm implemented on the LCS for a related experiment can be found in a previous paper describing the Sequential Assembly with State Estimation algorithm.

IV. Experiment Setup

The truss assembly experiments are ongoing as of this submission. The goal of the experiments are to demonstrate that the assembly system can construct a 2-bay truss whose node centers are 32 inches (812.8 mm) apart, and can achieve on the order of 1 mm and degree accuracy, following the sequence shown in Figure 4. The reference for accuracy was first established by performing a “dry run” which resulted...
Collaborative Assembly of Square Bay Truss:

1. for number of bays do
2. for each of 2 Strut-Joint Pairs (SJP) do
3. LSMS positions SAMURAI at storage: Figure 2A
4. SAMURAI grasps SJP
5. LSMS positions SAMURAI for capture: Figure 2B
6. NINJAR grasps SJP
7. SAMURAI releases SJP: Figure 2C
8. NINJAR positions SJs relative to truss base
9. for each of 10 remaining struts do
10. LSMS positions SAMURAI in front of storage
11. SAMURAI grasps strut: Figure 2D
12. LSMS positions SAMURAI for capture: Figure 2E
13. SAMURAI grasps joints: Figure 2F
14. SAMURAI attaches strut
15. SAMURAI releases joints: Figure 2G
16. for each strut-joint interface do
17. EBW stand-in joins strut to joint: Figure 3A,B
18. LSMS positions end-effector to grasp truss base plate
19. NINJAR releases joints
20. LSMS lifts truss by length of one bay: Figure 3C
21. NINJAR grasps joints
22. NINJAR inserts final diagonal strut
23. Repeat steps 19, 20
24. LSMS moves truss out of workspace: Figure 3D

Fig. 4. Summary of the square bay truss assembly sequence. Accompanying video can be found here.1

V. RESULTS

The first major experiment consisted of a single assembly trial utilizing all assembly robots to build a 2 bay backbone truss. Figure 5 shows that for all 4 SJP objects, the final position and orientation errors were within 2 mm and 3 degrees, meeting the order of 1 mm and degree goal. This error is better than what can be expected without the NINJAR. The broad clearance of the loose mechanical connection allows translational motion between struts and joints up to 3 mm on all axes, which would propagate to grow the SJP error over the construction of the truss. SJs 3 and 4, being located further away from the truss base plate, had larger errors due to sensitivity in orientation measurement of the truss base plate multiplied by the distance to the SJs, which is twice as large for the second bay. Three of the errors in Figure 5 are worthy of note. SJP 1 and 2, which were inserted by the SAMURAI, had large errors prior to the insertion of struts. The mechanical interface linking the NINJAR to the SJs had wide tolerances, enabling a range of valid grasping positions for the SJs while being held. In both cases, the subsequent insertion and adhesion served as corrective steps for the SJs. SJP 1 also had a large angular error after insertion but before adhesion, which was caused by the insertion of the struts. The adhesion step forced the strut ends to be coplanar with the joints, which corrected this issue.

Beyond meeting the accuracy goals, other behavior was observed. The LSMS and SAMURAI were able to position the SJs relative to the NINJAR to within 1.4 mm and 0.2 degrees prior to handoff, which was possible due to the SAMURAI achieving 0.3 degree angular accuracy when positioning the struts at the various angles. Additionally, the motion of the SJs was observed during the strut insertion steps, which is a collaborative manipulation step that formed a closed kinematic chain that imposed stresses throughout the truss and assembly robots. The maximum motion of a SJP during the strut insertion process ranged from 0.1 mm to 1.3 mm and 0.05 degrees to 1.2 degrees prior to rebounding to the prior position and orientation.

VI. CONCLUSION

The truss assembly experiment, along with the ongoing and subsequent experiments, demonstrate that a system of distributed specialized robots can collaboratively manipulate and assemble a truss structure starting from free struts and joints, and achieve an accuracy on the order of 1 mm and degree for a structure with a size on the order of meters. This is a significant step toward assembling truss structures in orbit and on the surfaces of other worlds, which will serve as the backbones for a variety of unmanned and manned structures.

As noted before, each subsequent assembly experiment will add autonomy and remove humans from the process. In a flight scenario, the presence of the human operator is expected for missions in low Earth orbit or geosynchronous orbit. For distances ranging from the distance to the Moon and beyond, autonomy will be required. Limited human participation may be expected in special circumstances; for example, astronauts...
in orbit around Mars might guide the assembly of a surface habitat; or a supervised autonomous process may go to sleep to allow humans on Earth to issue corrective commands to an assembly that encountered an unexpected problem.

The long term goal of this research is to remove the human operators completely, enabling distant assembly and manipulation operations. For this to be viable, autonomous space systems must have the ability to detect, identify, and correct a wide variety of problems including unanticipated problems. In this submission, a limited form of error correction enabled the assembly robots to interact safely, and to ensure the accurate placement of the SJPs. This is an early but vital step to achieving autonomous in-space assembly.

REFERENCES