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Identifying Driving Design Criteria for a Robotic In-Space Assembly System

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EXECUTIVE SUMMARY

Robotic in-space assembly (ISA) is in a closed-environment design space — all the objects in the environment are known, the objects have been designed and intentionally placed there. The robot(s) should not need to interact with non-manufactured items whose properties may not be known beforehand, such as rocks or dirt samples. This provides the opportunity to design both the robotic assemblers and the structure being assembled as a system rather than as two individual pieces.

This study focuses on identifying the major driving design concerns for a robotic ISA system. There are many design variables for developing a structure that must be assembled and the same is true for a robotic assembler. The major driving design considerations are those that have a large impact on the overall system and not just on the individual robot or the truss. For example, the size of each individual structural piece will drive the mass of the overall structure and will influence the length and required joint torques for the robotic systems.

There are many design criteria that will minimally impact the system but will impact the individual component, such as the robot's exact joint trajectory for moving an structural piece into place. For a redundant robot, different joint trajectories can be used to achieve the same end-effector path. The joint trajectories can be optimized to avoid collisions, to reduce joint torques, etc. While this can have a large impact on the robot operations, the impact to the structure and the overall system is low. The joint torques are defined more by the acceleration and velocity of the pieces being moved than the exact joint paths, as long as singularities are avoided. Therefore, the joint trajectories can be developed and modified further into the design process without having a major impact on the ISA system.

To truly optimize a robotic ISA system, each design variable should be chosen based on the effect on the overall system. In order to design and build these systems in a timely manner, it is not realistic to track all variables necessary to build a structure or a robot. Identifying the major and minor design criteria allows the overall system to be optimized while still allowing the structure and the robot to be developed in a timely manner while still greatly improving the overall system.

This study identifies a number of major design criteria for a robotic ISA: number of pieces, size of each structural piece, foothold location (for a walking robot), and acceleration of the structural components. It also identifies a number of minor design criteria, such as: joint trajectory, force distribution scheme when multi-arm systems are used, force of the robot on the truss (for a walking robot), and walking gait. It should be noted that some of the minor design criteria still require good engineering designs, and there may be circumstances under which they could become driving. For example, a multi-arm system working together can apply a squeeze force on the piece it is moving. This squeeze force does not contribute to the motion of the system and, in theory, could break the piece being moved. However, the structural pieces typically being considered are not exceptionally fragile (they must survive launch) and as long as the robot is "well-designed," this constraint is met easily. This is why these are categorized as minor design criteria; they are typically not driving but they also should not be forgotten.

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IDENTIFYING DRIVING DESIGN CRITERIA FOR A ROBOTIC IN-SPACE ASSEMBLY SYSTEM

1. BACKGROUND AND MOTIVATION

Space systems are inherently limited by the launch process— not just in terms of monetary dollars, but also in terms such as time and size. Space systems must be designed and built in order to reduce launch costs or else the systems would never get off the ground. In order to fit into the volume of existing launch vehicles, space systems use a number of different methods: some have limited their size while others use deployment systems in order to expand once in space. The James Webb Space Telescope, one of the largest and most important scientific satellites, has more than 100 deployment segments that expand from the 5-meter-diameter launch vehicle into its final form, which includes a 6.5 m primary mirror and 20 m-by-15 m sunshield [1]. These types of deployments are not without a cost, though, and as space systems become larger, the deployments will become too complex and the risk of failure too great [2–6]. The James Webb Space Telescope is pushing the limit of what deployments can do.

An alternative to complex deployment-and-unfolding schemes is *in-space assembly* (ISA), in which pieces or segments are launched and then are assembled in space. In addition to allowing for larger systems, this method also provides additional options in how pieces can be packaged into the launch vehicle. Typically, a single monolithic, system is designed based on the launch vehicle and can fit in only one configuration, and the orientation of the various parts is driven by the packaging. ISA can lead to a more densely packed launch vehicle, with pieces oriented or even supported to handle the launch loads better.

In addition, multiple launches can be used to build larger structures, such as the International Space Station. While the ISS was built using mostly human assembly, robotic assembly of the ISA allows the system to be built without the risk of human EVAs. In addition, robotic systems are not limited to an 8-hour workday, which will allow the structure to be assembled more quickly. Once the robotic systems have assembled the structure, they then can be used for repairs and upgrades. Robotic ISA will allow space systems to become more like their earth-based systems: flexible, capable of growth, and upgradable.

Robotic ISA is one of the few design problems in which both the structure being assembled and the assembler are open. This is ideal from a systems point of view; the robot and the structure can be designed together to make an overall better system. There are many trade-offs between the robot design and the structural design; one example is a structure built up using just a few very large pieces, requiring a very large robotic system. Another example would be a simpler robot that moves pieces into place but cannot connect them, which would require the connection mechanism to be built into each structural segment. Previous work demonstrated the benefit of designing the robot and the structure together [7–9].

This report contains the results of two main studies. The first study compares a stationary robotic ISA and a crawling ISA system, calculating the kinematics, dynamics, and estimating the mass of the entire system. This study is limited to the planar case and uses simplified rectangular truss segments. All of the manipulators are 3-degrees-of-freedom (DOF) planar manipulators with revolute joints.

The first study shows that the crawling robotic system is only more massive when the force put on the truss results in a higher truss mass. As a result, the second study focuses on the interaction of a crawling robotic system and the truss. This study extends the first study beyond the planar case. Each of the manipulators is expanded to 7DOF manipulators, allowing out-of-planar motion, and the simplified rectangular truss segments made up of 12 beams each are refined to triangular truss units made of up 21 beams.

2. COMPONENT DEFINITIONS

There are three major components for a robotic ISA system: the structure being assembled, the robot(s), and the assembly procedure. Each of these must be carefully planned and designed together in order to complete a successful ISA system.

2.1 Robotic Component

The robotic agent(s) are those that perform the assembly in space. The complexity, number, and design of these agents is part of the system-level design. This study focused on a single-robot system assembling a desired structure. The different types of robots are examined in the first part of this study. Figure 1 shows example of the different robotic types.

- **Crawling/walking:** Robotic system that moves along the structure during the assembly process; the system remains attached to the assembly at all times and uses the assembly to move itself.
- **Stationary:** Robotic system whose base remains fixed in one location.
- **Free-Flying:** Robotic system that moves along the structure during the assembly process under its own power; it uses its own propulsion system and does not attach to the assembly while in motion.

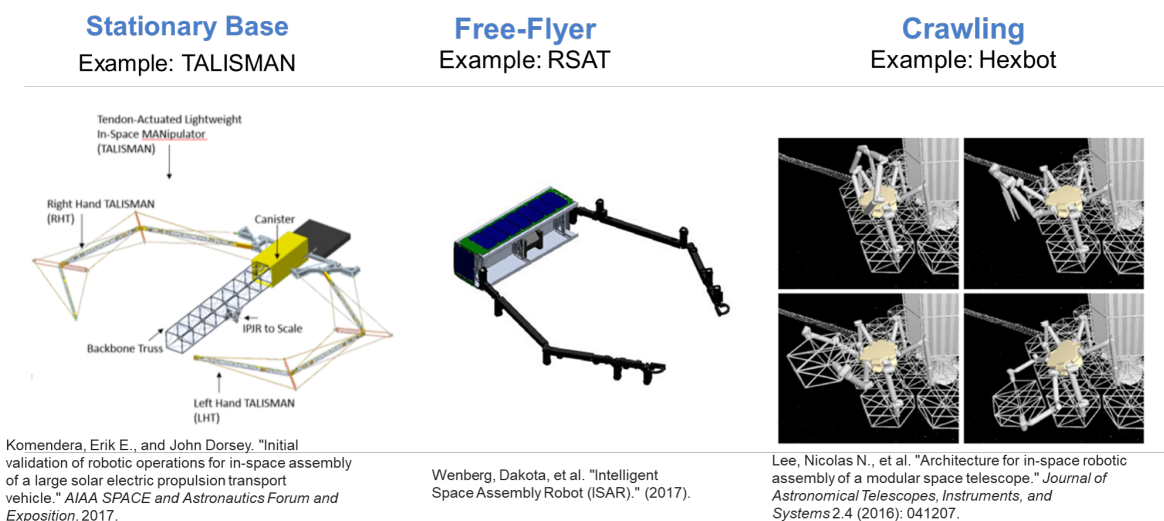


Fig. 1—Examples of different robotic types for ISA

2.1.1 Stationary Base Robotic System

The stationary base robot is defined by the use of a single positioning leg that remains firmly attached to the truss base. This single, long positioning arm moves the payload bay, otherwise known as the robot body. The payload bay houses the non-deployed truss segments and connects the the dexterous arms to each other and to the positioning leg. The two dexterous arms lower each truss segment from the payload bay and place them into the assembly; see Fig. 2.

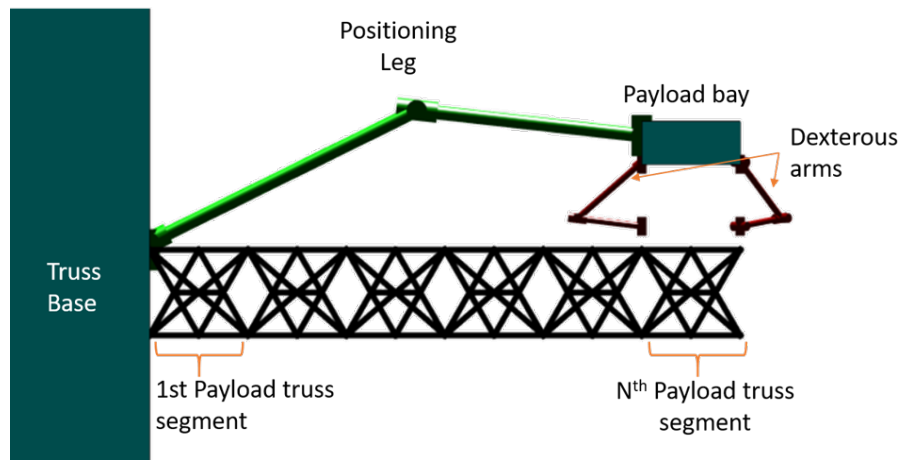


Fig. 2—Planar stationary robotic system

2.1.2 Crawling Base Robotic System

The crawling robotic system consists of multiple positioning legs. The planar simulations use two positioning legs, whereas the full nonplanar simulation uses four positioning legs. The positioning legs are attached to the robot body and are able to move across the truss. The truss segments have mounting points which the various legs move to; these mounting points are defined in a parameter file and are the same for each truss segment.

In the planar simulation, there are two points on each truss that the two positioning legs can mount to, one at the leftmost edge of the top of the truss and one on the rightmost; see Fig. 3. Both positioning legs are at the same leftmost mounting point as the dexterous arms lower and assemble a truss segment. Once the dexterous arms are done and have returned to their starting position (relative to the payload bay), the legs move one at a time to the right mounting point. Working together, the legs then move the payload bay horizontally so that it is place to assemble the next piece. Both legs share the same mounting point on the truss and the same grasping point on the payload bay, thus they have the same joint angles and geometry. Here, the force required to move the payload bay and to keep it still while the arms are performing their task is distributed evenly between the positioning legs.

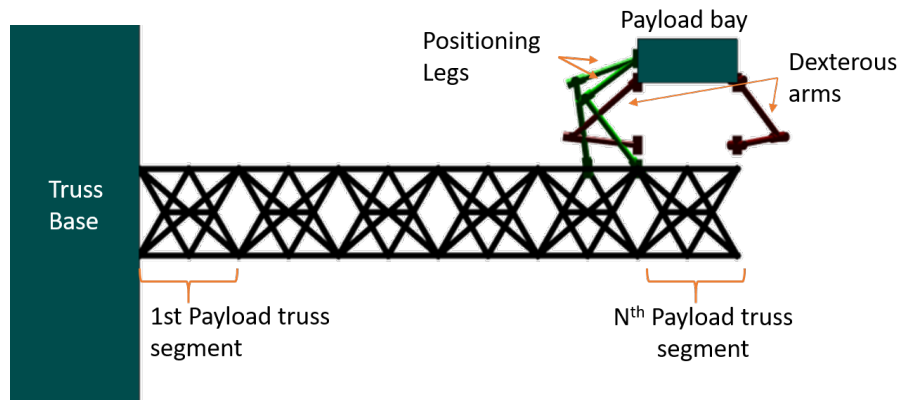


Fig. 3—Planar crawling robotic system

The second part of this study focuses specific design choices impact the total system for a crawling robotic, this study requires a nonplanar simulation. This simulation uses triangular truss segments rather than simplified rectangular trusses; see Section 2.2 for details. The corners are used for footholds and two different walking patterns are examined. As in the planar simulation, the legs work together to move the robot body into place and to hold the robot body stationary as the dexterous arms move the next truss unit into place. Unlike the planar case, the joint angles are not the same for the various legs. The triangular shape of the truss ensures that the joint angle for each leg is different from the others and an alternative force-distribution scheme is examined.

2.1.3 Free-Flying Robotic System

Free-flying robotic systems are not attached to the base structure; thrusters are used to move the robot body around the workspace. In this case, the workspace is not limited by the length of the manipulators but by the amount of propellant. These types of robotics consist of two parts: the manipulator(s) and the base. The base is a satellite capable of communicating with the main structure and performing maneuvers, and must be able to determine where it is relative to the structure. Forces and torques are not transferred to the structure as the free-flyer moves to new locations.

As a free-flyer system is not physically attached to the main structure, additional safeguards must be in place to ensure the safety of both the free-flyer and any nearby structures. A failure could result in the free-flyer's becoming lost or its running into the structure it is building. The necessary additional subsystems and redundancy needed for a free-flyer makes estimating the mass beyond the scope of this study.

2.2 Structure

The structure is the part of the ISA system that is being assembled. This is not limited to purely structural elements; it also can include wired modules and instruments. For a large telescope, the structure would consist of the supporting truss structure and the mirror elements. The structural definition also includes how many pieces, or segments, the structure is composed of and the type of structure. There are typically two types of ISA structures: erectable and modular. An erectable structure is one that is assembled from individual components. For a truss, this would mean assembling the structure from individual beams and corners.

A modular structure is one made of prebuilt modules. These modules, sometimes referred to as bays, are preassembled before launch. Assembling these modules together can save assembly time and complexity; the modules can have wires and thermal blankets already installed. This study focuses on assembling a linear modular structure made of truss segments. The nonplanar study uses truss segments, specifically those made of TriTrusses. TriTrusses, designed by NASA Langley Research Center, are triangular truss segments see Fig. 4. This segment type is statically determinate, has a light weight, and can be collapsed to fit better inside the launch vehicle. This triangular shape connects to other TriTruss modules at the corners of the top and the bottom, providing a total of six connection points per TriTruss segment [3]. These connection points also are used by the robotic agent(s) to grasp with either the dexterous arms or the positioning legs.

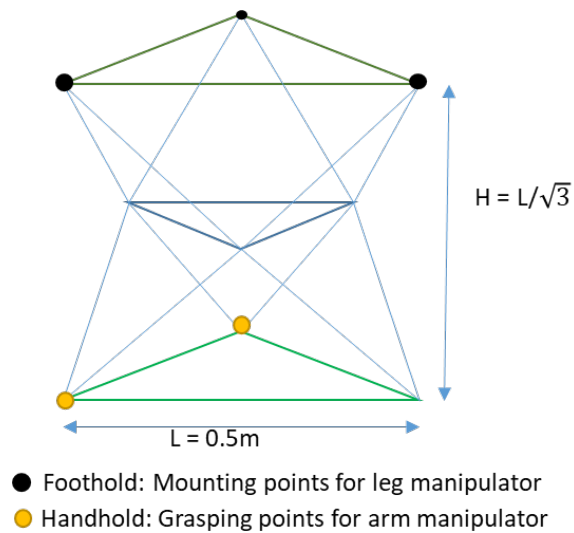


Fig. 4—TriTruss module, example length of 0.5 m

2.3 Assembly Process

The assembly process is the system-level design criteria that defines how the assembly takes place. These are the high-level assembly processes that both the structure and the robot need to know in order to be designed. Table 1 describes some of the main parts of the assembly process.

Many of the items in Table 1 are tied directly to the truss segments' design and the speed at which they are moved. The final structural design and the number of pieces the structure is constructed from will drive the size of each segment; driving the amount of mass the dexterous arms must move at one time. The structure element's acceleration and velocity are required to define the motion that will directly affect the joint torques. The number of pieces being carried at one time will directly influence the mass carried by the legs. These points will influence not just the joint torques, but the overall size and mass of the robotic system.

Table 1—Example of Some Assembly Process Components

Definition	Description
Number of pieces	Number of elements that make up the entire structure
Number of pieces carried	Number of elements the robot is expected to carry at a time
Connection type	How structural components are attached
Assembly order	Location of each structural module over time
Structural element maximum velocity	Maximum velocity components are moved at, used for defining safety requirements
Structural element acceleration	Desired acceleration of each structural element, used to define the expected forces for safety requirements
Foothold availability	Used to determine walking paths along the assembled structure

Defining how the connections between structural segments are made is an important part of the assembly process. The connections between modules can be made by the robotic system, or the individual structural components can have built-in mechanisms. Having the structural pieces perform the connections allows the robot to have fewer tasks and can reduce its complexity; however, the structural pieces now carry the burden of making and verifying those connections. Both the structure designers and the robot designers must know beforehand how the pieces are going to connect. This study assumes the robot will be performing the mechanical connections, tightening captured bolts that will attach each structural piece to the others. This design choice is required for defining the reach and dexterity of the robotic manipulators.

The assembly order is particularly important to the nonplanar crawling robotic system; see Fig. 5. The order will aid in determining where the available footholds are, which is needed when defining the required reach of the positioning legs. Defining the order the structural pieces is not enough to define entirely how the robot will walk on top of the pieces; see Chapter 5 for details.

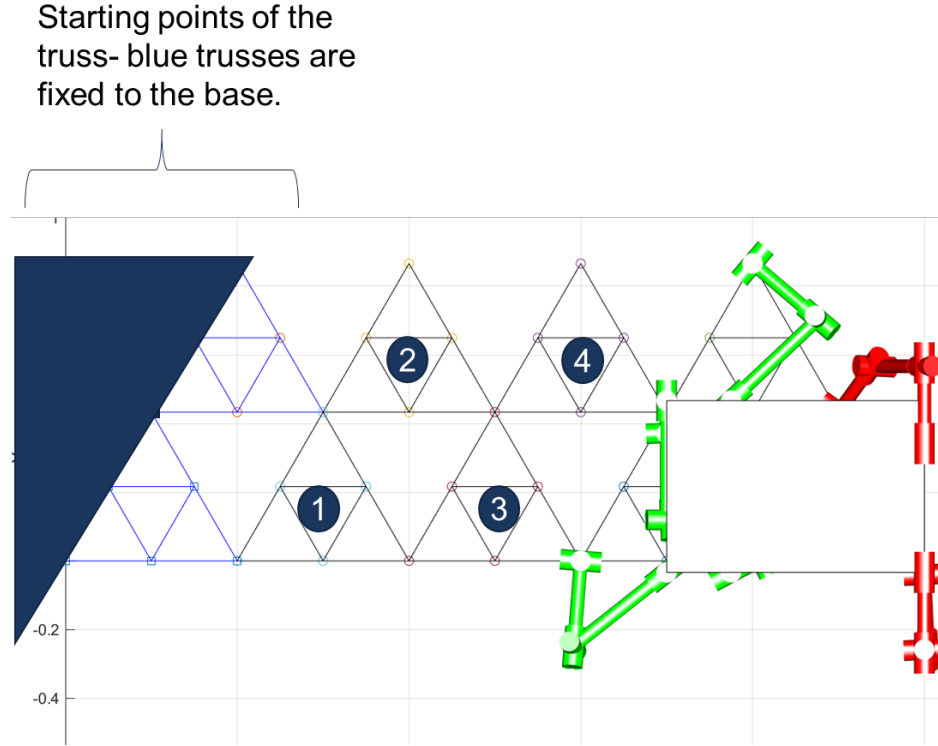


Fig. 5—TriTruss assembly order

3. MODELING SIMULATION

3.1 Overview

A simulation was developed in MatLAB for assembling a planar linear truss [7]. Utilizing Peter Corke's Robotics Toolbox [10], this simulation computes the trajectories, kinematics, and dynamics of the assembly process. Figure 6 shows the major components of the study, starting with defining the truss requirements. The truss requirements are the structural design parameters that are used to define the completed truss assembly, e.g. the total length, the required natural frequency, and the allowable maximum deflection. These are the driving design parameters that can be used to calculate the height and width of the final truss as a function of the desired truss length. From there, the truss can be divided into a number of different equal-length segments.

Once the quantity and size of each truss pieces has been calculated, the trajectory for each piece is determined; see Section 3.3 for details. In addition to defining the trajectory of the truss segments, the payload bay location and the leg mounting points are calculated for the entire assembly simulation. This is done using a trapezoidal trajectory design that provides the position, velocity, and acceleration for each component. Using this information, the location of each robot base and end-effector can be found. The position, velocity, and acceleration for each robotic end-effector is then calculated; see Eqs. (1-2). F is the force-torque vector of the task, which is acting on an end-effector. X is the Cartesian coordinate vector representing position and orientation. V_x is the velocity vector term, which includes the angular velocity, and G_x is the gravity term [11].

In each of the two robotic systems, the truss segments are lowered into place from the payload bay by two dexterous arms. After placing the truss segment into the truss assembly, the dexterous arms return to the payload bay. The payload bay then is relocated to the the next segment location. This relocation takes place either by moving the single large stationary leg or by using the two crawling legs.

The stationary robot has one long position leg that is attached rigidly to the truss base structure. Figure 2 depicts the stationary robotic system placing a truss segment. Here, the dexterous arms have finished placing the truss segment into the assembly and are returning to their holding positions at the payload bay.

The crawling robotic system seen in Fig. 3 uses the same payload bay and dexterous arms as the stationary robotic system. The positioning legs move the payload bay into place rather than the one stationary leg. The legs move from mounting point to mounting point, located at the edges of the truss segments. The positioning legs move one at a time, ensuring the robotic system remains attached to the assembled structure at all times. They work together to move the payload bay into position.

$$F = M_x(\theta)\ddot{X} + V_x(\theta, \dot{\theta}) + G_x(\theta) \quad (1)$$

The joint torques are related to the force applied at the end-effector via the Jacobian, $J(\theta)$. The Jacobian is a function of the instantaneous geometry and thus changes as a function of time.

$$\tau = J^T(\theta)((M_x(\theta)\ddot{X} + V_x(\theta, \dot{\theta}) + G_x(\theta))) \quad (2)$$

The individually shaded boxes in Fig. 6 indicate an internal optimization, such as when calculating the robot trajectory in order to minimize the change in joint angles along a trajectory. The joint trajectory for each manipulator is based on the desired end-effector position, velocity, and acceleration. An optimization is done here to ensure the joint angles will result in the desired end-effector position while minimizing the movement from the previous time step, ensuring a smooth motion. As the complexity of the robot manipulators increases, the complexity in calculating the joint trajectory also increases. For a redundant manipulator, constraints can be added to avoid singularities and collisions, and to minimize base torques.

The mass of each manipulator is estimated using the joint torques. This mass estimation is done using heuristics and a constrained optimization scheme to find the thickness of each link length; details are presented in Section 3.2. Once the mass of each manipulator is estimated, the force on each truss segment and the force on the truss assembly are calculated. Then the mass of the truss structure is calculated to survive the assembly forces placed on it by the robotic system. An iterative process is required, as the joint torques are a function of the mass of each truss segment and the manipulator mass. This simulation results in the total system mass, mechanical energy, and assembly time for each robotic system as they assemble the same linear truss.

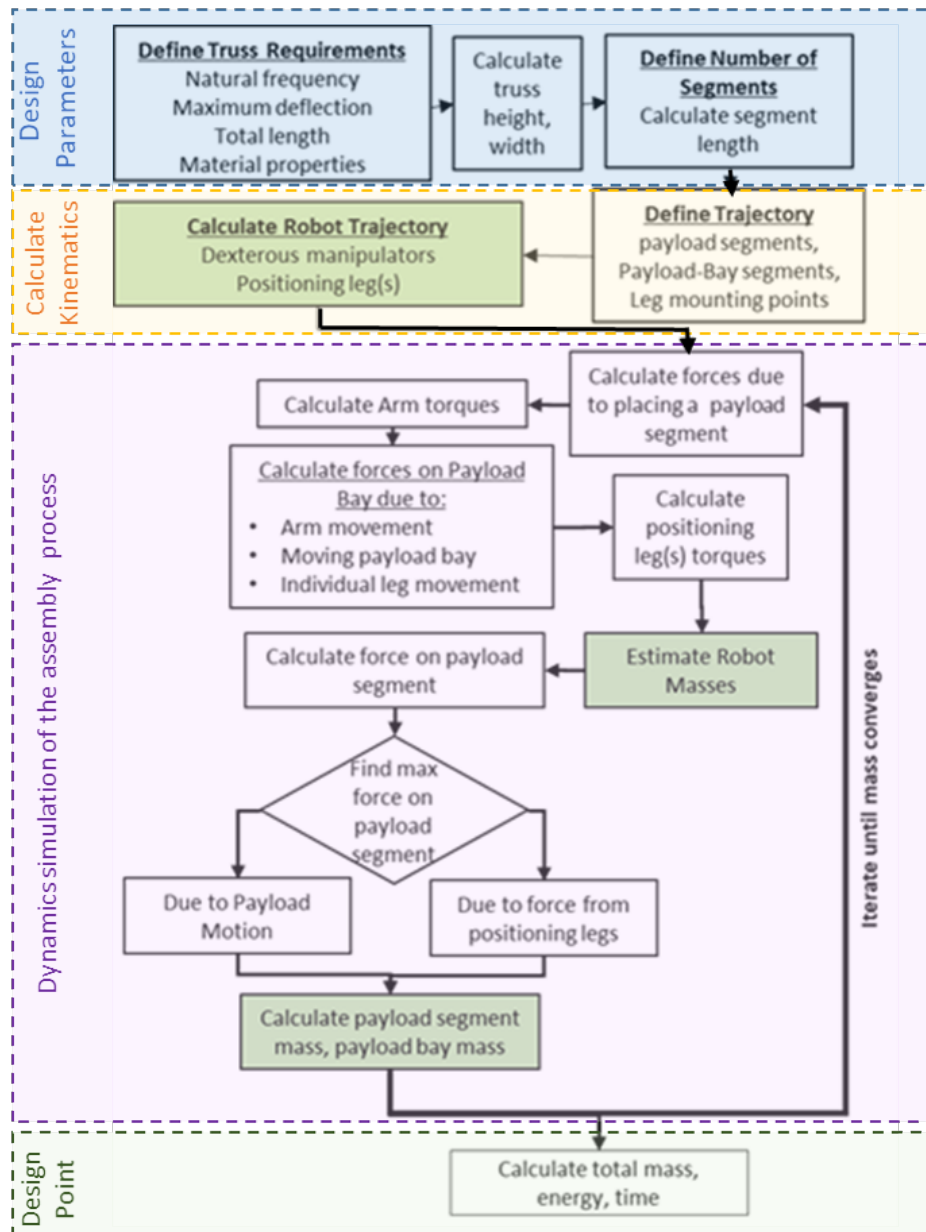


Fig. 6—Simulation flow diagram

3.2 Sizing Components

The masses of the robot, the structure, and the entire system all are used to evaluate the different robotic ISA systems. This section describes how the masses for each of the robotic manipulators, the robot body, and the structure are estimated.

3.2.1 Manipulator

The mass of each manipulator is calculated by estimating the masses of the motors, the harmonic gearing, and the structural links. The manipulators here are sized specifically to accomplish the defined assembly task; this represents a lower-bound mass estimate that will be used for comparison purposes. It should be noted that the manipulators here are sized based on the joint torques necessary to accomplish each trajectory in the space environment and not in Earth gravity.

A mass estimation for a motor is found using a heuristic based on commercially available high-end brushless DC motors similar to ones that can be used for space robotics. Equation (3) is the motor mass estimation depending on the required output torque, T_o in Newton-meters, and the motor speed, S , in thousands of revolutions per minute (kRPM), for small and large motors [12].

$$\begin{aligned}
 &\text{Small motors, } |T_o| < 3.17N \\
 &MotorMass(T_o, S) = 0.0676 + 1.3788|T_o| + 0.0010|S| \\
 &\text{Large motors, } |T_o| \geq 3.17N \\
 &MotorMass(T_o, S) = 2.5067 + 0.6017|T_o| - 0.2796|S|
 \end{aligned} \tag{3}$$

Each joint is assumed to use harmonic gearing to reduce the required motor torques; this is set at 160:1. Equation (4) shows the mass relationship between the rated output torque, T , from the harmonic gearing to the harmonic mass. The total actuator mass for each manipulator is a sum of the motor mass and the harmonic mass.

$$HarmonicMass(kg) = 0.0078|T(Nm)| \tag{4}$$

The structural mass of each manipulator link is added to complete the manipulator mass estimation. The manipulator links are sized to ensure the tip deflection is within an acceptable range when the maximum expected force is applied. This ensures that the deflection from the link lengths is within expected bounds. Figure 7 shows the outstretched manipulator in one of the worst-case poses. The link lengths must be sized to handle a maximum force and torque without resulting in too large of a deflection. The expected force, P , and the moment, M , are based on the truss segment's mass and acceleration. A constrained optimization is used to minimize the total structural mass while ensuring the maximum deflection constraint is performed [13].

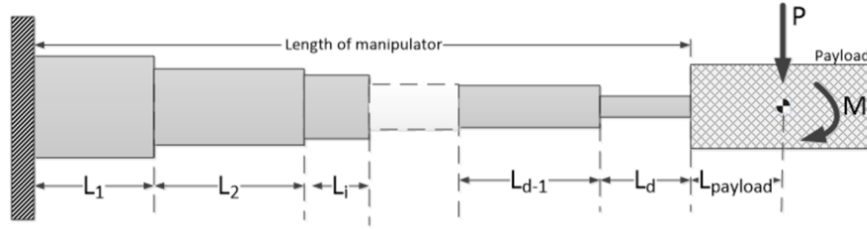


Fig. 7—Sizing manipulator structure

3.2.2 Truss Unit

The mass of the structure being built is important to consider along with the mass of the robot. The truss's mass is driven by the design constraints and is influenced by the forces from the assembly. M. Mikulas shows that the height of a truss directly relates to the stiffness, and he relates the stiffness of a truss to a circular diameter; see Fig. 8 [14]. Equations (5) and (6) allow the height of the cross-sectional area of the truss to be calculated, assuming a given desired stiffness and total length.

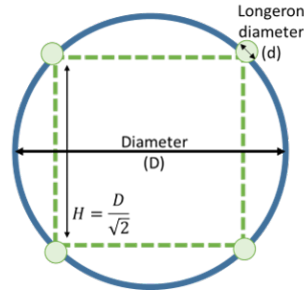


Fig. 8—Sizing truss structure

$$I = \frac{D^2}{8} A_{total} \quad (5)$$

$$f = \frac{\alpha}{2\pi} \sqrt{\frac{EI}{M_{total}L^3}} \quad (6)$$

The mass of each truss segment is calculated using a constrained optimization method. The longerons of each segment are sized to ensure they will not buckle under a maximum force. The maximum force is dependent on the assembly process. For example, the maximum force could be a result of the legs' reacting the forces into the truss as it moves, or as they hold the payload bay still while the arms move.

The maximum force also could be a result of a safety concern. The arms are moving the truss segments in close proximity to the assembled truss. There is a chance, though small (and safety precautions should

be taken to reduce this), that the arms could move the truss piece into the assembly and hit it rather than gently placing the piece. The truss structure should be able to survive this scenario, which is the worst-case scenario. The optimization method for sizing the truss is the same, with slight modifications, as the method used for sizing the structural mass of the manipulators.

3.2.3 Robot Body

The robot body is the structure that attaches all the robot manipulators together. This is also sometimes referred to as the payload bay; in addition to connecting the manipulators, it also holds all the non-deployed truss pieces as well. Carrying the truss segments defines the size of the payload bay. It is 10% larger in terms of length and width than a single truss segment; see Eq. (7). The height is determined based on the total number of truss pieces; here, the height is divided by DR, which is the deployment ratio. This is the ratio of the non-deployed height to the final deployed truss height.

$$Height_{robotbody} = 1.1 \left(\frac{Height_{Truss}}{DR} N_{truss} \right) \quad (7)$$

The payload bay definition includes where the dexterous arms and the positioning legs attach. The attachment point definition is the location of each arm base and the relative orientation. Figure 9 shows a robot body with the dexterous arms mounted above the robot body's midpoint with the positioning legs positioned around the bottom quarter.

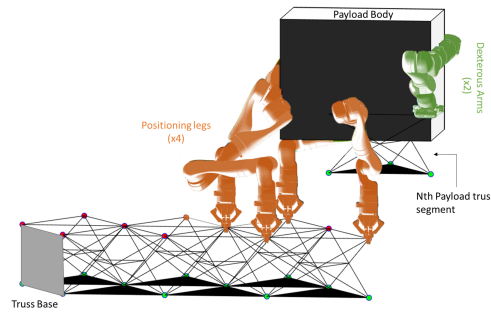


Fig. 9—Nonplanar crawling robotic system with a robot body sized to carry a single truss segment at a time

The mass of the payload bay depends on the truss segment size and the maximum force on the payload bay — either from the payload segment, itself, or from the motion of the legs or arms. This structure is treated like a single, rectangular truss sized to survive the maximum force experienced either from being moved by the positioning legs and arms or from a truss segment. To mitigate risk, it is assumed that the payload bay also must be able to survive an impact from a truss segment moving at the maximum allowable acceleration. A constrained optimization method is used to minimize the mass of the structure while ensuring it survives the expected forces. The mass of the payload bay is included in the total system mass.

3.3 Trajectory Generation

The required joint trajectory for each manipulator is based on the desired trajectories of the TriTruss pieces, the robot base, and the footholds. The trajectory for each dexterous arm is based on lowering each TriTruss segment into place. The legs have multiple trajectories they must handle: moving the robot body and moving from one foothold to another.

A trapezoidal velocity profile, as described by Craig [11], is used to define each path segment for the TriTruss being assembled, for the motion of the robot body, and for each leg as it moves from one foothold to the next. Once these are defined, the motion of the arms and legs can be calculated. Equation (8) is the motion over time, in which X_o is the initial position and $X(t)$ is the position as a function of time. There are three phases: an acceleration phase in which the object moves at a constant acceleration, phase two continues the motion at a constant velocity, and the final phase decelerates the object at a constant acceleration. Here, A is the acceleration and V_o is the initial velocity, often zero. In addition, a maximum velocity is defined to ensure the limit is not exceeded. There is a distinct trade-off between the time to complete each segment and the acceleration. This requires each motion to have known starting and ending positions and orientations.

Acceleration/Deceleration :

$$X(t) = X_o + V_o t + .5At^2$$

$$V(t) = V_o + At$$

(8)

ConstantVelocity :

$$V(t) = V_{constant}$$

An example maximum velocity and acceleration are defined as 1 m/s and 1 m/s^2 , respectively. This fully defined the motion of the TriTruss as it lowered into position from a known starting position and orientation to final ones. From here, the trajectories of each of the two robot arms are derived. There is a check to ensure the joint angular rates and acceleration limits, set at 1 rad/s and 1 rad/s^2 , are not exceeded, which may result in the slowing of the payload trajectory. The same process is done with the robot base and the trajectories of the legs as the robot body is moved from a predefined location to the next. The desired position of the robot base is determined first and then the joint angles are found to complete the path.

During the walking portion of the assembly, the robot will move one leg at a time from one foothold, located at a node on the top of the TriTruss, to another foothold. Each leg moves one at a time while the other legs keep the robot body stationary. The mounting points are chosen ahead of time as part of the task planning. The same trapezoidal trajectory method is used to determine the path between footholds.

Defining the path of the TriTruss bay, the robot base, and the path of each foothold does not result in a singular solution for a redundant manipulator. A redundant manipulator allows each manipulator to reach the same endpoint with multiple different configurations. Given the wide variety of tasks that an ISA robotic system must perform, having a redundant manipulator is very likely. Therefore, defining the paths for the major components does not define the entire system completely. This paper looks at how different joint angles used to accomplish the same task can affect the entire system.

3.4 Performance Criteria

Previous sections have defined the components of each ISA robotic system and how the trajectories are generated. This allows different robotic systems to be constructed to complete the assembly task. In order to compare the different systems, performance criteria must be defined. This study focuses on a few selected performance criteria in order to determine how each robotic ISA system performs.

3.4.1 Time

Here, the total maneuver time is defined as the duration it takes to assemble the truss and then to return to the robot's original starting position. This estimation only includes the time it takes for the robot manipulators to perform large maneuvers. Other motions, such as grasping and verifying all connections, are not included. These are highly dependent on the end-effector and the sensors, which are assumed to be the same for both robotic systems.

The crawling robotic system always was found to be slower in these studies. The acceleration and maximum velocity for each maneuver were defined at the assembly process level, which is independent of robot type. The crawling robotic system has more maneuvers to do than the stationary robotic system, as it must relocate the positioning legs. As a result, the crawling robotic system always takes longer.

3.4.2 Robot Mass

The robot mass is the sum total mass of all the manipulators and the robot body. Each manipulator's mass is the sum of the actuator mass, comprising the motor and the harmonic gearing, and the structural mass. The robot body is sized to ensure that at least one truss segment can fit within it; the length and width are therefore minimally that of the truss segment. The height is based on the number of segments being carried at once.

3.4.3 System Mass

The system mass is the total mass of the entire ISA system, combining the robot mass and the structural mass of the truss. This mass metric is important as it shows that focusing on minimizing the robot or truss mass alone does not necessarily result in a minimum overall system mass. In addition, this shows where the majority of the mass comes from. If the robot mass is only a small portion of the total, then going to extraordinary efforts to minimize the robot mass may not be an effective use of resources.

3.4.4 Energy

Reducing the energy consumption for the assembly task can reduce the size of the batteries and even the solar panels. Energy consumption as a performance metric is more useful to compare different types or numbers of manipulators. Generally, a specific manipulator will provide the average power consumed by the manipulator; for example, the Kinova Gen3 7DOF manipulator uses 36 W [15]. Specifying the exact trajectory to reduce the power consumption can lead to a reduction in the power. However, there are other methods for reducing the overall power usage. Automotive and industrial centers using robotics have found that operational procedures, such as reducing breaks and lowering stand-by modes, were effective for reducing power consumption.

Typically, the output energy for a maneuver is defined in Eq. (9). This is the energy output for each motor and it can be calculated during the entire assembly process.

$$Power_{output} = \tau(t)\dot{\theta}(t) \quad (9)$$

Equation (9) assumes that the motors are always moving, that they produce torque due to motor movement. There are many instances in which the manipulator actuators are producing torque in order to remain stationary. Therefore, there is no angular velocity and the output energy, and thus the input energy, are both zero.

Another method of estimating the energy required for a maneuver is to estimate the current from the calculated torque. Using the Kinova Gen3 hardware, the current was taken at various torques and a linear fit was applied. This provides an initial relationship between torque and current — which then can be used to size the power system. Ideally, the torque-current values would be taken at a number of different joint velocities in order to define the torque-velocity-current relationship more accurately. Additional research should be done in order to develop a better metric between torque and current for high-performance DC brushless motors with gearing.

3.4.5 Force on Truss

The initial robot type comparisons were done using a simplified rectangular truss, where the truss was assumed to be a beam. The following studies on the walking robot expanded the truss model to a space frame made out of TriTruss units. This expanded analysis calculates the maximum force experienced by each individual beam of the entire truss.

Each of the four legs is attached to a foothold located on the top side of the truss assembly. These legs react all forces to the truss; as the arms move each TriTruss piece and as the robot body shifts. The amount and direction of these forces depends on the assembly process as well as the joint angles of each leg. The legs are constantly reacting forces to the truss, even if only to hold the robot body stationary while the arms move. The assembled truss must be able to withstand these forces being applied.

The stiffness method is used to determine the forces and torques in each individual beam as forces are applied at different points of the structure; see Eq. (10). K is the global stiffness matrix for the assembled space frame and is formed from the geometry of the truss. The size of this matrix will grow as more TriTruss pieces are added to the structure. The δ term is the displacement at each node and F is the force matrix. This force matrix contains the known forces and torques being applied to the different nodes by the legs as well as the support nodes, those that are attached to the main structure and are assumed to be stationary [16, 17].

$$K\delta = F \quad (10)$$

Using the stiffness method, the force in each beam of the truss can be calculated. The force in each truss beam will change as the truss is assembled and the forces applied at the different nodes change. This

provides an estimation of what forces the truss structure can expect during the assembly process. If these forces are driving the beam design, rather than launch forces or operational forces, then this will directly influence the mass of the truss structure. If these forces are not driving, they must be constrained to ensure they remain lower than the driving forces.

4. ROBOT TYPE COMPARISON

This section summarizes the results of the studies done to compare robot types. The details of the individual studies can be found in IROS 2020, IROS workshop, and in the year one report of this Karles Fellowship project. [7–9, 18]. This section presents some of the example results and highlights the main conclusions from the studies.

The first year's effort focused on comparing a planar stationary robot to a walking robot. Figures 10 and 11 show an example of the stationary robot and the walking robot as they are set to complete a 20 m linear truss made of simplified rectangular truss segments. The structural pieces are sized to survive assembly; for safety reasons, the structure was designed to ensure the truss did not buckle if impacted by the final piece moving at maximum acceleration.

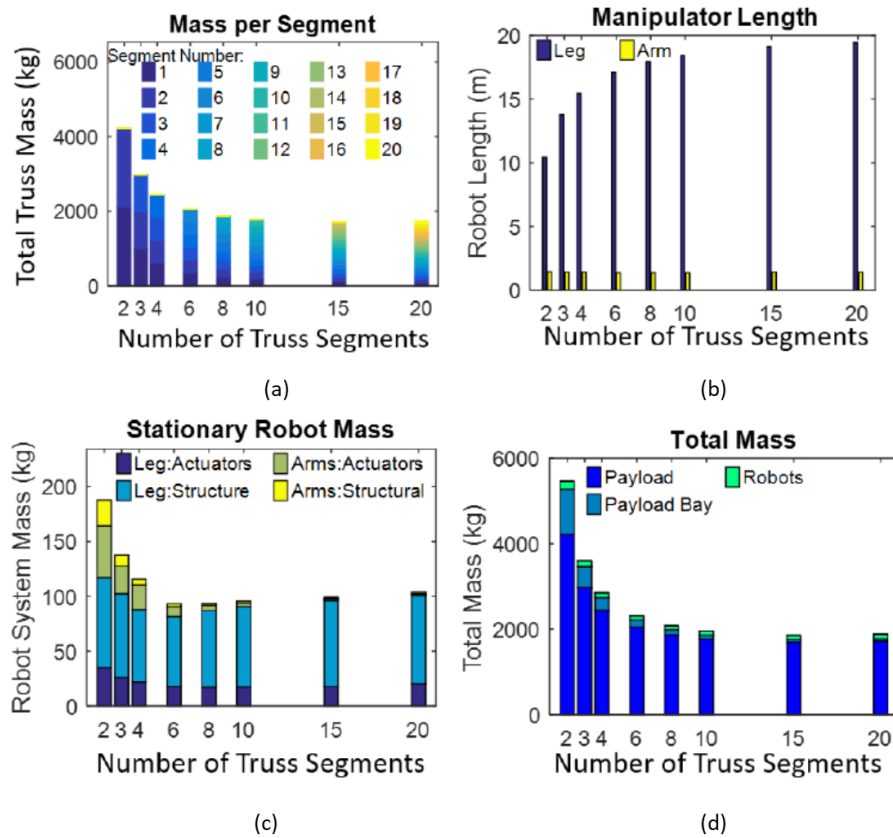


Fig. 10—Stationary robotic system building a 20 m planar truss

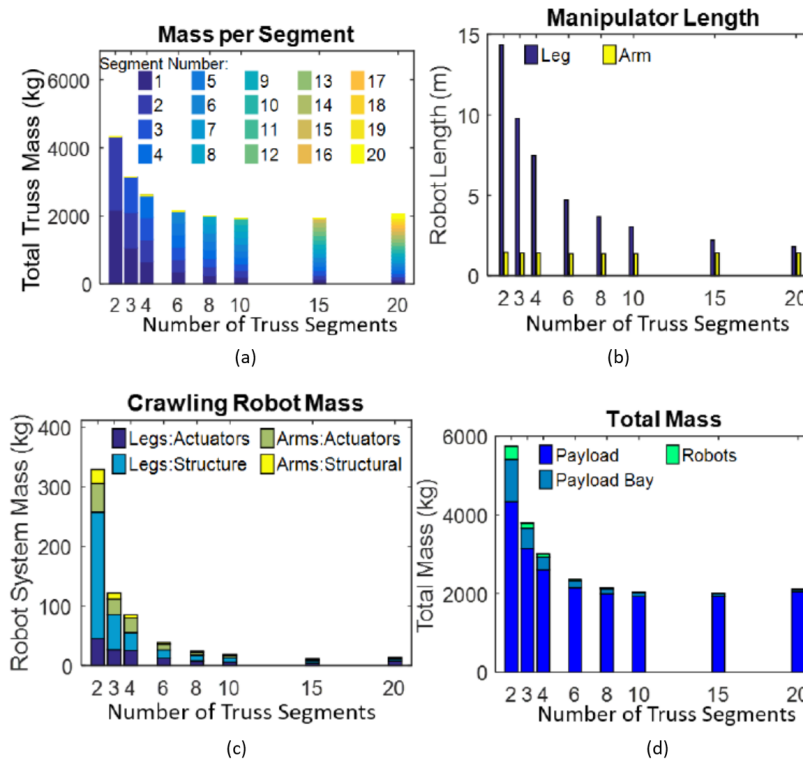


Fig. 11—Crawling robotic system building a 20 m planar truss

Comparisons between the stationary robot and the walking robotic system are presented below. The dexterous arms are defined by the task and do not change as the robot type changes; however, the positioning leg(s) are affected. The robot manipulator portion of the free-flying consists of the same dexterous arms used in the crawling and the stationary system; however, additional assumptions are needed to size the free-flying base. Historically, there are very few free-flying robotic systems, and finding an appropriate robot-to-base mass ratio was difficult. As a result, comparing a free-flying system to the stationary and crawling systems was not done at this time.

Figure 10(a) shows the total truss mass as the number of segments increase for a stationary ISA robotic system. The total truss length is fixed at 20 m; as the number of truss segments increases, the length of each piece decreases. As the number of pieces increases, the more connecting hardware is required. This is reflected in the 5% mass penalty.

A single positioning leg moves the robot body, referred to here as the payload bay, into the correct location above the center of the truss piece being placed. This allows the dexterous arms to lower a truss piece vertically into place. As the truss segments become shorter and more numerous, the center of the final truss piece is farther from the truss base. As such, the length of the positioning leg increases as the number of segments increase, see Figure 10 (b). This increase in length of the positioning leg results in higher moments on the positioning leg even when the individual truss segments are of lower mass. In all of these simulations, the positioning leg has a length greater than 10 m.

The lengths of the dexterous arms do not change as the number of payload segments increases, as the length is based on the height of the truss segments. The height of each truss segment is based on the final

truss length and the required stiffness; it is not dependent on the number of segments used to make the final truss. Together, the dexterous arms move the individual truss pieces; thus, as the mass of each piece decreases, the required joint torques also will decrease. As the mass of each truss segment decreases, this leads to a reduction in both the actuator mass and the structural mass in each of the dexterous arms.

The total robotic mass is the combination of the two dexterous arms and the positioning leg; see Fig. 10(c). As the number of truss segments increases, the dexterous arms become lighter due to requiring smaller actuators and a reduction in the structural mass. Conversely, the positioning leg becomes longer, resulting in a higher structural mass. Here, the mass of the robotic system is driven by the structural mass of the positioning leg. Assembling the truss with six truss segments, each 3.3 m, results in the minimum robotic system mass. It should be noted that this robotic system is designed to specifically work in the space environment to perform these assembly tasks.

Combining the robot mass, the truss mass, and the payload bay mass results in the total system mass, see Fig. 10(d). It is clear that here, the total mass is driven by the truss mass and that the robot system is only a small fraction. This is a case in which continuing to minimize the mass of the robotic system alone will not have a major impact on the system.

Figure 11 shows the detailed mass analysis for a crawling robot. Unlike the stationary robotic system, as the number of payload segments increases, the length of the positioning legs decreases, Fig. 11(b). The lengths of the positioning legs are driven by how far they must reach when positioning the payload bay and when taking a step to relocate the the next foothold. Each step is the entire length of a truss segment; each leg moves one at a time, releasing its grasp on the foothold at one end of the truss, moving to another foothold, and then grasps onto it. Decreasing the length of each truss segment results in smaller footsteps and reducing the required length of the positioning legs. The total mass of all dexterous arms and positioning legs decreases as the number of payload segments increases for a crawling robot.

The dexterous arms have the same design constraints as those of the stationary robotic system; the mass and length of the dexterous arms are based on the truss segments, and their design is independent of the type of robotic system used. The reduction in the overall robot system mass is predominant from the reduced size of the positioning legs.

Figure 11(d) shows that the total system mass is driven by the truss mass. This is clearer here than in the case of the stationary robot; the robotic mass is a very small percentage of the total overall mass. In this case, in order to truly make a mass-efficient design, one should try to reduce the truss mass and then the robot mass.

Figures 10 and 11 show detailed views of a stationary and walking robotic systems for ISA. This study was repeated for three different length trusses: 10 m, 20 m, and 50 m and with a nominal payload acceleration 10 mm/s^2 and at reduced value of 2.5 mm/s^2 . The total system mass is shown in Fig. 12.

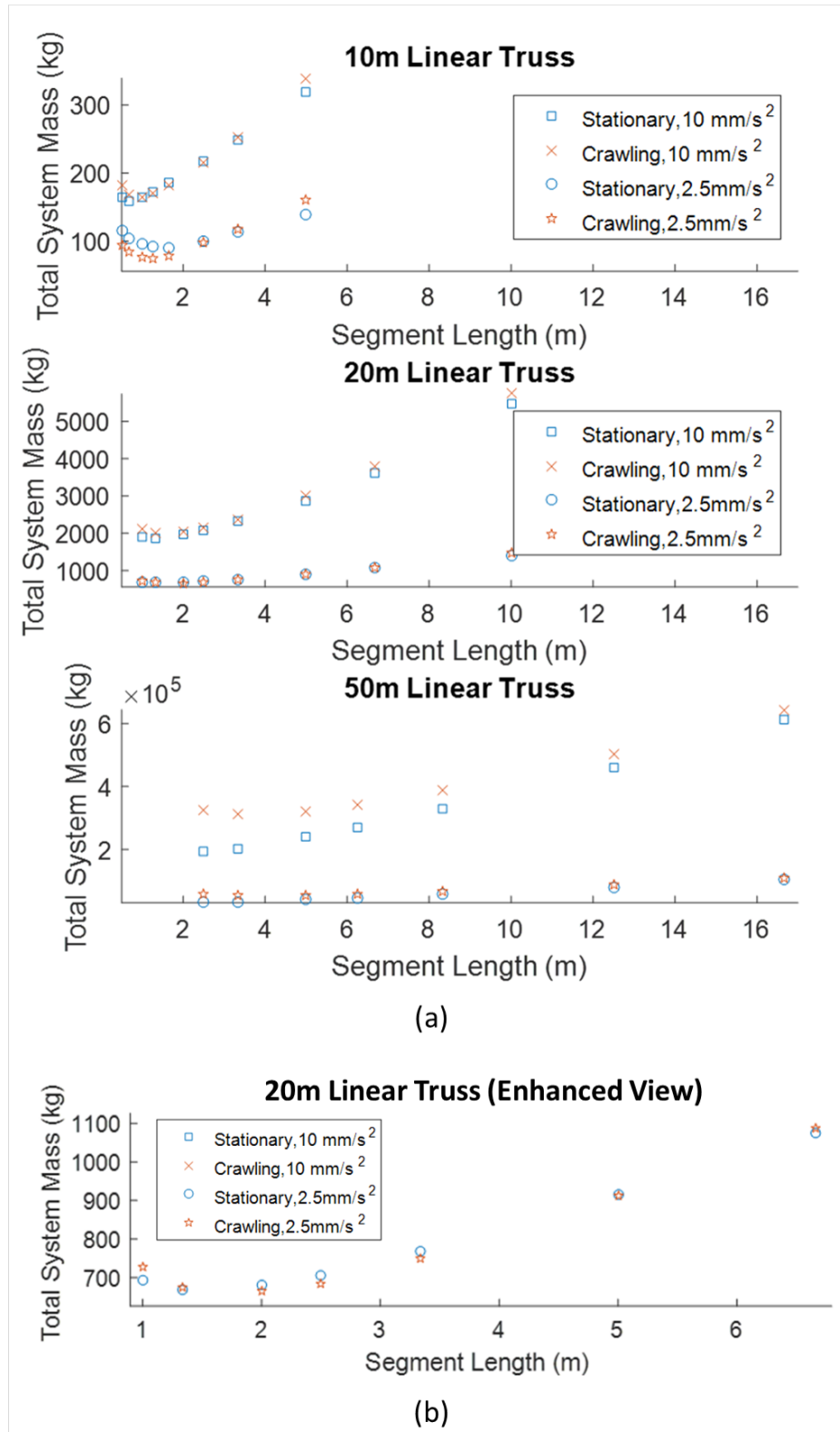


Fig. 12—Planar stationary and crawling robotic systems as they assemble different lengths of trusses with two different accelerations

As the structure becomes larger, the stationary robotic system has a lower mass. This is due to the crawling robot exerting forces on the end of the truss structure during the assembly process, whereas the stationary robot only exerts forces at the robot base at the start of the truss. The forces exerted by the crawling robot are a result of the legs reacting as the dexterous manipulators assemble each segment and as the crawling robot moves from one location to another. These forces require the structure to be stronger in order to prevent buckling; larger structures are more impacted than smaller structures. Reducing the payload acceleration will reduce these forces, which can be seen in Fig. 12. The bottom graph of Fig. 12 shows an enhanced view of the 20 m truss at the reduced acceleration. It is clear here that by controlling the payload acceleration, and thus the forces exerted on the truss end, the crawling robotic system can have a lower system mass than a stationary system.

5. DETAILED STUDY OF A WALKING ROBOT

Previous results show that the force a walking robot exerts on the truss can drive the structural design if not constrained. Many assumptions were made in the previous study, including the assumption that the structure was a cantilever beam and the robots were all 3-DOF planar manipulators. This study removes those assumptions and focuses on a walking robot, that moves along the truss system, see Fig. 13.

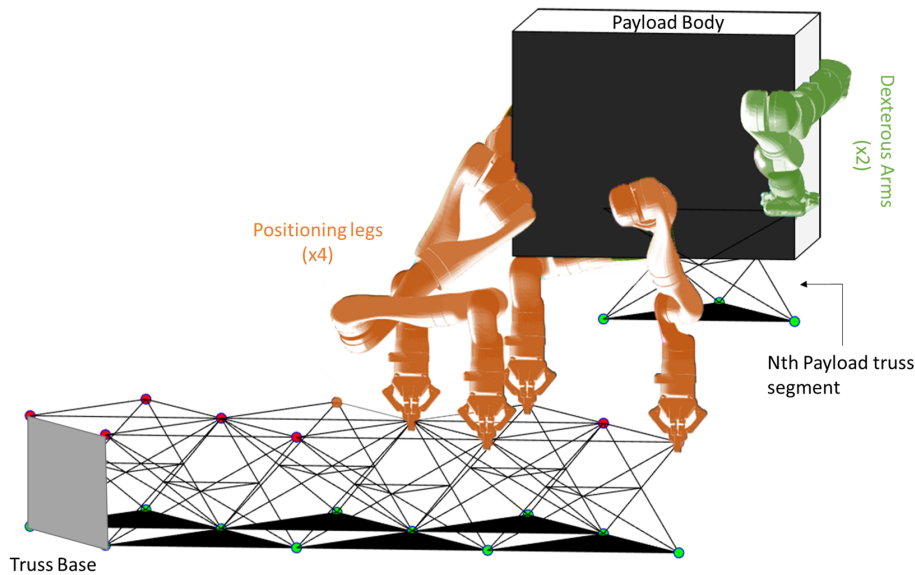


Fig. 13—Crawling robot assembling linear TriTruss assembly

The nonplanar crawling robotic system consists of four 7-DOF positioning legs that relocate the robot body, providing the robot with three points of contact with the truss at all times. Two 7-DOF dexterous arms are attached to the robot body and are used to assemble the individual truss segments into the assembly. The truss segments used here are fully defined TriTruss segments.

During the assembly, the two dexterous arms work together to move a TriTruss unit from the robot body into position in the assembled truss. During this time, the legs keep the robot body stationary. Once the TriTruss bay has been assembled, the arms return to a holding position. The legs then work together to shift

the robot body to the next location. As necessary, the robot walks to the next location, moving a single leg at a time from one foothold to the next while the other three keep the robot body stationary.

It is assumed that the legs and the arms are not moving at the same time. However, it is this author's belief that as trajectory and path planning advance and learning techniques are applied, full-body motion can be accomplished. Full-body motion would allow the legs and arms to move at the same time, more closely to how biological systems move.

Even with having defined the path of each TriTruss and thus the locations of all footholds and handholds, there are many more variables to determining the length of each manipulator. The position of each end-effector has been defined; however, the attachment point to the robot body, has not been defined. The size of the robot body and location where each manipulator is mounted will affect the overall length of each manipulator. There are many variables that will influence the required length of each manipulator: TriTruss size, assembly order, movement of the robot body, and where each manipulator is mounted to the robot body. It is possible to optimize the length of each manipulator to further optimize the entire system. For this study, all the manipulators are all identical 1 m long arms with the same kinematic configuration.

The final linear truss consists of two rows of TriTrusses. Two rows were selected for two reasons; the first is that two rows provided the necessary mounting points for the legs. The legs walk along the truss, using footholds located at the nodes of the TriTruss; they do not attach to the beams. As a result, if the four-legged robot is walking along the top of a TriTruss system, then at least two rows of TriTrusses are required to provide enough footholds. The second reason for having two rows is that it results in a more stable assembly. The robot alternates between assembling a TriTruss in the bottom row and then the top row. The assembly process and the size of the TriTruss units determines where the leg-mounting points are, see Fig. 5.

5.1 Gait Study

The assembly process defines the number of truss segments and the order in which they are placed. This does not fully define how a robot will walk across the truss; even defining all the available footholds, there are still multiple ways of crawling across the truss structure. One of the overall constraints is that three legs must be in contact with the truss at all times to transmit forces and torques to the structure. Figures 14 and 15 depict two methods of walking across the same structure. This structure is made of eight TriTruss units, each 420 mm long, for a total length of 3.4 m.

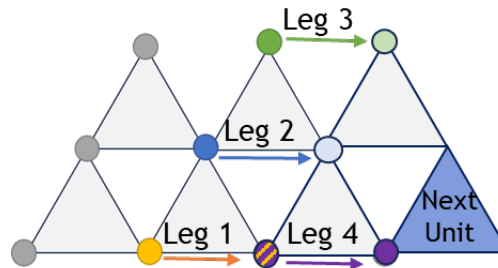


Fig. 14—Gait option 1

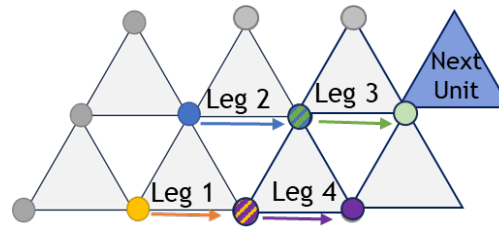


Fig. 15—Gait option 2

This study uses six manipulators: four manipulators dedicated to walking and two manipulators dedicated as arms. The fourth leg, leg 4, is typically used to ensure that the main constraint is met: three legs are attached to the truss at all times. Leg 4 is attached to the structure as one of the other legs is being moved. Depending on the end-effector, this could be one of the dexterous arms acting as the fourth foot.

Gait method one, seen in Fig. 14, is designed to minimize the total robot footprint, defined as the length between the arm grasping point and the legs. This method ensures that the maximum distance between the farthest foothold (leg 1) and the arm's grasping point (Arm 1) is 1.5 TriTruss lengths. This allows the robot body to remain short.

The second gait restricts the legs to using only footholds that already are connected to other TriTruss segments. These footholds are more structurally stable than an unconnected node. An example of an unconnected node being used as a foothold is the top node that leg 3 connects using the first gait method. This method requires a longer robot body; the maximum distance between the farthest foothold (leg 1) and the arm's grasping point is 2.5 TriTruss lengths.

Gait option 1 allows for a short robot body; however, one of the legs, leg 3, must attach to the truss at an unconnected node. This node is not connected to another TriTruss and is less stable. Figure 16 shows the

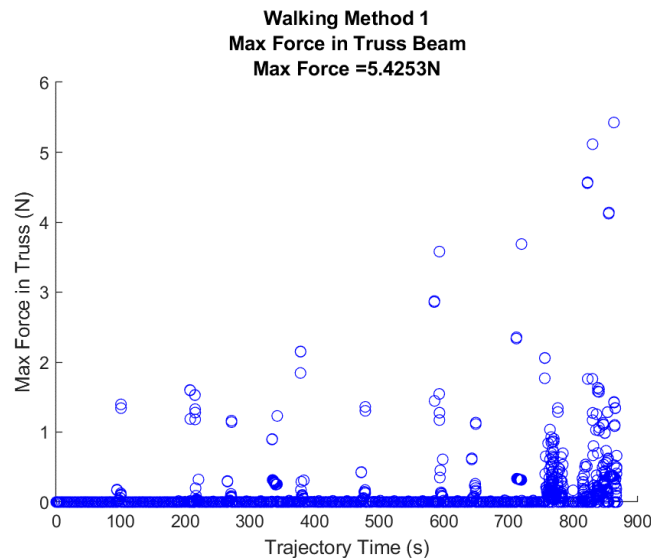


Fig. 16—Walking method 1

maximum force in the assembled truss structure as the crawling robot moves along and assembles it. The overall maximum force occurs when the robot is placing the last TrTruss segment. The maximum absolute force reacting through an individual truss member is 5.4 N. This maximum force does not contain any safety margin — this is the expected maximum force an internal beam member will see during the assembly process due to the robot.

The second walking method requires a longer robot body, but none of the legs is attached to an unsupported node. The maximum absolute force seen during this assembly occurred when the dexterous arms lowered a truss into place. As seen in Fig. 17, the maximum force in an internal beam member for this robotic ISA system is only 3.4 N.

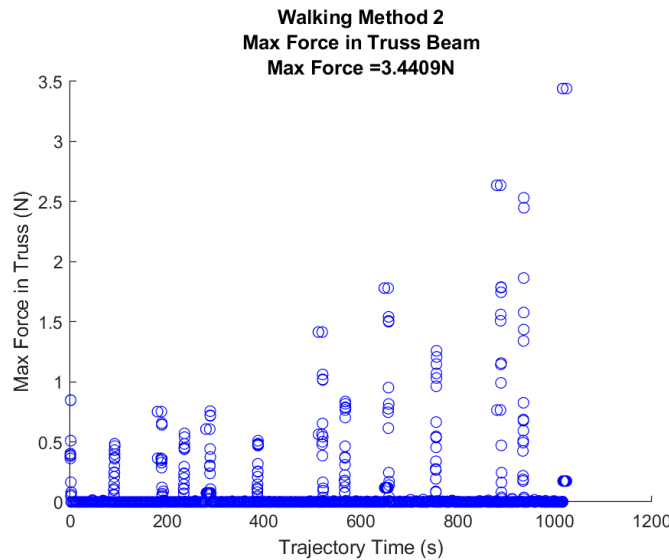


Fig. 17—Walking method 2

In each of these two designs the maximum force occurred when the dexterous arms were moving the truss segment into place. Even though the dexterous arms are performing the same maneuver, how the robot is connected to the truss will change how the force is reacted to the truss. Here, each of the truss segments is small, only 420 mm in length and about 1 kg. While the total force seen is very low and not a design concern, it should be noted that the robotic systems used here are very small and lightweight. They are handling small truss segments and if the truss segments or the robot system becomes larger, it will directly increase the force the truss must withstand.

Examining the results of both walking methods, it is clear that the maximum force occurs as the dexterous arms move the truss segment into place and the legs hold the robot body steady. In this case, the force transferred to the truss is minimal, which allows the robot designers to adjust leg and arm trajectories without much impact on the truss design.

5.2 Force Distribution Study

A walking robotic system has a number of closed kinematic chains. Two or more manipulators handling the same rigid object can allow forces and torques to be passed from one arm to the others. This allows the

force to be divided between the manipulators based on the geometry of the situation. A simplistic approach is to divide the necessary task force evenly by the number of manipulators performing the task. For example, if two arms are used to lower a TriTruss into place then the force required to move the TriTruss would be divided between the two arms evenly; see Eq. (11). Je_i^T is the force transformation from the payload center of mass to the i th end-effector; this is known as the grasping matrix and it is a function of the geometry of the system.

$$F_{arm_i} = (1/n_{arms})Je_i^T F_{payload} \quad (11)$$

This is not the only method of dividing the forces between manipulators. Rather than divide the task force evenly among the arms, Carignan and Akin [19] suggested dividing the force in order to minimize the total torque, $|T^T T|$; minimizing the total torque should reduce the required motor power.

$$f(T_1 \dots T_n) = \sum_{i=1}^{n_{arms}} |T^T T| \quad (12)$$

Closed kinematic chains allow forces and torques to pass through the object being handled and into the other manipulators. However, this can put excess forces and torques on the object, itself. These are considered to be internal forces (or squeeze forces) in the nullspaces of each of the i manipulator's grasping matrix, Je_i , and do not contribute to the motion of the payload, see Eq. (13). I is the identity matrix, Je is the grasping matrix for the combined manipulators in the closed kinematic chain, and $F_{internal}$ is the internal force being applied by the end-effectors. The payload must be able to survive the expected internal forces that are being applied [20].

$$F_{internal} = (I - J_e^{-T} J_e^T) F_{payload} \quad (13)$$

This robotic system consists of redundant manipulators that form closed kinematic chains. There is an infinite number of ways a redundant manipulator can move the end-effector along a desired path. The extra degrees of freedom allow multiple joint-angle trajectories to achieve the same end-effector position. Changing the joint trajectory of a redundant manipulator can impact the dynamics of the entire system. This section provides an overview of the manipulator's dynamics and how it is impacted by the changing the joint trajectory while maintaining the same end-effector trajectory. The general equation for a robotic manipulator in Cartesian, or task space, is given in Chapter 3.

A single manipulator design is driven not only by the task it must accomplish, such as moving a TriTruss into an assembly, but also in how it moves along a path to get there. The Jacobian is a function of the joint angles and the geometry. Changing the joint angles along the trajectory can result in different joint torques. The joint torques are also a direct result of the force on the end-effector, which is required to accomplish the desired task, as well as the manipulator's joint trajectory. The maximum required joint torque for each joint directly drives the size of the motor in that joint.

Once the joint trajectories are defined, the dynamics of a closed kinematic chain of manipulators is still not defined fully until the force distribution between the manipulators is defined. The dynamics of the manipulators not only influences the squeeze force on the structure, which can drive the mass of the structure if these forces are not constrained, but also influences the forces at the robot base and the forces that each of the legs must transfer to the truss assembly.

The total torque, $|T^T T|$, is a measure of the mechanical energy required to complete the task; see Fig. 18. There is a clear reduction in the total torque as the first truss is lowered into place. After the first truss is lowered into place, the arms both return to their starting positions to grasp a second truss, the maneuver starting at 15 seconds. The total torque for this motion is the same regardless of the force distribution scheme because the arms do not form a closed kinematic chain at this point. They are not carrying a truss and both arms are moving independently; there is no way to transfer forces between them.

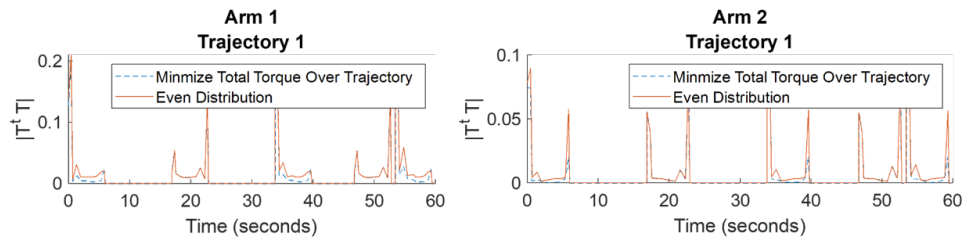


Fig. 18—Total torque for even and force-minimization distribution schemes

The force exerted by each arm end-effector is dependent on the force distribution scheme employed as well as the chosen joint trajectory. This study includes two dexterous arms that are connected to the robot base and their task it is to lower a TriTruss bay into the assembly. Each of the two arms grasps a single TriTruss at one of the two grasping points and then lowers the bay into place in the assembled truss. Here, the trajectory of the TriTruss bay is pre-calculated, but each of the two arms has 7 DOF and can complete the desired trajectory a number of different ways.

Figure 19 shows a few different trajectories each used to lower three TriTruss bays into place. It should be noted that not all the trajectories take the same amount of time. Trajectories 2 and 4 are significantly slower than the other trajectories, the joint trajectory limits were exceeded and the maximum velocity was decreased. The two trajectories increased the time in order to avoid exceeding the joint angle rate limit or the joint acceleration limit while moving along the desired TriTruss path. Trajectory 2 reduced the velocity but was able to maintain the same desired accelerations as trajectories 1 and 3. Trajectory 4 reduced the acceleration magnitude by 1/4.

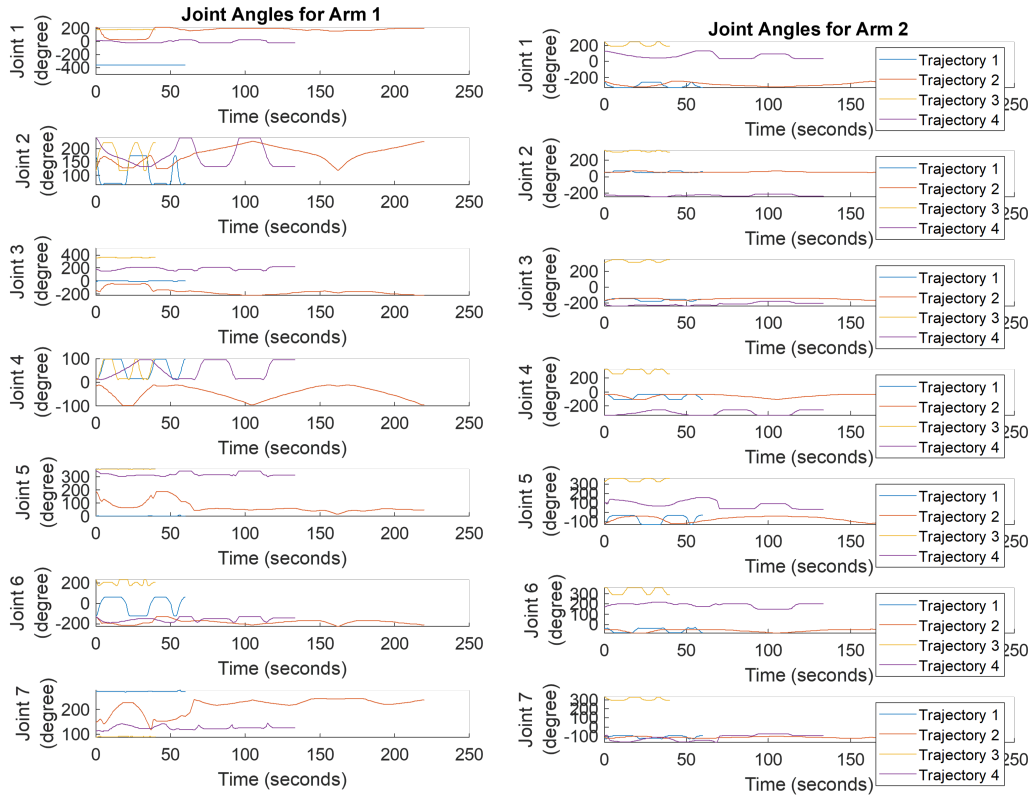


Fig. 19—Joint trajectories for arm 1 and arm 2 as they lower TriTrusses into place

A torque-based force distribution scheme not only depends on the grasp matrix, but also on the joint torques. A torque-based force distribution scheme like the one presented here will depend on the joint trajectories and will change depending on the path of each joint. Trajectory 4 is clearly transferring forces and torques through the TriTruss unit in order to reduce the total torque for the system.

The force exerted by each arm end-effector is dependent on the force distribution scheme employed. Figure 20 shows the resulting end-effector forces for the force distribution scheme that minimize the total torque for each arm, Fig. 21 shows the sum total of both arms. When the force is divided evenly between the arms, the force at the end-effector is the same magnitude for all trajectories. The different trajectories affect the timing but not the required force or torque, as the accelerations for the TriTruss are the same for all cases. Trajectory 2, with the slower time, has the same acceleration as the other trials but a lower velocity.

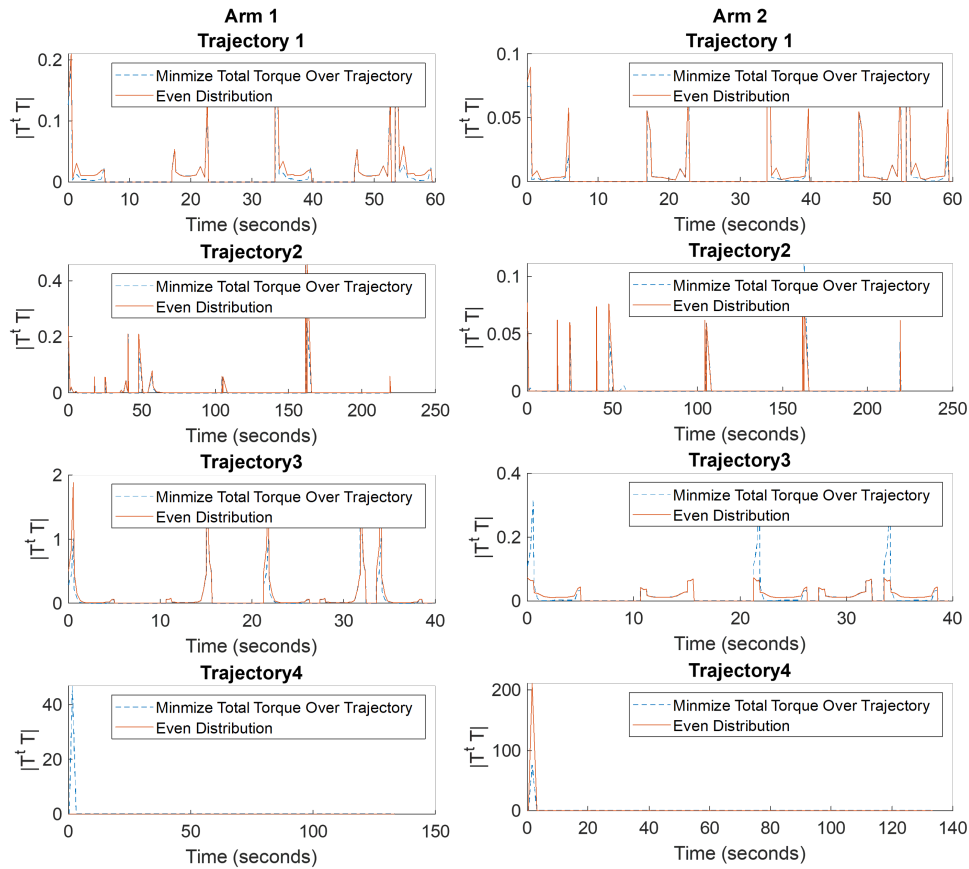


Fig. 20—Total torque for even and minimal torque force distribution over the four different trajectories

Figure 22 shows the maximum force in each of the 21 beams that constitute each TriTruss module as it is lowered into place by the two dexterous arms. The evenly divided force distribution method produces a lower force than the minimum total torque distribution, as no squeeze forces are required. The minimum torque force distribution scheme reduces the total torque by transferring forces and torques between the two arms through the TriTruss, resulting in higher forces acting on TriTruss units. If these forces/torques are not limited, it could drive the mass of the TriTruss. The overall system has a lower total torque, but the forces and torques being transferred intentionally through the TriTruss unit are significantly higher.

The legs react to the forces from the robot body to the truss assembly. The maximum force transferred to the truss assembly varies for the four different trajectories. Trajectories 1, 2, and 3 all have the same magnitude but occur at different times; see Fig. 23. These three maneuvers all move a TriTruss unit at the same acceleration, thus the forces transmitted to the legs are very similar. Trajectory 4 moves the TriTruss unit at a reduced acceleration, which is seen with a lower maximum force being transferred to the truss assembly. While the overall magnitude of the force being transferred to the assembled truss is very low, it is clear that reducing the acceleration will reduce the maximum force transferred to the truss assembly.

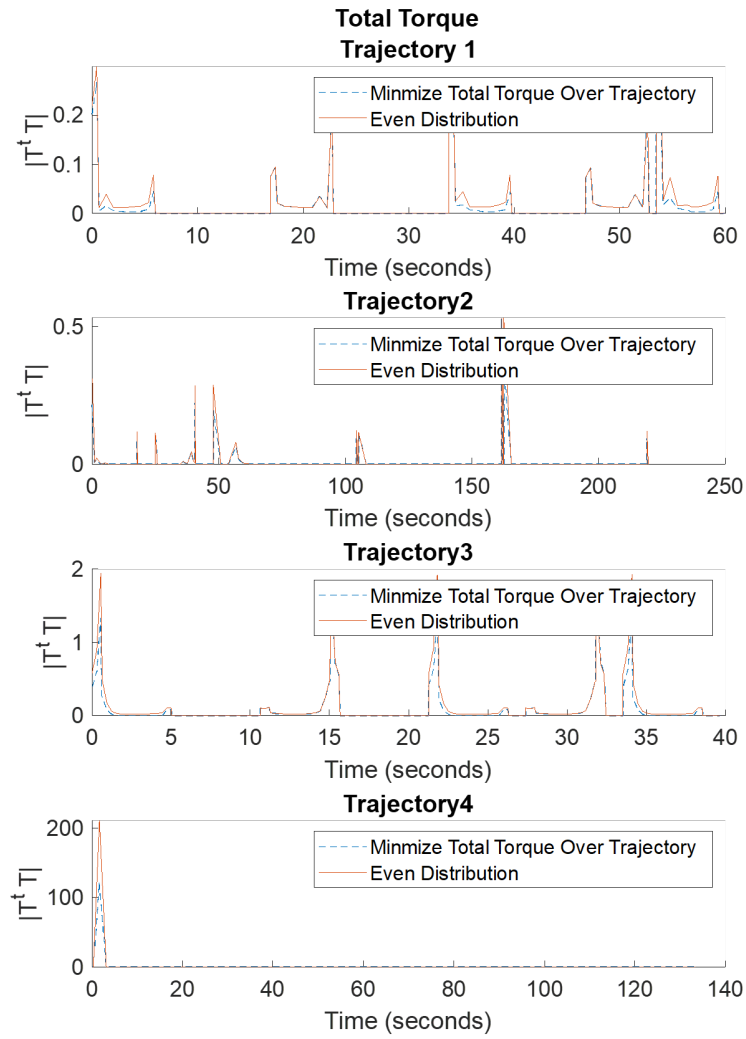


Fig. 21—Sum of the total torque for Arm 1 and Arm 2 for each trajectory

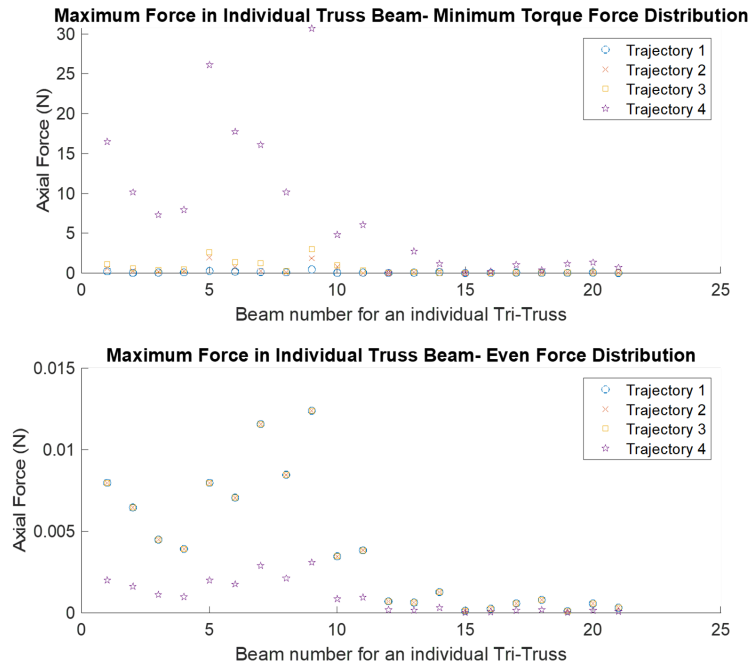


Fig. 22—Maximum force seen in each beam of an individual TriTruss as it is lowered into place

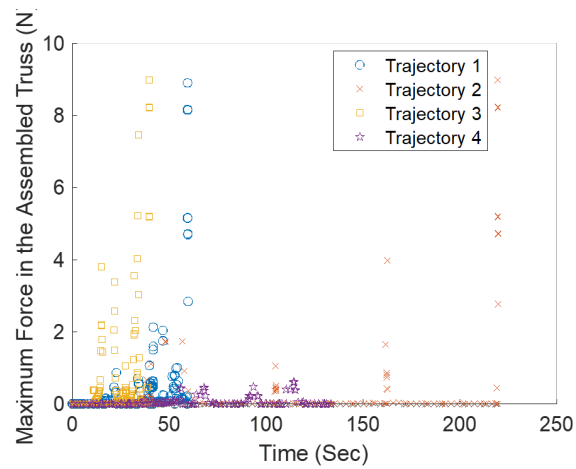


Fig. 23—Maximum beam force in the assembled truss over the entire assembly process

6. FUTURE WORK

This study shows that *how* an ISA structure is assembled can affect the entire system. This study focused on two different robotic systems: a stationary robot and a crawling robot. There are many design variables that can be studied. This study was limited to assembling a linear truss made up of truss modules. ISA is not limited to linear structure; a telescope made up of rings of hexagon is a common ISA structure. Structures also can be made up of multiple layers, requiring the robotic systems to move between layers.

The number of limbs of each of the robots was given to be fixed in order to compare the systems better. The stationary robotic system included a single positioning leg and two dexterous arms. Two different crawling robots were examined: a planar system and a nonplanar system. The planar system included two positioning legs and two dexterous arms. The nonplanar system required an additional two positioning legs. The detailed walking study done here used the same robot for both the positioning legs and the dexterous arms. There is no inherent difference between a positioning leg and a dexterous arm; the dexterous arm may require more degrees of freedom, however, that is not necessary. It is possible for a dexterous arm to perform the duties of a positioning leg. The number of limbs is, therefore, an interesting variable to study. Reducing the number of limbs may reduce the robotic mass and power, however, it depends on how the design changes to compensate for the reduced number of limbs. Future work would include changing the number of limbs in order to optimize each of the robotic types further for ISA.

7. CONCLUSION

This study focused on identifying the major design parameters for a robotic in-space assembly. A major design parameter is one that has a major impact on more than one of the main subsystems that make up a robotic ISA system: the robotic system, the structure, and the assembly process. A number of major design parameters were found, including size of the truss units, assembly order, foothold location, and how the truss modules are moved.

Many minor design parameters also were identified, including: walking gait, force distribution between multiple limbs making up a closed kinematic chain, and the joint trajectories for a predefined path. Varying the minor design parameters will result in a small change in the structure and/or the assembly process. For example, changing the walking gait will change the location of the robotic legs relative to one another and will drive their required lengths and even motor torques; this also increases the force placed on the different footholds. However, the force transferred to the truss structure is relatively minor. As long as the force transferred to the truss structure is below a certain limit, then the gait can change without directly changing the truss design. However, even making a small change to the truss size or the assembly order, both major design parameters, can greatly effect the robot design and the assembly process.

The final designs of the TriTruss bays and the robotic system are based on how the structure is to be assembled. The assembly process includes the assembly order, trajectory of each TriTruss bay, the position of the robot body, the manipulator trajectory, etc. ISA is an unconstrained structured-systems problem for which both the robot and the truss system should be designed together. In order to truly design the robotic system and the truss system together, the assembly process first must be defined and the major coupled design parameters must be identified.

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