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Factory Floor: A Robotically Reconfigurable Construction Platform

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Abstract— **Passive robotically-reconfigurable truss structures offer considerable utility as they can quickly adjust to changing functional requirements and resources at a level of sophistication that no human builder could match. Furthermore, robot built structures can be constructed in environments such as surface of Mars or in micro-gravity, which would otherwise be too time consuming or dangerous for humans. In this paper we discuss some of the mechanical design challenges of developing a passive robotically-reconfigurable truss system, and present the concept of the *factory floor*, which can construct truss-like structures without climbing on them. In the proposed system, each level is constructed on a ground plane using a truss and node configuration and is elevated to make room for the next level. This process is repeated to create 3D truss structures or reversed to decompose the structure for the next task.**

I. Introduction and Motivation

Much can be learned from abstraction of behaviors or properties found in nature and their implementation into robotic systems at the mechanical and control level. The robustness of natural systems to compose and decompose elements offers benchmarks for the robotic assembly and disassembly of synthetic structures.

Application areas for robotically assembled structures have focused on large space structures though deep-sea mining and martian or lunar structures are other possible applications [16] [14] [18]. If these structures could be taken apart, they could be reconfigured to adapt to needs as situations change. Towards this longer term goal, this paper focuses on the electro-mechanical platform for which algorithms can then be developed to autonomously (de)construct structures as needed. One example algorithm develops local reactive behaviors that result in the ability to ”robustify” the assembly of this distributed platform [12]. In view of these motivations the design aims to allow distributed computation, manipulation, sensing towards a larger coupled structure with minimal interaction constraints and cost.

Note that all processes here are reversible and so assembly processes equally apply to disassembly.

II. Related Work

While there have been many robot hardware platforms for a variety of robotics research[11], there have not been many platforms for autonomously assembled structures. In [17], a modular structure is proposed in which an assembler robot puts together structures made of cubes. The assembler robots climbed on top of the structure building what looks like a brick wall. While this paper proposes a design that

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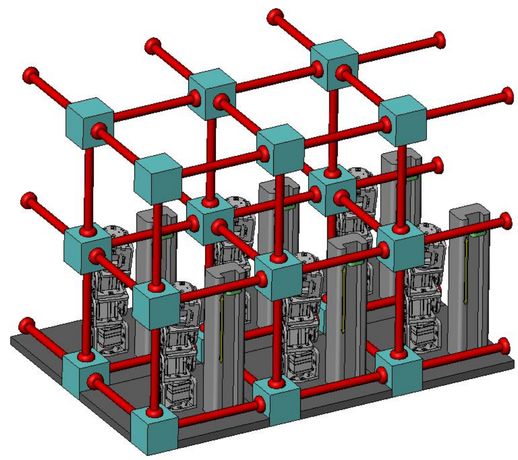

Fig. 1. A simple illustration of truss-like construction where items in red are trusses, items in blue are nodes, and items in gray represent the robotic assemblers.

can form 3D structures and has passive cube modules the implementation had active cubes and could only implement 2D structures. Other work has focused on the control of robots that assemble trusses[3].

Developing a robotic system capable of assembling truss-like structures presents a very coupled mechanical design challenge. The robot, or builder, can not be fully realized without considering the geometry of the truss and the means of connecting trusses together. Likewise the truss design can not be finalized without fully understanding the limitations of the builder. Prior work in robotic construction of static structures has predominately focused on enabling a robot to navigate a structure and manipulate (i.e. reorient and place) the structural elements. Shady 3D [18] was designed to be an active mobile module capable of manipulating passive structural modules within a 3D truss structure; however, this robot lacked the ability to physically attach the passive structural modules to the structure. Hjelle and Lipson [9] developed a “hinge” robot capable of traversing simple cubic truss structures as well as removing and docking trusses. A passive truss configuration was presented whereby a rod with threaded ends could be inserted into one of 18 threaded sockets of a node, which acts as a connection point for multiple trusses. Two rods are required to the span the distance between two nodes, which is accomplished by partially unthreading the two rods from the center to thread into adjacent nodes. While truss manipulation and attachment were demonstrated more work is still needed to enable to robot to manipulate and attach the nodes. Another method for achieving a desired shape is through robot self-disassembly by starting with a collection of robots in an amorphous arrangement and removing the unnecessary ones [6] [7]. This method of quick disassembly has several merits including the ability to respond to changes in design requirements through material subtraction; however, this approach in itself is not suitable for building structures of arbitrary heights.

For space applications, Skyworker [16] is a mobile manipulator designed to transport payloads and assemble truss structures for future space facilities. It is capable of moving along a truss structure and adding (or removing) trusses; however, it was not designed to autonomously dock trusses as it requires position feedback from an independent vision robot. Another method for space construction considers free-flying space robots rather than using the truss structure to support robot building activities [14]. Space robots consist of a satellite base and a manipulator for orienting, transporting, and connecting trusses. While their movement is theoretically not constrained by the truss structure (i.e. they don't need to be attached to the structure to build), there is added complexity in maintaining 3D control of robot position and maneuvering the building element while avoiding collisions. Experiments thus far have only demonstrated 2D construction. Furthermore, this method does not extend well to environments with gravity as weight ultimately affects the size of the free-flying robot, the power requirements, and the size of the building elements.

In addition to passive structures there are is a community of researchers building self-assembling active structures in which most elements are active. These are usually referred to as self-reconfigurable modular robots[1][2][4][5][8][10]. The difference is that most of the elements in this system are passive - so they can be optimized for weight and cost.

III. Design Criteria

Developing a robotic system to assemble truss-like structures requires careful consideration of the interplay between the robot and the building elements. Here we refer to the way in which the robot transports, manipulates, and connects[1] (or disconnects) the structural elements. To guide the mechanical design efforts, the functional requirements were constructed as follows

1) **Truss Design**.
   - **Assembling**. Trusses must be able to be connected and disconnected, without excess movement, into the structure.
   - **Passive**. Trusses should be passive (i.e. consume no power) when they are not being handled by the robot.
   - **Manipulate**. The truss must be of a size, shape, and weight such that the robot can easily manipulated the position and orientation.
2) **Robot Assembler/Disassembler**.
   - **DOF**. Robot assembler must offer enough degrees of freedom to transport, manipulate, and connect the building elements.
   - **End effector**. Robot end effector must be able to handle all building elements (i.e. trusses and nodes).
   - **Minimal feedback**. Final design should minimize the positioning and alignment feedback needed for truss structure assembly.

[1]For this purposes of this work we assume that the ability to connect building elements also implies the ability to disconnect

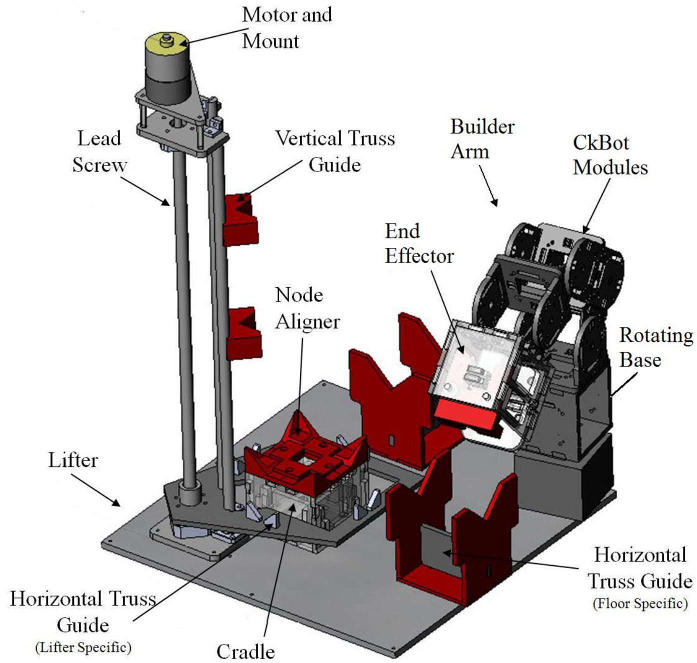

Fig. 2. An illustration of one factory floor tile with one possible arrangement of components.

IV. Factory Floor Overview

The factory floor is a reconfigurable passive truss assembler. The system is composed of tiles which may consist of a building arm, an elevator, and passive structural guides (see Fig.2). The tiles can be grouped together to fill any foot print which also defines the boundary limits of the final structure. In the proposed system, the building materials consist of trusses and nodes, which are delivered to the perimeter of the factory floor. We assume a task specific robot known as a "collector" (not pictured), locates and delivers building materials to specific locations along the perimeter. Builder arms closest to the perimeter are capable of selecting trusses and nodes and either dock them for construction or pass them inward to builder arms on land-locked tiles.

The assembled structures are composed of cube-shaped nodes, and bar-shaped trusses. The nodes have features on each face so that a truss may be attached to each one creating a simple cubic lattice structure.

Robotic construction first begins with the selection and placement of nodes into *cradles*, which are passive guiding structures (Fig.5B). The cradles are evenly spaced between tiles to reflect the length of the trusses and feature chamfered interior walls to ensure proper node placement and orientation. Magnets on each face of the node and on the cradle offer additional passive alignment. These passive alignment features on the cradles and other elements are meant to reduce the precision required by the builder arms to complete the task.

When the nodes are in place, horizontal trusses can be connected (Fig.5C). Horizontal truss guides have also been incorporated to ensure that the lengthwise axis of the truss aligns with the axis of the node appendages. As an alternative to building a climbing robot, the proposed system builds static structures one level at a time at the foundation level and then elevates the entire structure to build the next level (Fig.5D). In effect, the structure is built in a series of layers from the top down. The elevators in this particular implementation use a lead screw and DC motor construction and are stationed next to each cradle. A lifting element cantilevers from the lead screw and surrounds the cradle. When not in use, the lifting element is recessed below the nodes so that they do not interfere with truss and node placement. When activated, the lifter supports the junction near the end of the trusses. V-shaped guides on the lifter prevent the structure from shifting during lifting or lowering. Once the structure has been lifted to the desired height, the next set of nodes are inserted into the proper cradles. The trusses are then vertically inserted in the spaces between the elevated nodes and the cradled nodes (Fig.5E). Vertical truss guides have been incorporated into the elevator to assist in truss and node alignment. Once completed, the vertical trusses now support the elevated portion, and the elevators are lowered to the ground position. Horizontal trusses can be inserted again and the process repeats to create 3D static truss structures (Fig.5F).

A. *Robotic Arm and End Effector*

The robotic arm is an assembly of CKBot modules in which each module has 180 degrees of rotational freedom and is powered by a hobby servo [13]. The module arrangement uses four CKBot modules, with a specialized fifth rotating base module that allows the arm to rotate 360 degrees. The four modules offer enough degrees-of-freedom to dock and pass nodes and trusses (both vertically and horizontally). The end effector (see Fig.3) uses a slider-crank mechanism and a single Hitec HSR-5990TG servo to control the position of the *claw*. The claw enables the end effector to grab trusses and actuate the ends of the truss for connection (see Truss Mechanical Design section for description of truss manipulation). The claw is connected to two linear bearings, which ride on two precision ground aluminum shafts built into the internal cavity of the end effector. Two rigid links with pin joints connect the servo to the claw. This arrangement offers a straight forward conversion from the rotary position of the servo to the linear position of the claw. Currently the end effector is capable of delivering over 240 N (54 lbs) of squeezing force. CKBot modules in which each module has 180 degrees of rotational freedom and is powered by a hobby servo [13]. The module arrangement uses four CKBot modules, with a specialized fifth rotating base module that allows the arm to rotate 360 degrees. The four modules offer enough degrees-of-freedom to dock and pass nodes and trusses (both vertically and horizontally). The end effector (see Fig.3) uses a slider-crank mechanism and a single Hitec HSR-5990TG servo to control the position of the *claw*. The claw enables the end effector to grab trusses and actuate the ends of the truss for connection (see Truss Mechanical Design section for description of truss manipulation). The claw is connected to two linear bearings, which ride on two precision ground aluminum shafts built into the internal cavity of the end effector. Two rigid links with pin joints connect the servo to the claw. This arrangement offers a straight forward conversion from the rotary position of the servo to the linear position of the claw. Currently the end effector is capable of delivering over 240 N (54 lbs) of squeezing force.

The end effector is also capable of picking up and releasing nodes. The under portion of the device features a square cutout into which the node appendage fits and a magnetic bond holds the face of the node flush with the bottom of the end effector ((see Fig. 4A) (see Node Design section for further detail). The under portion of the claw features a node release mechanism which consists of two static appendages that extend downward. When the claw moves to a closed state (i.e. downward) the appendages extend beyond the bottom of the end effector forcing the node to separate (see Fig. 4B).

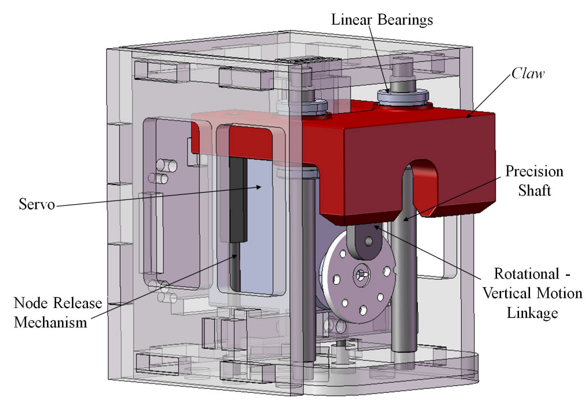

Fig. 3. The end effector is used to transport and dock trusses and nodes for construction

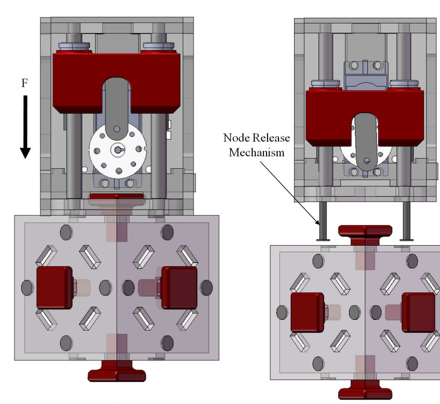

Fig. 4. (a) The bottom face of the end effector magnetically attaches to the nodes for transportation and placement. (b) The a node release mechanism is built into the end effector to either pass or dock nodes.

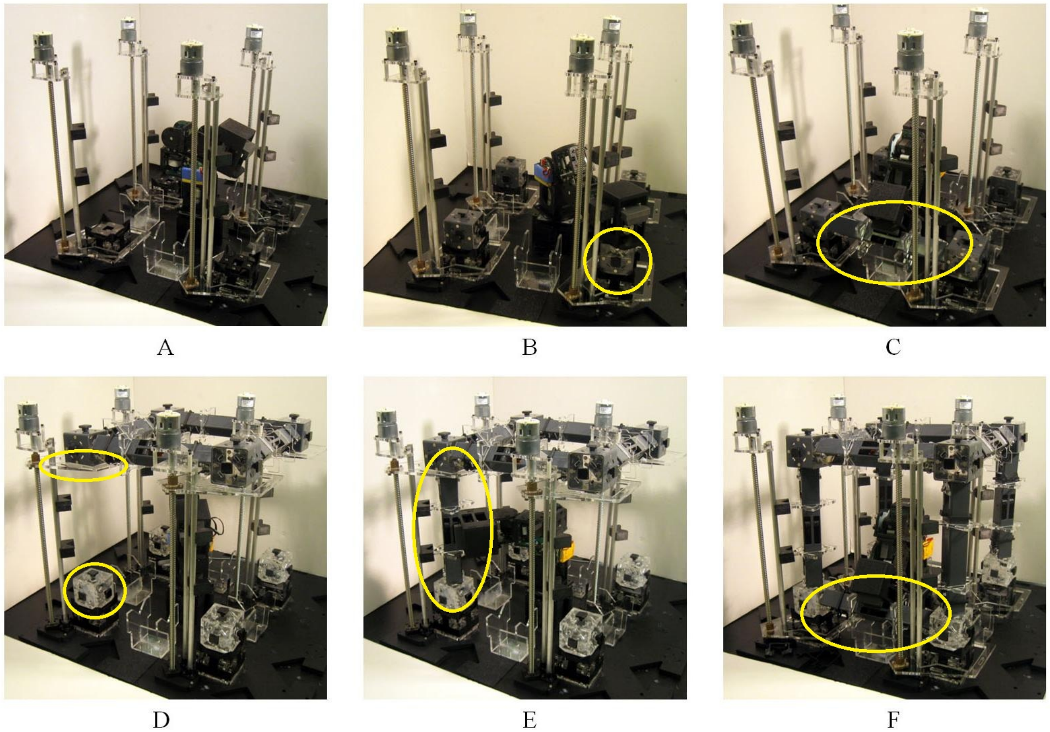

Fig. 5. Illustrates truss assembly with a configuration of four tiles and one end effector. Assembly steps are as follows (A) the factory floor starts in an empty state, (B) end effector docks nodes in cradles, (C) end effector attaches horizontal trusses to neighboring nodes, (D) the truss and node layer is elevated and next set of nodes are docked on cradles, (E) vertical trusses are inserted, (F) elevators are lowered and the next set of horizontal trusses can be inserted.

B. Truss Design Considerations

There are several elements to consider in the truss design, many of which are listed in Section III; however, at the highest level one must first consider the method in which the truss will be connected and disconnected from the structure. In our development efforts active (i.e. motorized) and passive connection methods were considered. Active connectors are not new, especially among modular robots where these designs offer strong, and completely retractable connection mechanisms [15]. Incorporating actuation into the truss invites additional features such as embedding microprocessors and sensors to detect if a truss successfully docked or adding a locking mechanism to ensure a rigid connection. In an early design we considered a configuration in which the end effector could pass power to the truss and change the state (i.e. open or closed) of its connectors by changing the direction of the current. This was achieved by attaching a cam to the motor axis (i.e. one motor at each end) such that a rotation in one direction would open the connector, and a reverse rotation would lock the connector halves together. The finished prototype, however, revealed that the added mass, assembly, maintenance, component cost and the need for a robust electrical connection precluded this design from practical implementation. The cost factor is amplified as we plan to build hundreds of trusses.

On the other hand, passive connections offer configurations with fewer components, and therefore fewer modes of failure. It is easier to identify problems with passive connectors, and one can quickly iterate different solutions without the challenge of integrating electronics. The drawback of passive connectors is that 1) it complicates the builder arm and node as they require a mechanism to open and close truss connectors for docking and 2) the builder arm and node actions are tightly coupled with truss insertion and removal.

C. Truss Mechanical Design

The proposed truss can be directly inserted or removed between two nodes in the structure as desired. The 1-DOF end effector is sufficient to open and close the passive compliant connectors. As illustrated in Fig.6, the body of the truss is square tube (35.5 mm) PVC with a wall thickness of 2.1 mm and a present length of 29.3 cm. Portions of the tube walls have been machined out to create the 6 cm long compliant arms. On one face of the truss midsection two cutouts allow the end effector to pick up the truss by inserting a claw feature into a cutout. Two cutouts are needed to allow the trusses to be relayed from one end effector to another (see Fig.8). A simple cam design pivots about a rod below the cutout foot print. Small diameter steel cables connect the cam to rigid links located near the end of the truss arms. When the end effector closes into the cutout, the cam rotates and causes the cables to pull on the rigid links which in turn force the truss arms to deflect away from each other (see Fig.7A). The truss is now in the *open* state (Fig.7B) and can be inserted between two nodes. Truss-node connection is completed when the end effector retracts and the truss arms spring back to their initial *closed* state. The connectors at the end of the truss arms close around the node appendages and complete the connection. The process is reversed to disconnect the truss from the nodes. In addition to the restoring force of the compliant arms, rare earth magnets have also been included to draw the compliant arms together and to ensure a stronger connection (labeled as *magnetic attacher* in Fig.6). Presently each truss arm deflects outward by approximately 16° which creates a sizable opening (36 mm) between the connectors measuring about 150% of the diagonal length of the node appendage.

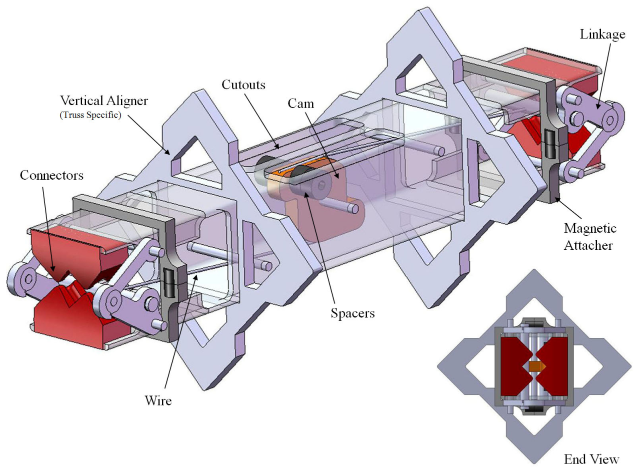

Fig. 6. Isometric view of assembled truss with an end view.

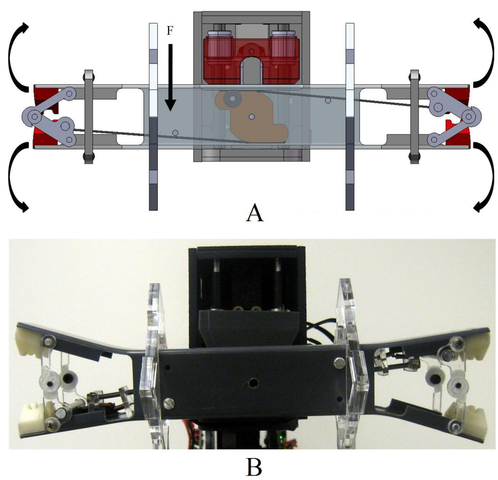

Fig. 7. The end effector prepares trusses for connection with nodes by squeezing the truss mid-section (A), which though a simple cam mechanism causes the truss connectors to open (B). The process is reversed to close the truss connectors around the node appendages.

D. Truss Design Challenges

One of the challenges of any compliant mechanism centers on determining the part geometry that will achieve the desired behavior. The truss design is no exception as one must consider first the squeezing strength of the end effector, the desired opening width of the connectors, and material limits. In this particular implementation, much of the mechanism design was constrained by physical limitations which included designing the linkages long enough to displace the truss arms by roughly 150% of the node appendage diameter while not interfering with truss docking. The design was further constrained by the fact that end effector's claw could only displace a distance less than half the width of the truss (<16.7 mm) before colliding with the cam axel. Therefore in order to maximize deflection of the truss arms while operating within the effective clamping range of the end effector, the applied load via the cable force on the rigid linkages was shifted away from the axis of symmetry.

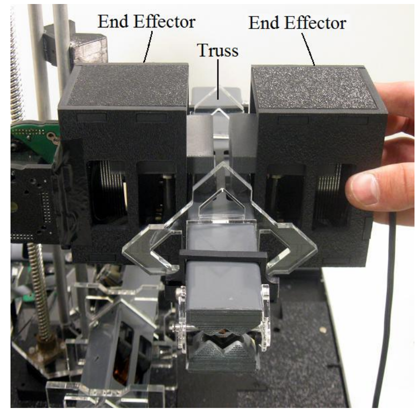

Fig. 8. Illustrates the method of passing a truss from one end effector to another.

The present configuration requires approximately 45 N of force to deflect the truss arms by 16° for one truss end, and therefore, 90 N to simultaneously actuate both ends. This is well within the range of the gripper's capability (37% of it's maximum clamping capacity).

E. Node Design

The node offers a means of connecting multiple trusses together and can take on a variety of shapes and configurations. In [9] the nodes have 18 female threaded faces which allowed parallel, perpendicular, and diagonal truss connections. For ease of manufacturing, the node design (shown in Fig. 4 with the end effector) proposed here has 6 faces and T-shaped appendages extend from each one. This design decision is what enables the trusses to be inserted and removed directly from the structure. The node is fabricated by first machining cutouts on each face, and then inserting and gluing the appendages in place. Additionally, each node face has a symmetric arrangement of rare earth magnets which aids in transportation and assembly. During transportation, the end effector is magnetically attached to the node and the strength of this connection is more than sufficient to support the weight of a single node. During assembly, the magnets help align and hold the node in the cradle.

V. Discussion

Climbing mobile manipulators represent one end of the robot building spectrum while the factory floor represents the other. Both extremes have their advantages and disadvantages. Climbing robots offer the potential to build structures of any sized foot print and of any height that the truss members will support. This method of construction does require a rather complex robot that is capable of navigating the truss structure, removing and transporting building elements. In fact the creators of Skyworker suggest that these are too many features for one robot and recommend distributing building tasks across a number of task specific robots [16]. The factory floor offers the ability to create static structures with very little robot feedback, and construction is split among several components such as the elevator and the builder arm. Furthermore, construction occurs one level at a time making it straight forward for the system to track assembled parts. One of the drawbacks of the design centers on the elevators; the height of the end structure depends on the number of elevators employed and their lifting capacity. Another disadvantage of the factory floor concept concerns the introduction of design changes to the structure. If for example, new information reveals that a change is required on the top level of an already constructed fifty level structure, the entire structure must be decomposed and then reassembled. This scenario suggests that a hybrid of the two building methods would lead to more adaptable and robust assembly. In such a situation, a climbing robot would be advantageous to address minor design changes while not interrupting the construction process.

In addition to the design criteria listed in section III, cost has been a design constraint that has significantly influenced the final configuration. In fact, the builder arm represents roughly 90% of the entire cost of one tile. A more desireable arrangement would be one in which the building foot print could be increased for a fraction of the cost. One approach to minimize the number of builder arms is to enable them to locomote on and outside the factory floor. The advantage of such a configuration would allow one builder arm to accomplish the same task as n rigidly fixed arms albeit at a much slower rate. Furthermore, the mobile builders could assume additional rules such as becoming a collector by gathering building materials located outside the factory floor.

VI. Conclusion and Future Works

The goal of this work is to develop a simple low cost robotic system capable of (dis)assembling truss-like elements to validate building algorithms for a variety of researchers around the United States. It is planned to build hundreds to thousands of elements, so cost cannot be ignored.

Future work includes reexamining the design features of the truss and node configuration and convert them into a more rigid arrangement. While simplicity has been the goal for the truss and nodes, even further simplification will be explored. The first construction run will contain many dozen of elements. Future runs will consist of many hundreds up to one thousand. At which time the limits on the strength of the elevator will be determined, robustness and failure modes can be characterized. Furthermore, it would be ideal to include simple binary feedback mechanisms (such as one to indicate whether a truss is present or not present) into the distributed construction algorithms to enable 'self-awareness' capabilities.

VII. ACKNOWLEDGMENTS

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