A Robotically Reconfigurable Truss

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Abstract—*This paper addresses the design of passive robotically-reconfigurable truss structures and progress towards a robot capable of manipulating such structures. The elements are designed to be inserted and removed singly in "random access," thus eliminating some assembly order constraints and enabling a physical realization of the construction process. The proposed robot is a "hinge" robot that can demonstrate manipulating said elements. The robot is also designed to be able to traverse arbitrary scale truss structures. With the addition of reconfiguration algorithms discussed by Lobo in [1], we suggest that such reconfigurable structures and robots could open the door to a machine metabolic process where structures are decomposed and recomposed autonomously to meet varying needs to a variety of applications from infrastructure recovery to space exploration.*

Index Terms—*reconfigurable robotics*

1. Introduction

Biological metabolism is the process by which an organism breaks down food into its constituent modular elements (catabolism) and then uses those raw materials to create new tissue (anabolism). Metabolic processes demonstrate interesting properties that are difficult to replicate in synthetic structures, such as continual reuse of modular elements in new organisms, autonomous disassembly and assembly processes, self repair, continuous adaptation to functional requirements, and robustness to resource fluctuations. Duplicating these properties in a robotic ecology and composing, decomposing, and then recomposing items out of such modular elements could have a wide range of applications, ranging from infrastructure recovery to space exploration. Figure 1 shows a concept image of a robotic ecology metabolizing truss structures in the proposed way.

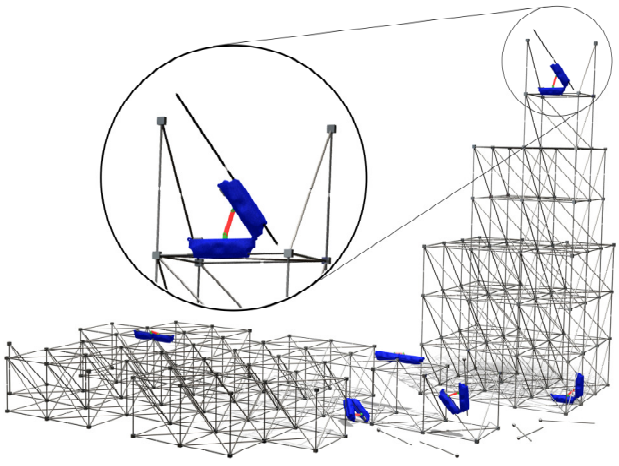


Figure 1. Structural metabolism concept. Artist rendition of several robots performing metabolism on a truss structure. Structural metabolism implements properties of biological metabolism, such as autonomous disassembly and assembly, automated design from encoded requirements, and robustness to resource fluctuations.

Machine metabolism is a long-term goal, consisting of a multiple challenges. First, what minimal set of modular elements would serve as a basic starting point for implementing metabolic processes in a physical system? Doyle *et al.* [2] suggest that a large number of source and target structures can be described through a relatively small set of well-optimized building blocks, known as the bowtie architecture. Second, what algorithms can determine which target structures meeting certain functional specifications are attainable using a given set of building blocks, and how would they be specified? Third, how does one optimally transform a source object into a new target object while maintaining both physical structural constraints and kinematic robotic constraints? More broadly, such challenges are compounded by uncertainty and fluctuations in the supply of resources and lack of global coordination mechanisms between multiple robotic agents – much like biological cells need to construct tissue under varying conditions and resource fluctuations, using massively-parallel and uncoordinated local stochastic processes. In this paper we limit our study to simple cubic truss structures with single face-centered diagonals (as in Figure 1), thus constraining the elementary set to only two elements. Within this framework, we propose physical elements designed to realize such robotically manipulatable truss structures, as well as a robot designed to manipulate these structures. While the robot is only capable of minimal truss manipulation currently, we anticipate that full structural manipulation is achievable in this framework.

2. Background

Self-reconfigurable modular robotics traditionally considers systems with homogeneous self-mobile modules that change their own shape by rearranging the connectivity of their parts [3]. This mobility is important in a system intended to reconfigure repeatedly or frequently, such as locomotion over different terrains [4] or playback of dynamic three-dimensional systems [5]. However, in a system intended for the construction of static structures, self-mobility is

unnecessary [6]. Additionally, since the static structures can be produced much more cost effectively, many applications become possible that were previously prohibitive.

Many robots have been developed to climb and/or manipulate truss-like structures. SM^2 was developed as a truss-walking inspection robot controlled via teleoperation [7]. An inchworm robot was developed by Kotay and Rus [8] that used electromagnetic attachment to navigate around a structure, though no structural manipulation capabilities were added. Ripin *et al.* [9] developed a pole-climbing robot capable of climbing irregular palm-tree like structures, but it is limited to pole-climbing problems. A robot for climbing high-rise buildings using balconies as steps was developed by Amano, Osuka, and Tarn [10], but no generalization to horizontal or other movements was done. Skyworker was developed for orbital assembly tasks [11], and was demonstrated performing truss-like assembly tasks [11]. However, the truss structure was not specifically designed for robotic manipulation and required an independent vision robot to perform the assembly. TREPA is a parallel robot able to maneuver a wide variety of structures, but there is no facility for structural assembly [12]. Tavakoli *et al.* [13] present a pole-climbing robot capable of performing manipulative tasks (such as replacing a light bulb), however, the robot cannot traverse more complex truss structures. ROMA was developed as a caterpillar-like robot to climb complex 3D structures, but, again, provides no specific structural manipulation facilities [14]. Finally, Shady3D [15] was developed as a novel approach to climbing 3D structures with a modular robot; however, the manipulation abilities were again lacking. None of these works show physical structures designed with robotic manipulation particularly in mind. It is notable that only Skyworker showed the ability to navigate, assemble, and disassemble complex truss-like structures.

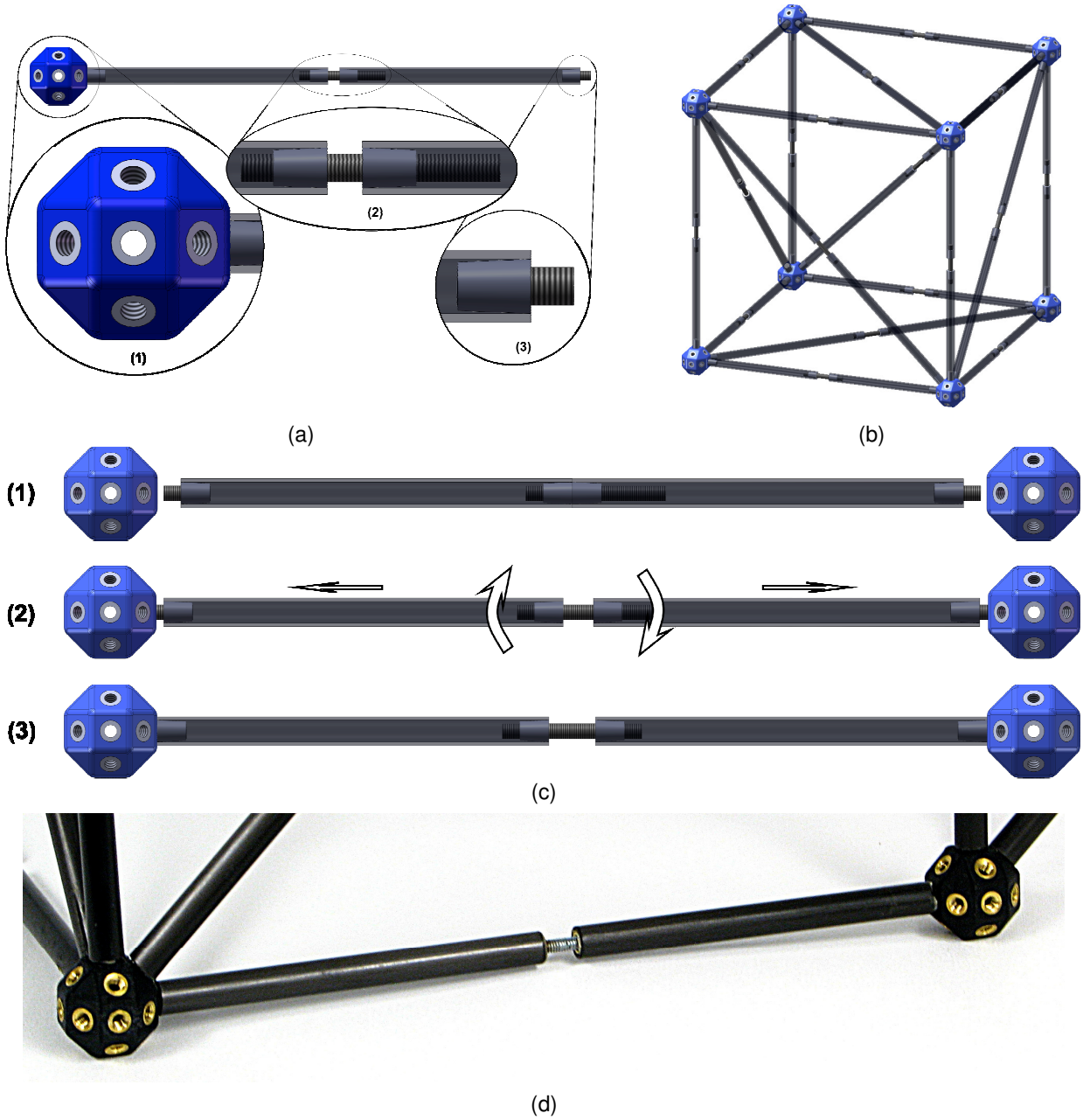


Figure 2. Random-access truss elements allow order-independent assembly: (a) Elements consist of an 18-axis threaded node (detail shown in a1) and a long strut. This strut is split in the center with a threading mechanism (a2) and uses a threading mechanism on either side to attach to the node (a3); (b) Elements can be used to construct a variety of structures such as this cube; (c) The truss elements can be accessed in a random-access manner by inserting the contracted element between nodes (c1), twisting the two element halves (c2) causing the center thread to lengthen and the end threads to enter the nodes (c3). Note that all threads are right-handed threads. (d) A physical implementation of node and strut.

3. Truss Structure

We designed a set of truss elements particularly suited for robotic manipulation. Our criteria, then, consist of the following:

- **Simple.** With increased complexity (such as mechanisms, actuation, or sensing) comes greater manufacturing challenges and increased cost, which ought to be avoided for practical implementations.
- **Strong.** Effective elements would be able to be used in a variety of load-bearing situations.
- **Manipulatable.** Except in the case of complex anthropomorphic end effectors, most robotic manipulators are not dexterous enough to effectively manipulate common human building blocks, such as extruded aluminum. Our elements must be designed to simplify the manipulation task for robotic manipulators as much as possible.
- **Assemble-able.** The amount of feedback required for the assembly process (such as positioning and fastening the elements) ought to be minimized.
- **Accessible.** Finally, we want to be able to add or remove elements from the truss structure in a random-access fashion: at any location, interior or exterior, without affecting the remainder of the structure. This allows reconfiguration of the truss without extraneous removal of elements.

The elements we designed consist of struts and nodes capable of assembling cubic trusses with face-centered diagonals. Figure 2a contains a close-up image of a strut and node and Figure 2b contains an example of a cube constructed with such parts. The nodes consist of 18 threaded sockets in each of the necessary axes, inserted into a 3D-printed shape. The struts consist of two identical carbon fiber rods internally threaded on both ends via threaded inserts fastened inside the rods with epoxy. Connecting two of these rods in the center via a threaded stud completes a strut. The center threading mechanism (using only right-hand threads) allows the two halves of the strut to be turned in opposite directions, thereby extending the length of the strut. If the ends of the strut are lined up with the appropriate hubs on either end, the extension length will match the length required to thread into the hubs. (See Figure 2c.)

This mechanism allows the strut to be inserted or removed with no translation or rotation of the nodes, satisfying the accessibility criterion. In effect, the parts are completely random-access. The simple twist action required for fastening satisfies the manipulatable criterion. Since regular threaded fasteners are known to be difficult to align properly for proper insertion, properties of existing self-aligning threaded fasteners (as discussed in the next paragraph) are used to satisfy the assemble-able criterion. Finally, the struts are simple and strong, satisfying the remaining criteria.

One of the fundamental problems with robotic manipulation of threaded fasteners is proper axial alignment between the male and female portions of the fastener. Work has been done on this using force and position feedback from robotic hands [16] or by "backspinning" the bolt on the nut to determine proper orientation [17]. These processes require a relatively large amount of feedback and control to perform correctly. Several patents [18-20] list possible fastener modifications that serve to enable self-aligning. In our case, the use of a larger diameter fastener with much coarser threads allows us to achieve successful fastening with alignment angle errors up to 5° and 5 mm, which allows successful robotic manipulation. (See further discussion is section 5.)

Figure S1 shows some of the design process iteration steps in completing this design.

4. Manipulator Robot

A variety of robot morphologies are capable of manipulating truss structures as described above if given an appropriate end-effector, including the ubiquitous robotic arm with revolute joints. Most of the standard morphologies, however, are limited by their stationary workspace. A robot that was able to climb on a truss structure and manipulate its elements *in situ*, however, overcomes the limitation of scale and is able to reconfigure arbitrarily-sized trusses (within the limits of time and energy). Different morphologies for truss-traversing robots have been developed in the past; however, as discussed in section 2, these robots typically have very limited (if any) provision for truss manipulation.

We propose, then, a "hinge" robot (overviewed in Figure 3) that is capable of traversing the simple cubic truss structures discussed in section 3, removing a single strut, transporting a strut to an arbitrary location in the truss, and placing the strut in a new location. Both the long (diagonal) and short struts can be manipulated, with the robot being able to distinguish between the two by their orientation in space (i.e. diagonal or otherwise). Nodes are transported as part of the struts. The

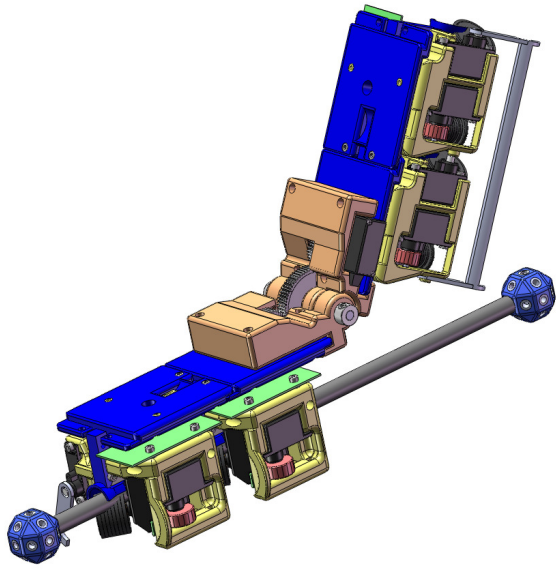


Figure 3: The hinge robot that we propose is composed of four modules that are each capable of gripping, translating across, and rotating about truss elements.

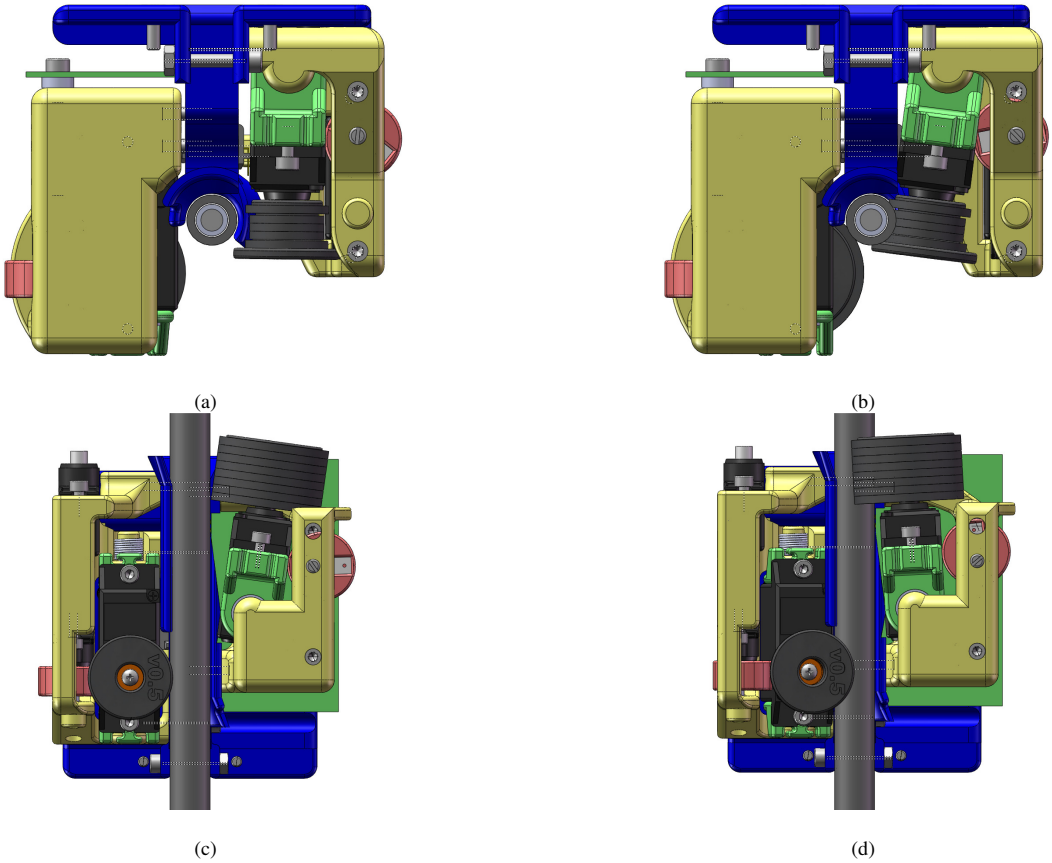


Figure 4: Each module of the hinge robot has a pair of drive servos and engagement servos. (a) and (b) show a side view, showing the engagement of the drive wheel with the truss element via actuation by a cam, driven by the engagement servo. (c) and (d) show the engagement process from the bottom. Both translation and rotation mechanisms would not typically be actuated simultaneously, but are in this instance to demonstrate the concept.

associated planning is beyond the scope of this paper and will be addressed in future works; this work concentrates on the design of the robot and its motion primitives.

4.1. Overview

The hinge robot is nominally positioned on a single strut in the truss structure. Since the robot is divided into halves separated by a revolute joint (discussed in section 4.3 below), the halves may orient themselves at an angle relative to each other. This allows one half to be located on one strut, while the other half can be moved to a location about a second strut. The robot can then transfer its nominal position to the second strut. Repeated application of this procedure allows the hinge robot to move anywhere on the truss.

Each half of the robot consists of two modular elements. Each module has basic control on-board, as well as basic actuation for rotation and translation (discussed further in section 4.2) on the truss elements. Sensing will be distributed among the modules. (The details of this remain for future work.)

The structural components of the hinge robot are made from 3D-printed ABS plastic.

4.2. Actuation

Actuation is provided by four servos per module. Drive and engagement servos are provided for each actuation category, translational and rotational. Each drive servo is mounted on a ball-bearing swivel with spring return. To engage the drive servo with the truss element, the engagement servo uses a cam that presses on the body of the drive servo to tilt in into contact with the strut. Each drive servo has a drive wheel attached that will contact the strut; friction between the drive wheel and truss element provides the capability of motion. (Figure 4 demonstrates this process.)

The strut is actuated while “inside” the module. It sits in a partial cylindrical track in the middle of the module. The drive wheels are positioned on either side of this track such that they can “swing” in to contact the truss element and thus provide actuation. The track is also designed to provide the necessary force to complement the drive wheels. In other words, the track wall opposite the rotational drive wheel completes an extra 40° of circumference in order to keep the strut stationary during both directions of rotation. The track wall directly in front of the drive wheels is remove to all the drive wheel contact with the strut.

The drive wheels are shaped to provide a large amount of gripping surface between the drive wheel and the strut. For the wheels that provide rotational actuation, a simple standard

cylindrical wheel is used; for the translational actuation, the wheels "wrap" around the strut (see Figure 4b) to provide more gripping surface. While the wheels themselves are 3D-printed in ABS plastic, square o-rings fastened to the wheels provide the traction surface.

4.3. Hinge

Each half of the robot—that is, each pair of modules—has another servo attached to a gear. (Seen in the overview of Figure 1.) This gear serves as a planetary gear with respect to a sun gear of twice the diameter centered at the hinge location. Thus, as the servos complete their 180° of rotation, the angle between the halves of the robot changes from 35° to 180°.

5. EXPERIMENTAL

In order to demonstrate the feasibility of such a truss design with threaded fasteners, we performed fastening experiments to assess the maximum angular and linear error (between the central axis of the male and female portions) for a threaded fastener. We use a test jig as shown in Figure 5, which allows us to move the female portion of the fastener vertically (to account for linear error) and the fastening robot angularly on the horizontal plane to determine angular error. This is done manually (by placing the strut in the robot half and turning it by hand) and robotically (by controlling the robot half from computer software). The process is not autonomous.

During the fastening process, the angle of the male portion of the fastener is allowed to change, allowing the characteristics of the fastener to align the strut as possible.

8-32 standard bolts (on the end of a carbon fiber rod as per the strut design described earlier) and 1.25 in long drywall screws (see Figure 6) were tested with this arrangement to determine the maximum offset at which fastening could be completed. The fastener threads into either a standard mating nut (in the case of the standard bolt) or a custom-designed and 3D printed mating part (in the case of the drywall screw).

Fastener	**Maximum Successful Angle or Offset**
8-32 standard bolt	1°
	0.5 mm
6-8 drywall screw, 1.25 in long	6°
	5mm

Table 1: Fastening test results for hand fastening, using the apparatus shown in Figure 5.

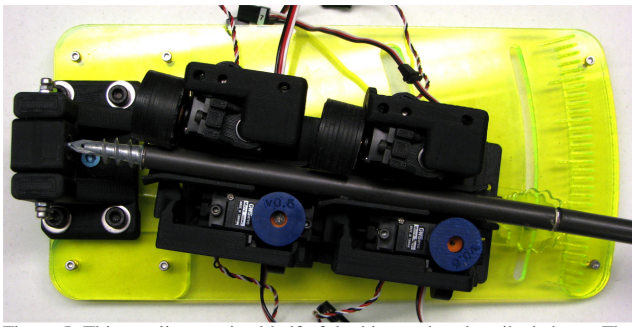


Figure 5: This test jig contained half of the hinge robot described above. The set up could change the angle in the horizontal plane and the linear offset vertically. This was used to test the capabilities of different threaded fasteners.



Figure 6: A sample of the 1.25 inch long drywall screw

As expected, the drywall screw fastener significantly outperforms the standard fastener in both dimensions of error. (See Table 1 for the details.) In addition, we were able to have success in fastening the drywall screw via robotic (though not autonomous) manipulation.

6. CONCLUSION

We have shown the design of a robotically reconfigurable truss structure, capable of constructing arbitrary simple cubic trusses with single face-centered diagonals. These truss element support random access, allowing struts to be inserted or removed at any point in the truss without affecting the rest of the structure. Additionally, the design of the threaded fasteners has been tested for compatibility with a limited-feedback robotic system, and demonstrates the capability of successful fastening with up to 6° of angular error. We believe that the truss traversing and manipulating robot discussed in this paper will be capable of manipulating such fasteners, and is a design capable of manipulating truss structures of arbitrary size.

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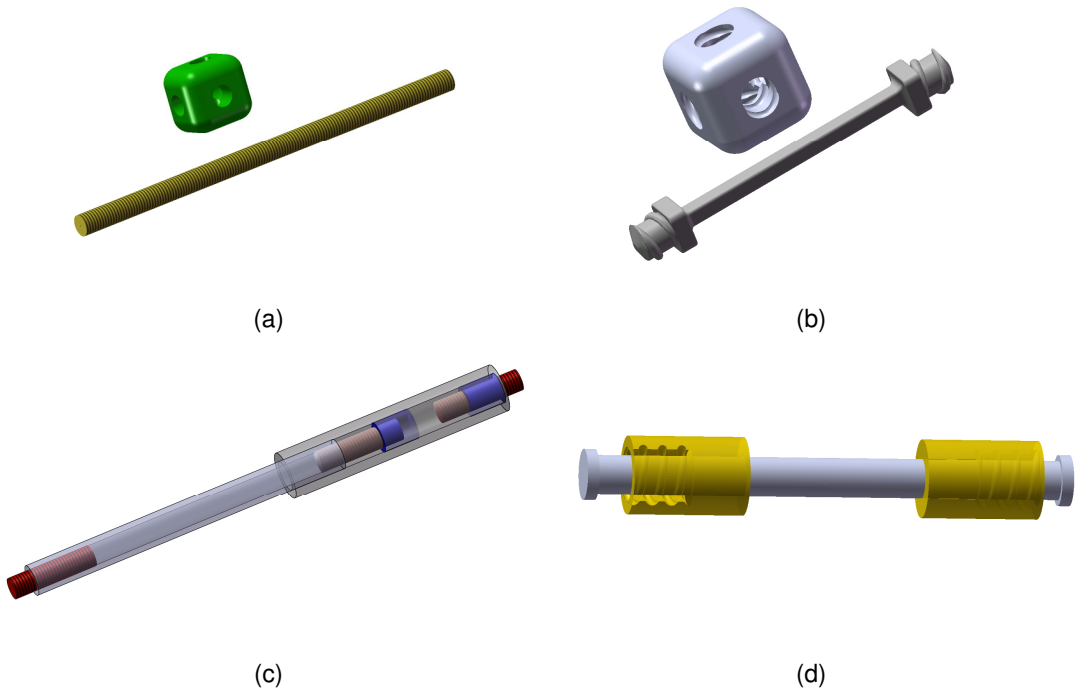


Figure S1. Previous iterations of designed parts. The first simple threaded rod truss element design is shown in (a). This design had several problems; primarily, a turn of the strut would loosen one node connection and tighten the opposing one. A novel double-threaded hub design is shown in (b). In this design, the strut has right-hand threads on one end and left-hand threads on the other end. The node is threaded in both directions in the same hole, allowing insertion by only twisting the strut in a single direction. However, the nodes still require translation for full assembly. A concentric tube strut is shown in (c), using threaded connectors nearly identical to the design presented in this paper. Finally, a design using threaded end caps that move along a strut is shown in (d).