Towards a Variable Topology Truss for Shoring

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Abstract - This paper introduces a new type of versatile modular reconfigurable robot. This robot is a self-reconfigurable truss structure. The requirements and challenges involved to build a functioning system are explored. These include the functional requirements, and the implications on hardware design, software issues and topological analysis. One potential application for this robot is the shoring of damaged structures during search and rescue operations.

Keywords - self-reconfigure, truss, search and rescue

1. Introduction

When typhoons, bombings, or earthquakes hit cities, they all result in major infrastructure damage. The most common result in these emergencies is a loss of structural strength in man-made infrastructure.

In many rescue situations, fatalities and injuries from rescuers outnumber those of the initial victims. This can come from secondary collapse due to after-quakes and structural instability. The safest (and standard) procedure to search damaged buildings is to shore the structure as rescuers proceed. The process commonly consists of cutting and nailing 2x4, 2x6 and 4x4 wood beam support structures [1]. This is a slow process and requires bringing wood or deployable struts to each site. Large disasters with many failed structures cannot be handled this way as the supplies and time are simply not available.

1.1 The VTT Vision

A robotic system that enters a damaged structure and quickly shores the structure could save lives by keeping the rescuers safe from harm while accelerating search. If the system is extractable and reusable, multiple structures could be searched.

Trusses are inherently materially efficient, lightweight, yet strong; they are the standard framework for bridges, cranes, and roof tops—anywhere large strength and low weight are required. A truss that could robotically change its shape and topology, a Variable Topology Truss (VTT), would be an ideal approach to solve the above scenario.

The advantage of having such a reconfigurable system extends to many other uses following the initial hours after a disaster. This robot could also redeploy and create structures such as a communications tower or shelter (Fig. 1), explore areas, manipulate objects or self-repair.

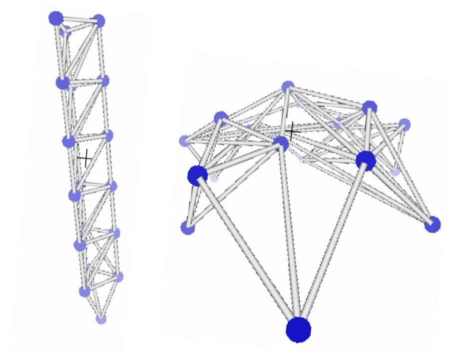


Fig. 1. A tower and dome configuration for one 51 member system using different topologies

1.2 Related Work

There are a variety of systems that have similar concepts: robotic trusses that change member lengths and self-reconfiguring robots, but there are no systems that are self-reconfiguring trusses.

Variable Geometry Trusses (VGT) [2] change member lengths resulting in a change in geometry. These systems used prismatic joints that had small extension-compression ratios of 1.7 or less. This limits portability and versatility. Higher ratio mechanisms such as tape spring deployment actuators (for space applications [3]) have large ratios (100 or more) but cannot support much weight. The ideal system would have both large extension and strength-to-weight ratios.

Tetrobot [4] is a robotic truss system like the VGT; the members are active prismatic joints. However, instead of parallel manipulator arms, Tetrobot explored a variety of configurations including legged walking systems. In addition, the truss elements can be reconfigured - manually rearranged. This was the first truss-based reconfigurable robot. However, the same issues from small extension ratios limit the applicability of this system, and the system is not self-reconfigurable.

Self-reconfigurable robots have been studied for over two decades. There are dozens of groups who have constructed many versions of reconfigurable robots. Over 800 papers, a book [5], and a survey [6] have been published.

In all of these cases, the novel capability is reconfiguration which involves the rearrangement of rigid bodies that have a discrete set of connecting locations (connection ports) which dock or undock. [7, 8]. Docking in this case is decomposed into three portions based on the position of the docking connectors: 1) controlled approach along an approach direction 2) connectors contact such that further motions occur with sliding contact, 3) connectors reach the docked position where they are latched (typically a mechanical interference lock).

No self-reconfigurable robot to date has been large enough while possessing the structural strength and robustness required for humanitarian scale missions.

2. Towards a Variable Topology Truss

Shoring is the process of reinforcing a structurally damaged building. For a system to succeed in shoring in the humanitarian disaster context, we can break down the sequence of robot actions, shown in Table 1.

Table 1: Shoring task breakdown

Shore subtask	**VTT need**	**Approach**
T1) The system is transported in a portable form	VTT is collapsable.	High exp. ratio joints
T2) The robot self-deploys	VTT can locomote over rough terrain	Topology similar to Tetrobot
T3) Identify shoring requirements	VTT can find damaged areas	Human remote guidance
T4a) The building is shored (conform).	VTT can conform to a shape.	Topology reconfiguration
T4b) The building is shored (support).	VTT can support large forces	Truss topology analysis
T5) Extraction and redeployment	VTT is reconfigurable	See T1 and T4a

2.1 Mechanical Hardware

Truss members which have rotational elements at the node decouple the forces and moments such that members are in pure tension/compression. This decoupling results in a reduced maximum stress in the links [9], allowing the members to support larger forces for a given amount of material.

Like the VGT and Tetrobot, geometric shape change occurs by changing the lengths of the members. If link lengths are controlled, all joint angles need to be free in order to avoid being over-constrained in statically determinate truss structures. Thus, the truss members have **active prismatic joints**, and the truss nodes have passive revolute joints. We would also like the nodes to be reconfigurable to enable topological change. Thus we need **passive chainable revolute joints,** that is the number of members connected at a node must be variable. We can divide a system into a repeatable unit that contains one active member and a passive chainable revolute joint at each end. This combination we call an **edge module** (Fig. 2)**.**

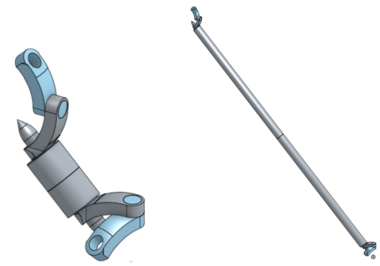


Fig. 2. An edge module repeated element with prismatic joint compressed and extended.

A. Active Prismatic Joint

The ideal prismatic joint is one that can have large extension-compression ratio as well as large load bearing capabilities. Collins et al. developed a new prismatic actuation technology called the Spiral Zipper shown in Fig. 3 [10]. It has both large strength-to-weight ratio and large extension-compression ratio.

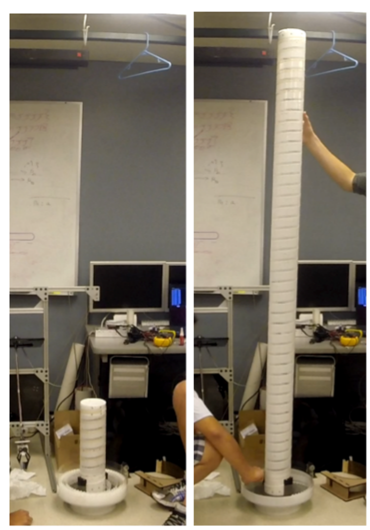


Fig. 3. Spiral Zipper, showing compression ratio of 14:1, though much larger extension ratios are possible. The plastic band can support 530N.

By "zippering" the top of a band to the bottom, a rigid, lightweight tube can be formed on the fly.

Buckling is the most likely failure mode for long slender beams in compression. The band forms a circular tube which is the optimal shape for stiffness-to-weight ratio under buckling loads. When under tension, the tube will have a reinforcing winched cable on the inside of the tube (not shown). This allows the arm to reach farther, and be lighter and stronger than other methods such as telescoping tubes, rack and pinion, or scissor structures.

Experimentally, strength to weight ratios of approximately 10:1 were shown for a prismatic actuator capable of extending 1m with a plastic band. Spiral Zipper tubes made of acetal plastic, 1.5m long, have been shown to support 530N. This is a fraction of that required for shoring operations, (typically 10,000N for a T-spot shore [1, pg 2-8]) but has enough strength-to-weight ratio to be promising if stronger materials are used. For example, the Young's modulus of spring steel is about 100 times that of the acetal, which would result in a critical buckling load 100 times larger (e.g. 53,000N) assuming the same geometry.

To maintain the advantageous decoupling of moments and forces, the system needs passive revolute joints for the nodes of the truss.

B. Passive Chainable Spherical Joints

The function of the nodes must constrain the end positions of the members without constraining the angles. Universal joints or spherical ball joints do this by having multiple revolute joints whose axis of rotation meet at one point. Changing the truss topology requires nodes that allow members to attach and detach at the node. Universal joints and spherical joints are not extendable or chainable; you cannot add more elements to that joint. No automatic device that is compact and low weight has been seen to do this (yet). One way to implement this type of node is a spherical link chain shown in Figs. 6-9.

Spherical links have elements with revolute joints at both ends of a link whose axis of rotation intersect at one point. Multiple links can form a chain. As a result, the motion of this chain revolves around that one intersection point. This is the behavior we want out of a passive chainable node of a truss.

Each link of the spherical link chain has some form of joining mechanism (e.g. a peg) we call a male connector, the second link has a mating mechanism (e.g. a hole) we call a female connector. Two edge modules can be joined by mating male and female connectors. A latch would be activated to hold it in place (or deactivated to unlatch). Each edge module adds two links into the chain, adding one open male and one open female and consuming one male and one female connector that are mated. Thus no matter how long the chain is, there is always one free male connector and one free female connector at the other end [11].

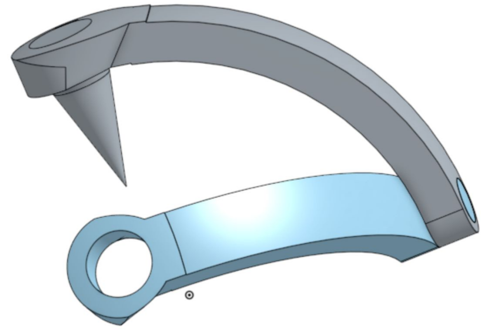
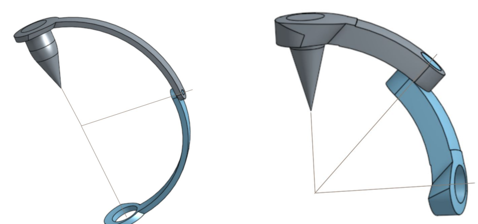


Fig. 4. A two-link spherical linkage with a rotational joint at the end of each link.



a) **b)**

Fig. 5a) Spherical linkage with two links, each spanning 90 degrees. The workspace of the end of the 2-link chain would be the surface of a sphere (4-pi steradian).

5b) A shorter two-link chain, each spanning 45 degrees, has reduced range, with the reachable positions sweeping out a hemisphere (2-pi steradian).

Since the node is in the form of a chain, more links can be attached at either end of the chain (increasing the degree of the node) up until collisions occur at the node.

However, there are several concerns with spherical links as nodes. These include:

1) possible link collisions as the angles change
2) compliance/imprecision in the joint and links
3) range of motion

The issue of compliance of links can be compensated by having thicker links. For example, the links in Fig. 5b are substantially thicker than those of Fig. 5a. This would increase the stiffness of the links and ease the manufacture of higher precision joint interfaces capable of withstanding larger torques and moments with less deflection.

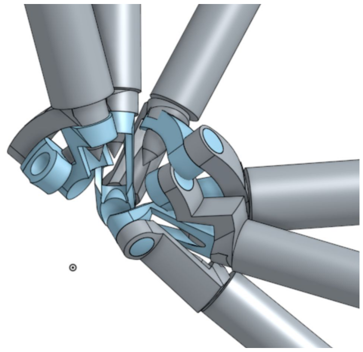


Fig. 6. Six edge modules intersecting at one node.

2.2 Motion Control

At this point we consider statically stable position control of the VTT. This has two portions: positioning of links and the reconfiguration of nodes.

A. Truss Kinematics

To simplify the implementation and lower costs, it is often most effective to reduce the number of required actuators. Each edge module shown in Fig. 2 has six rigid bodies that move relative to each other, two in the active prismatic joint and two spherical links on each end. Each joint attaching two bodies could be active (with an actuator), but reducing this system to one active prismatic joint and all others passive joints minimizes complexity and cost. This is also natural to assume as we want the nodes to be passive. However, when an edge module is alone, the spherical links on each end are uncontrolled. The system gains controllability when enough edge modules are joined together.

Fig. 7. Six edge modules forming a tetrahedron.

In 3D Cartesian space, we obtain full controllability when there are six edge modules forming a tetrahedron as in Fig. 7. The system is statically determinate and we can control the position of each node arbitrarily by changing just the lengths of the prismatic joints.

The truss as a robot is essentially a parallel robot. We can guarantee that the truss is statically determinate if we constrain the system to be constructed with tetrahedrons [12]. That is, we start with a tetrahedron then add three joined edge modules at a time to form an added tetrahedron to the structure, which will also be statically determinate, guaranteeing controllability.

B. Docking

The docking process consists of the same three steps used in previous reconfiguring robot systems listed in Section 1.2, 1) Mating ends approach, 2) Mating ends meet to proceed with sliding contact. 3) Mates latch when in position.

The spherical link nodes shown in Fig. 4 and 5 have one end with a cone and one end with a hole. Docking in this design occurs by having the cone enter the hole until the ring forming the hole becomes flush with the top of the cone where it is latched.

A spherical linkage chain with peg-in hole connectors result in (de)attachable spherical joints at each end allowing nodes with arbitrary degree [11]. To allow for imprecision in control, the geometry of the ends can be changed, for example, making the cone and holes larger (Fig. 8).

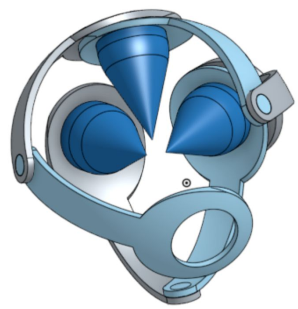


Fig. 8. Links with larger holes and pegs to relax precision requirements on the docking process.

Since trusses must always maintain controllability, reconfiguration occurs by merging two nodes, or having two spherical link chains join to form a longer spherical link chain. After the merge, the node can then split at a different point in the chain - now altering the topology of the truss. Note that temporarily, the system will be overconstrained (statically indeterminate) while the nodes are merged.

2.3 Reconfiguration Analysis

To reconfigure (merge or split) a node, the following constraints must be obeyed:

1. The truss must remain rigid.
2. If two nodes are neighbors, they cannot merge, as this would eliminate the member connecting them, and the number of members must be preserved.
3. If two nodes are second degree neighbors (neighbors of neighbors), again they cannot merge, since the members that connect them to their shared neighbor would overlap.

It is therefore necessary for two nodes to be third degree neighbors or higher for them to merge.

There are additional restrictions on the reconfigurability of the VTT. Collision between the members, actuator length limits, and joint angle limits all limit geometric reconfiguration. Self-collisions can be considered as obstacles in the configuration space, which may result in some regions of the configuration space being disconnected from other regions, even during purely geometric reconfiguration. Finding a collision free path in configuration space if one exists remains one problem to solve.

A. Connectivity versus Topology

The connectivity of a truss is a specification of which labeled members are connected to which other labeled members, while topology disregards the labels. The connectivity of a truss can be represented by a labeled graph, so topologies would correspond to isomorphism classes of these graphs. If the graphs corresponding to two connectivities are isomorphic, then we say they have the same topology (see Fig. 9).

Depending on the context of the problem, it may be more useful to say that these example trusses are mutually reachable configurations in a space of three distinct connectivities, or it may be more useful to describe the unique properties of the two distinct topologies.

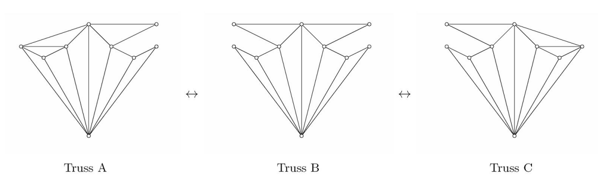


Fig. 9. Truss A, B, and C are three 2D rigid trusses with different connectivities. Applying our reconfiguration constraints in 2D, we see that Truss A can reconfigure into Truss B, and Truss B can reconfigure into Truss C. While all three trusses have different connectivities, it is clear from symmetry that Truss A has the same topology as Truss C.

Reasoning about the topologies is useful for performing higher level tasks, whereas reasoning about connectivities is required at a lower level. For example, a damaged building might require a topology that is required to successfully shore it, and it will be the job of the path planner to find a path through configuration space to a truss connectivity to attain the required topology.

B. Algorithmic Issues

The reconfiguration planning problem can be divided into two parts, the geometric reconfiguration (similar to that shown [4, 13]), and the topological reconfiguration (similar to self-reconfigurable robots [14].)

During the reconfiguration process a variety of constraints must be maintained. The number of beams is conserved, but the number of nodes change as nodes merge and split as the topology changes.

Self-collision detection is an issue that needs to be solved. The reconfiguration mechanism at each node needs to be designed and tested. Collisions is one area of interest for possible interaction between the geometric and topological portions of reconfiguration. There may be geometric configurations with the same connectivity that are not reachable due to collision constraints while maintaining that connectivity. But, it may be possible to reach by temporarily changing connectivity. For example, during DNA replication, DNA can become entangled. Topoisomerase works on the topology of the DNA, cutting and resealing strands as tanglements form [15].

There are a variety of algorithmic issues to explore related to the topological reconfiguration planning problem. The most computationally expensive step of topological reconfiguration planning is determining whether two graphs are isomorphic, as each new connectivity must be tested against all existing non-isomorphic connectivities. The complexity of the graph isomorphism problem is currently thought to be solvable in quasi-polynomial time for the general case, although in practice it can be solved much faster on graphs with certain properties. Practical trusses may have certain properties that may speed up this step significantly.

2.4 Functional Configuration Design and Analysis

Once we have a reconfigurable truss robot system, how do we apply it? This section focuses on the tasks related to the structural strength of the trusses as target configurations.

A. Damaged Building Assessment

When a building needs to be shored, some truss configuration and placement must be selected to properly shore the building. For this to be done automatically requires a system to understand the construction of a building and the potential damage that may have occurred by some form of remote sensing. To be able to do this in a search and rescue setting where time is critical is very difficult and we consider it to be out of scope for this proposal. For the near future, we will assume that a human expert would be able to assess the damage by viewing remote cameras or other sensors conveyed by the VTT system and thus indicate to the system where and how to shore the damaged structures.

B. Structural Analysis

For most applications and especially the shoring application, the structural strength of truss structures will need to be understood. In particular, for the shoring application, truss designs will need to be synthesized that will support expected loads due to further structural collapse. Understanding what forces can be supported for a given structure and how to synthesize efficient structures for a given set of edge modules is an unsolved problem. For this purpose, methods developed from the dynamic manipulability analysis of closed chains can be leveraged to determine the most structurally rigid configurations. Viewing a VTT as a closed chain, one can derive the configuration-dependent mass matrix of the VTT in the usual way as done when deriving the dynamic equations for rigid multibody systems [16]. Once the mass matrix is available, then for each configuration, it is possible to determine the directions, in both the joint and task spaces, in which the mechanism is stiffest, by determining the principal axes of the mass matrix and its task space counterpart. Fast and numerically robust algorithms have been developed for the computation of both the joint and task space mass matrix and their principal axes.

Conclusions

This paper introduced a new type of robot system suitable for shoring damaged buildings during a search and rescue operation. The hardware concepts necessary to meet the functional requirements were introduced, and many of the challenges associated with the planning, control, and implementation of a VTT system were identified. Future work will address these challenges in further detail.

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