Shape Morphing for Variable Topology Truss

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***Abstract*— Variable topology truss (VTT) is a new class of self-reconfigurable robot. A variable topology truss can change both its shape and its topology so that it can be reconfigured into various structures with respect to different environments and tasks. It is a significant challenge to control modular robot systems due to the complexity of its configuration and high dimensionality of its state making it difficult to avoid self-collision. We present a new research direction to do shape morphing for variable topology trusses. It is modeled as a multi-agent system with each agent being a controlled node in the truss. A new approach to compute the collision-free configuration space for each controlled node is provided and some future work is discussed.**

I. INTRODUCTION

The variable topology truss is a new type of self-reconfigurable modular robots. Comparing to movable truss structures like the variable geometry truss (VGT) [1], variable topology trusses can not only change its shape by changing the length of the truss members, but also have the additional capability to change its topology by merging or splitting nodes [2]. Hence, the variable topology truss system has both the force and kinematics benefits of VGTs and the versatility of self-reconfigurable robots [3]. For example, the robot can reconfigure itself from a dynamic rolling gait configuration into a robust support structure for shoring.

VTT systems are composed of edge modules which include both the linear actuator and two ends that can dock with other ends [2]. One of the constraints that guarantees the controllability of a VTT system is that the topology of the modules should nominally form a statically determinate truss. As a result every node has at least three members attached. In addition, a VTT system requires at least 18 members in order to reconfigure [2], thus motion planning for these systems can have very high dimensionality and the obstacle space can be very complicated to deal with.

II. RELATED WORK

The variable topology truss was first introduced in [4], which describes the hardware and challenges associated with the planning, control and implementation. A modified retraction-based RRT algorithm was introduced for VTT motion planning in [3]. Our work differs from this work in that we model the truss as a multi-agent system and explicitly compute the collision-free space for each agent. Then we can coordinate these agents for different motion tasks rather than sampling in a very high-dimensional space. A shape morphing algorithm for linear actuator robots (LARs) is presented in [5]. While the robots are actually a mesh graph topology, the obstacle space caused by self-collision is straightforward and, for most shape morphing tasks, there is no need to consider self-collision. For variable topology truss systems, the configuration can be in complicated shapes and self-collision can happen frequently.

There has been extensive work on control and planning for multi-agent systems in which each agent is usually a vehicle. Many techniques have been developed to control groups of robots, such as inter-robot collision avoidance [6], dimensionality decrease [7], navigation functions for multiple vehicles [8] and with specified proximity constraints maintenance [9]. Although the constraints and obstacles in a variable topology truss are usually more complicated, it is promising to solve this shape morphing problem as a multi-agent system.

III. SHAPE MORPHING PROBLEM

The structure of a variable topology truss can be modeled as an undirected graph $G = (V, E)$ where V is the set of vertices of G and E is the set of edges of G: each member can be regarded as an undirected labeled edge $e \in E$ of the graph and every intersection among members can be treated as a vertex $v \in V$ of the graph. Every $v \in V$ has two properties: `ID` and `Pos` where `ID` is used to label the vertex and `Pos` is used to define the Cartesian coordinates of the vertex namely $v[\texttt{Pos}] = [v_x, v_y, v_z]^\intercal \in \mathbb{R}^3$. In this way, the state of a member is fully defined by `Pos` properties of its two vertices written as $e = (v_1, v_2)$ where v_1 and v_2 are two vertices of edge e. The shape morphing problem can be stated: change every $v\,[\texttt{Pos}]$ where $v \in \widehat{V} \subseteq V$ from its initial position $v\,[\texttt{Pos}]_i$ to its goal position $v\,[\texttt{Pos}]_g$ without changing the topology of a VTT. During the motion process, some constraints have to be maintained, such as the rigidity of the whole truss and collision avoidance. In this multi-agent system, each node $v \in \widehat{V}$ is an agent and the challenge is to coordinate all $v \in \widehat{V}$ navigating in this variable topology truss.

A. Collision-free Space

The collision-free space for each agent (controlled node) v is denoted as $C_{free}(v)$. For simplification, the nodes are considered to be points and members are treated as lines. The basic case is considered first. In the basic case, there are only two edges disconnected with each other, as shown in Fig. 1a. Node v_4 is the controlled node.

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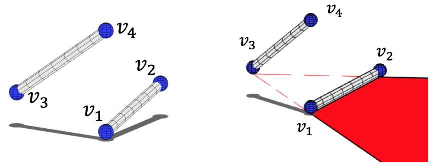


(a) (b)

Fig. 1. (a) The Basic Model and (b) Collision-free Space for the Basic Model

As shown in Fig. 1b, in this case, v_4 can move to almost anywhere as long as its path does not intersect with a semi-plane shaped obstacle, the red region in Fig. 1b. This obstacle is called the *obstacle plane* and formed by the the member (v_1, v_2), as well as two rays. One of the rays starts at the position of v_1 and goes in the direction of $v_1\,[\texttt{Pos}] - v_3\,[\texttt{Pos}]$. The other ray starts at the position of v_2 and goes in the direction of $v_2\,[\texttt{Pos}] - v_3\,[\texttt{Pos}]$. In short, this obstacle plane is defined by the fixed member (v_1, v_2) and the neighbor node v_3 of controlled node v_4.

For a controlled node v in a VTT, let $N(v)$ denote the neighbors of node v and E^v represent the members connected with v. For v, the collision could occur if and only if any $e \in E^v$ collide with any $e' \in E \setminus E^v$, which is exactly the same as the base model described above, namely node v can move freely as long as its path does not intersect with any obstacle plane formed by any combination from the set $N \times (E \setminus E^v)$.

Therefore, for any truss structure, there are only two possibilities for the collision-free space. First, if all the obstacle planes do not divide the whole Cartesian space into separate subspaces, then the collision-free space of a node is almost all the Cartesian space except some obstacle planes. This can be illustrated by a tetrahedron.

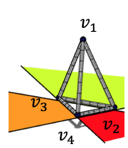
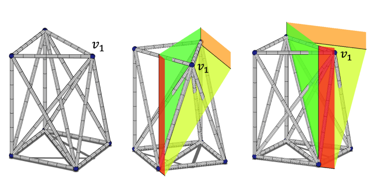


Fig. 2. All the colored planes form the obstacle space for v_1.



(a) (b) (c)

Fig. 3. (a) A VTT Configuration and (b) (c) Different Views of Collision-free Space for Example Configuration with Colored Planes as Boundaries

The collision-free space of v_1 in a tetrahedron is shown in Fig. 2. It can be seen that, if singularity is not considered, v_1 can reach anywhere in space except the three colored obstacle planes, which are formed by neighbor node v_2 and member (v_3, v_4), neighbor node v_3 and member (v_2, v_4) and neighbor node v_4 and member (v_2, v_3).

And the other possibility is that some of the obstacle planes divide the whole space into two or more separate sub-spaces. The collision-free space is the smallest sub-space that contains the current position of the controlled node. An example is shown in Fig. 3a, the collision-free space is shown in Fig. 3b and Fig. 3c. In Fig. 3c the red and orange planes can extend to infinity both rightwards and upwards. The green one goes to infinity upwards and yellow one reaches infinity rightwards. In this case, there are 70 obstacle planes in total, but the four obstacle planes shown form the smallest sub-space enclosing the controlled node, indicating that v_1 could only move inside this $C_{free}(v_1)$ and other obstacle planes have no effect on $C_{free}(v_1)$ in this configuration.

B. Multi-Agent Planning

$C_{free}(v)$ for each agent (controlled node) v can be computed and it can be affected when moving other nodes. There are two basic problems we need to consider: a) control the truss to enable $v\,[\texttt{Pos}]_g$ to be inside $C_{free}(v)$ and b) avoid collision during the motion. For a), if $v\,[\texttt{Pos}]_g \in C_{free}(v)$, then this agent can be moved directly, otherwise other nodes need to be moved to enlarge $C_{free}(v)$ to include $v\,[\texttt{Pos}]_g$. For b), the collision can happen between two agents or between an agent and the truss.

IV. Conclusions

We present a new research direction for shape morphing of variable topology truss. Multi-agent system model is used to control multiple controlled nodes to navigate in a variable topology truss. A new approach to compute the collision-free space for a node is presented and this multi-agent planning problem is briefly discussed.

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