Reconfiguration Solution of a Variable Topology Truss: Design and Experiment

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***Abstract*—In this letter, an active ball joint actuator, called the master node, is developed for the purpose of reconfiguring truss structures. We propose a variable topology truss system, which is an advanced variable geometry truss system that can reconfigure its own topology to expand its functions. However, reconfiguration of a variable topology truss is difficult, because the controllability of trusses needs to be maintained during the process. We solve this problem by adding the master node to the system, which can move trusses without losing their controllability. The master node is designed and fabricated for a variable topology truss. The reconfiguration test using the master node is performed on a reduced prototype of the system. The results prove that using the master node for reconfiguration is viable.**

***Index Terms*—Cellular and modular robots, mechanism design.**

I. Introduction

A SYSTEM composed of linearly actuated trusses is called a variable geometry truss (VGT) system. Because of their flexibility, VGT systems can be used for various tasks. Miura first presented the concept of a VGT system and suggested using it for space cranes [1]. This was realized by Hughes *et al.* [2]. VGT systems can also be used for locomotive systems, especially on irregular surfaces. TETROBOT was developed to perform manipulation and locomotion tasks by Hamlin and Sanderson [3]. Curtis *et al.* designed and tested VGT systems with tetrahedral topology for space exploration [4]. However, the capability of a VGT system to execute different tasks is restricted by its constant topology, because a system needs the optimal topology for each task.

The versatility and adaptability of robotic systems can be significantly improved by reconfiguring them. Small modular robots can be attached or detached, depending on which specific topology the system needs to be configured to. The concept of reconfigurable systems with modular cell robots was first introduced by Fukuda and Nakagawa [5]. Yim improved the concept of modular reconfiguration robots and developed the Polybot system [6]. Polybot can reconfigure itself to perform locomotion with three different gaits to adapt to different environments. This system was improved to SMORES to increase its versatility in locomotion [7]. Reconfiguration can be carried out even on floating structures. Paulos *et al.* developed a self-reconfiguration modular boat robot system for constructing floating structures [8]. Saldana *et al.* developed a flying modular robot system to build elevated structures [9]. Thus, modular robot systems can perform a task regardless of environments with reconfiguration. However, previous reconfigurable modular robots only focused on one task for each robot.

We developed a variable topology truss (VTT) system by combining the concept of a VGT system with the idea of reconfiguration for search and rescue operations on disaster sites [10]. The previous rescue robots mainly focused on searching task rather than active rescue tasks [11], [12]. Lee *et al.* focused on transferring victim task but the robot did not show the locomotion on irregular environments [13]. If one system can perform various tasks including locomotion on irregular condition and active rescuing, the efficiency of rescue operation will be highly improved. Currently, we are considering two different topologies, one for locomotion and another for shoring up collapsed structures [14]. Locomotion is the most important task for searching, and shoring up is imperative for rescuing victims. These two tasks have very different requirements, and therefore they need their respective optimal topologies. We applied the concept of reconfiguration to the VTT to address this requirement. However, self-reconfiguration of the VTT is a difficult task, because it involves detaching a truss from one joint and reattaching it to another.

In this letter, an active spherical joint actuator is designed and fabricated for reconfiguration of the VTT system. The previous reconfiguration method required three attached trusses to maintain controllability in the detached state [10]. Such a method can suffer from issues with control due to the complex movement of trusses and the limited accuracy of the motion. It also constrains topology transformation because of the

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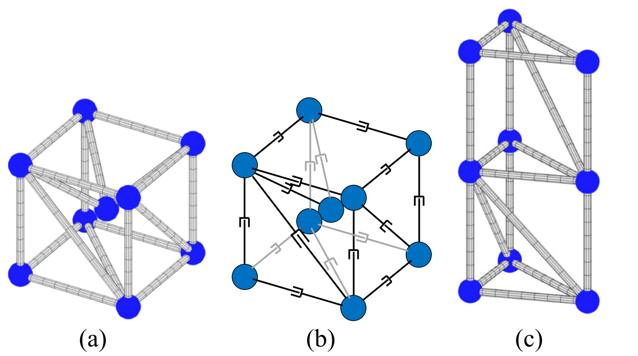


Fig. 1. Conceptual diagram of the VTT system. Each truss can adjust its length and freely move around the vertex. These are the two main topologies that are provided by the VTT: (a) the topology for locomotion; (b) locomotion topology drawn with prismatic joints; (c) the topology for the task of shoring up.

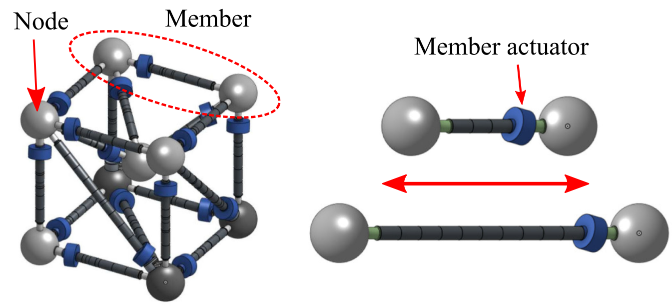


Fig. 2. Composition of the VTT. Nodes are denoted by gray spheres and members are denoted by black cylinders. Members can adjust the length of itself with a member actuator.

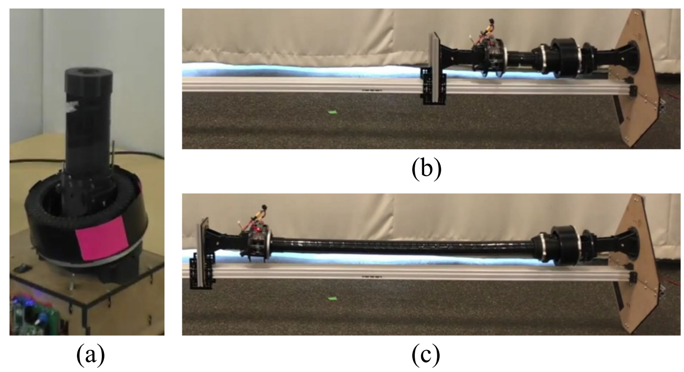


Fig. 3. The fabricated member of the VTT with a spiral zipper: (a) the spiral zipper actuator; (b) the minimum length of the member; (c) the maximum length of the member.

movement strategy it employs. Instead of attaching three trusses, we design an actuating node, called the master node, that can grip and move a target truss to the desired position. This actuating node not only simplifies the reconfiguration process, but also aids in transforming the topology into other ones. The functions of the master node thus fabricated are tested via appropriate experiments.

II. Variable Topology Truss

The VTT system is actuated by adjusting length of trusses. It can also perform various tasks by reconfiguring its topology appropriately. In a disaster site, the VTT system needs to satisfy two primary functions. First, locomotion is the most important task for conducting search and rescue operations. The VTT should be able to satisfactorily move to any destination point to find survivors. Second, the VTT should be able to shore up collapsed debris to rescue survivors. With the help of reconfiguration, the VTT can perform both tasks with their respective optimal topologies. Fig. 1 depicts a conceptual diagram of the VTT and the two main topologies it uses to perform search and rescue operations.

Each topology was derived by analyzing *topology neighbor supergraph* which was introduced by Spinos *et al.* [10]. The VTT has 9 vertexes and 18 edges, which is sufficient for various reconfiguration. It uses the topology presented in Fig. 1(a) for locomotion and that presented in Fig. 1(b) for shoring up. The locomotion topology was designed to be a regular polyhedral shape to perform regular rolling locomotion. The shoring topology was selected between column-like topologies that can be easily transformed from the locomotion topology.

The VTT comprises passive spherical joints and active linear actuators. Linear actuators called “members” are used as trusses of the VTT, and passive ball joints called “nodes” are connected to the linear actuators. The VTT is actuated by manipulating the lengths of the members. The overall composition of the VTT is presented in Fig. 2.

Members of the VTT are linearly manipulated with an actuator. To satisfactorily execute tasks, a linear actuator corresponding to a member should have a large enough extension ratio to provide the flexibility required for adequate manipulability of the total system. We used a spiral zipper as a linear actuator of the member, which has a large enough extension ratio [15]. A spiral zipper generates linear motion by zipping and stacking a thin band using an electric motor. It has a maximum extension ratio of 14:1, which cannot be achieved by conventional linear actuators. In addition, a spiral zipper only weighs 1.7 kg without losing out much on strength. Fig. 3 depicts the spiral zipper actuator and the member of the VTT that uses a spiral zipper as an actuator.

A passive spherical joint needs to be used as a node. A node should correspond to at least three members at once and provide free spherical motion for them. We embodied a node by adding the member-end part to the member, and connecting separate member-ends with the 12-bar-linkage mechanism to enable spherical motion. A spherical structure is used to support the member-ends so that they can move around the sphere while maintaining contact with it. One member-end is affixed to the sphere, and the other member-ends are connected to this member-end and to each other. The docking mechanism is added to attach and detach the other member-ends. Fig. 4 depicts the member-end structure, the movement of the linkage mechanism, and the docking mechanism. This member assembly was fabricated and tested as depicted in Fig. 3. The movement of the member-end was tested on a simplified prototype of the VTT. The simplified prototype was designed to have 6 members

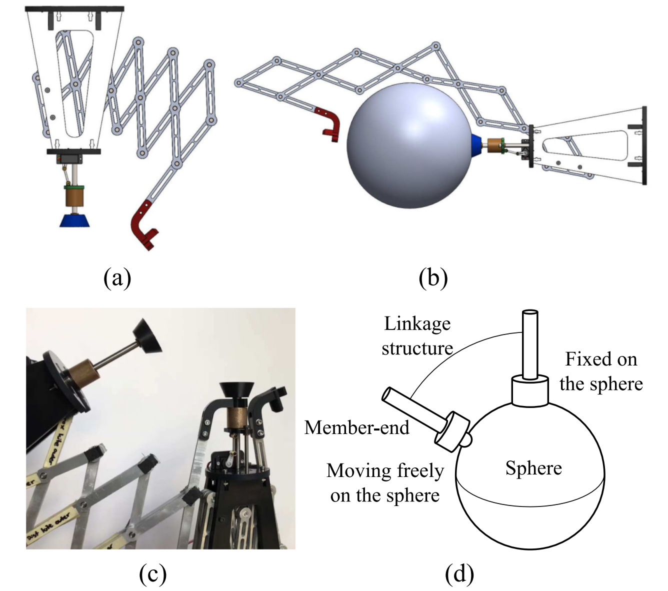


Fig. 4. A design of a member-end of the VTT. (a) The linkage mechanism of the member-end; (b) the maximum reach of the linkage structure; (c) docking mechanism between two member-ends; (d) the member-end connection with the sphere and the other member-end.

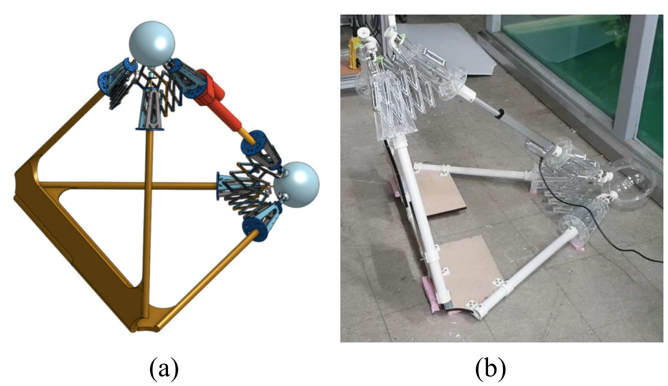


Fig. 5. A simplified prototype of the VTT for testing movement of passive nodes. The shape was simplified to a tetrahedron and the member actuator was changed to conventional linear actuator. (a) 3D design drawing of the simplified prototype; (b) the fabricated prototype VTT.

and 4 nodes, and a tetrahedral shape, as depicted in Fig. 5(a). To simplify the prototype, the member was replaced with a conventional linear actuator. The prototype was fabricated as depicted in Fig. 5(b), and it was verified that the member-end can provide spherical motion to the members.

III. Topology Reconfiguration Method

A topology reconfiguration is the special feature of the VTT. To reconfigure its topology, some members need to be detached from certain nodes and moved to be reattached to other nodes. The main problem faced by reconfiguration processes is maintaining controllability of the moving trusses while they are detached from the nodes, because there is no angular actuator in the system. Therefore, a reconfiguration strategy is required to prevent free-floating of members during reconfiguration.

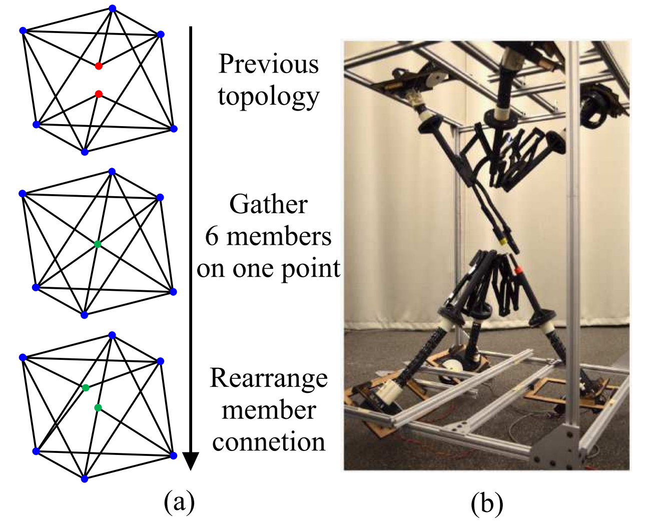


Fig. 6. The previous reconfiguration method: the VTT reconfigures itself with three members attached. (a) A process of reconfiguration. (b) Reconfiguration test bed.

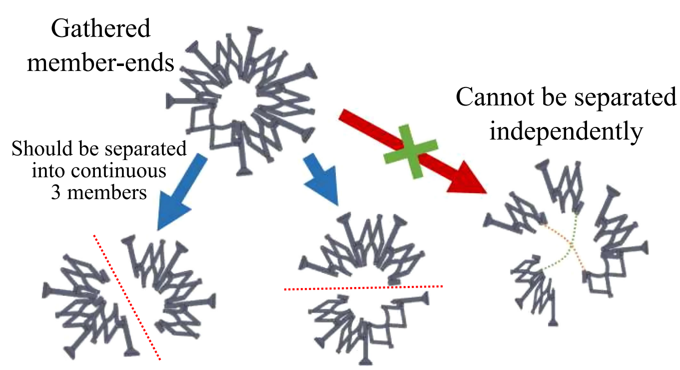


Fig. 7. Restrictions on the regrouping mechanism during reconfiguration.

Previously, we had solved this problem by grouping three member-ends at one node, and moving the entire member-end group at once [10]. The previous method is explained in Fig. 6. Kinematically, an example of such reconfiguration is depicted in Fig. 6(a). This method was tested on the test bench for reconfiguration, presented in Fig. 6(b).

However, the previous method suffered from a major problem. The degree of freedom in the reconfiguration process was seriously restricted owing to the constraints inherent in the method. Only three manipulations were possible during reconfiguration, splitting, merging, and regrouping. The six connected member-ends could be divided into two groups or merged into one group and could be regrouped while they are attached. The regrouping mechanism also had a serious shortcoming, because member-ends could only be regrouped with adjacent ones, and not with the others, because of a limitation of the docking mechanism. Fig. 7 presents a brief overview of this problem.

This problem can be solved by adding active spherical actuators to the node sphere. By moving the target member with a spherical actuator, the member can be fully controlled without connecting member-ends to each other. The spherical actuator,

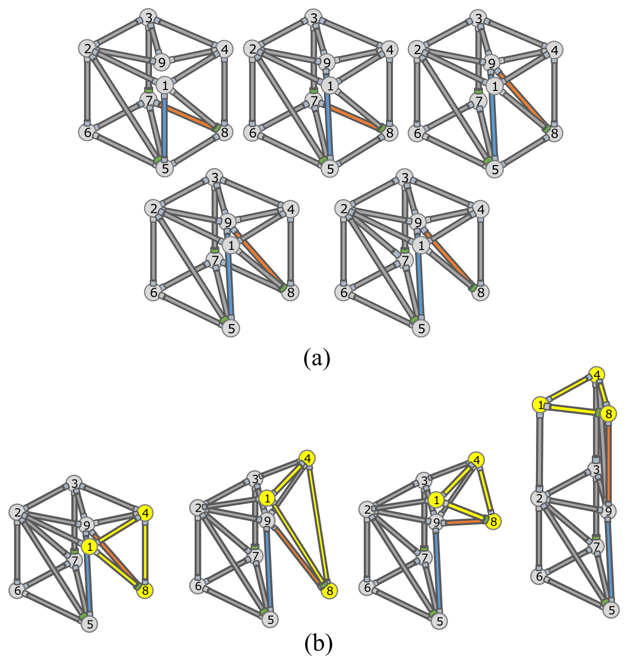


Fig. 8. Reconfiguration strategy using the master node method. Only three master nodes are needed to achieve the reconfiguration. (a) Reconfiguration from the locomotion topology to the shoring-up topology; (b) changing the geometry to the shoring-up form.

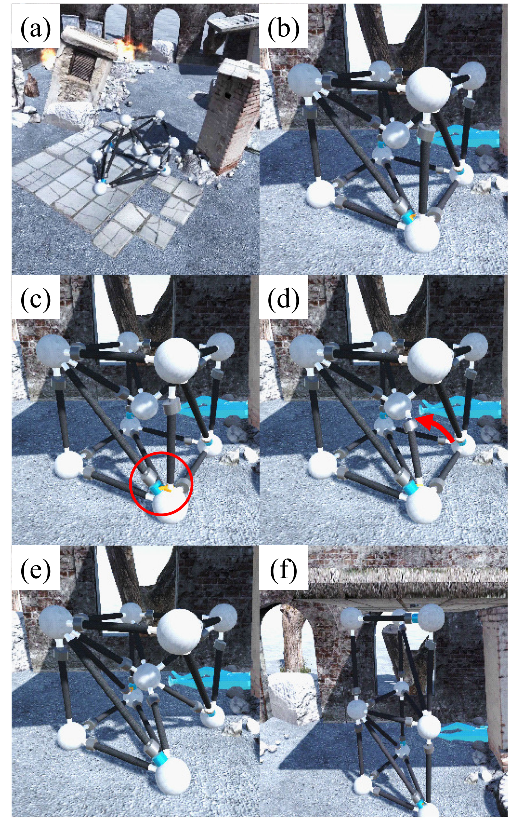


Fig. 9. Conceptual images of the VTT performing search and rescue mission on a disaster site. (a) Locomotion; (b) arriving at the destination; (c) the master node grasping the target truss; (d) moving of the target truss; (e) finishing reconfiguration; (f) shoring up.

called the master node, should be able to grab and release the target member and provide spherical motion. With the master node, the reconfiguration strategy can be considerably simplified without any significant restrictions. We developed a reconfiguration strategy for the two proposed topologies presented in the previous section using master nodes. Fig. 8 depicts the reconfiguration process and the changing geometry between the two topologies. Only three master nodes are required to execute the proposed reconfiguration strategy. The reconfiguration process is presented in the supplementary video clip, and Fig. 9 depicts it as recorded in the video.

IV. Design and Fabrication of the Master Node

The master node is required to provide spherical motion to the member-end. In addition, it should be able to grasp and release the member-end. We have developed a master node that can meet these requirements for the reconfiguration process. In this node, a chain actuator mechanism is used for providing polar angle motion. Azimuthal angle motion is provided by a turret mechanism. Finally, we have designed a gripper that can be locked and unlocked with a simple servo motor. These are the three actuators that the master node is equipped with. Fig. 10 depicts the overall design of the proposed master node.

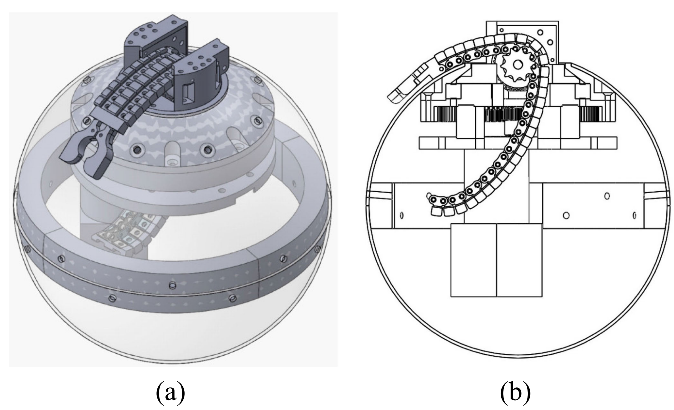
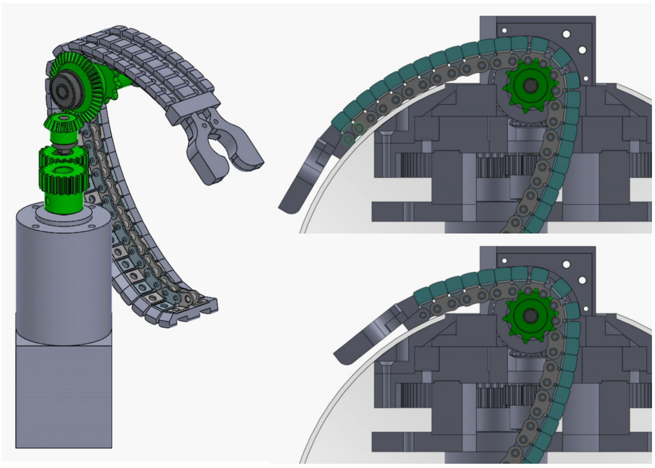


Fig. 10. The overall design of the master node: (a) isometric view of the master node; (b) cross-sectional drawing of the master node.

We used an open chain actuator mechanism to provide polar angle motion to the member-end. Fig. 11 shows the 3D model of our open chain actuator without the casing. The previous closed chain mechanism could only control the pulling motion via chain tension. An open chain mechanism can control both pulling and pushing motions using the same actuator, if the trajectory is properly constrained. Unlike the other linear actuators, the axis of the open chain actuator does not need to be matched with the expanding direction. Therefore, the space that the actuator occupies can be adjusted and it can be placed in the sphere. The open chain version is actuated with an electric motor with a sprocket, which is located on top of the master node as shown in Fig. 10(b). The trajectory of the end-effector is constrained to only have spherical motion. The movement of the chain away from the sphere is constrained by design of the chain



(a) (b)

Fig. 11. Design of the open chain actuator for polar angle motion: (a) isometric view of the actuating parts and the chain structure; (b) polar angle movement of the open chain.

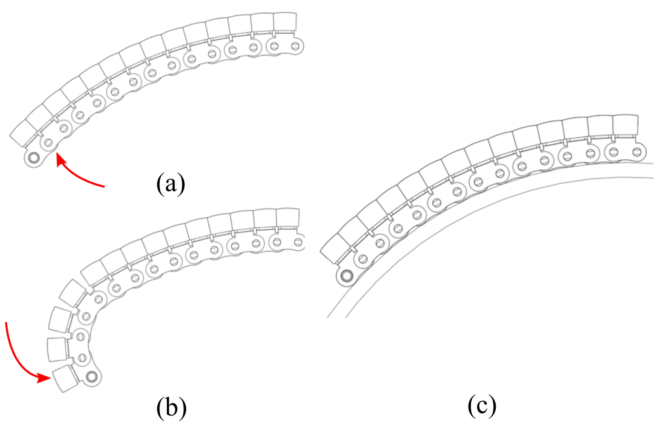
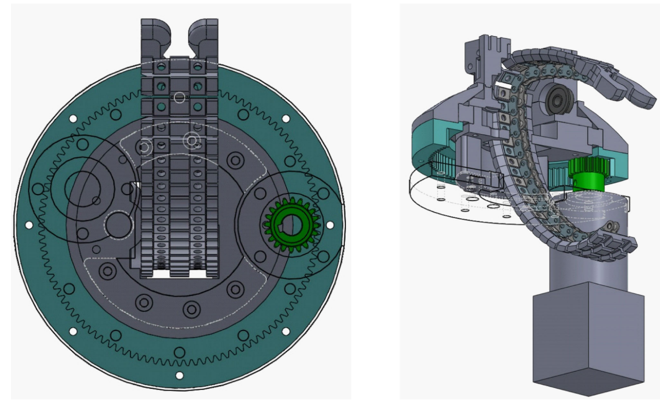


Fig. 12. The chain of the actuator is designed to constraint the trajectory: (a) the outer side motion is prevented by structure itself; (b) Inner side motion is not constrained; (c) The inner side motion is prevented by the sphere structure of the master node.

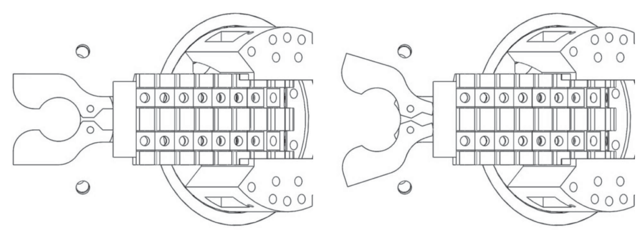
itself, which prevents bending towards the outside as shown in Fig 12(a). Its motion towards the sphere is blocked by the sphere structure as presented on Fig. 12(c). Because of the trajectory constraints arising from design of the actuator, the chain actuator can provide a polar angle motion to the end-effector. Fig. 11(b) shows the spherical motion of the end-effector.

The azimuthal angle motion of the end-effector is provided by a turret mechanism. The master node should be capable of providing polar angle motion and azimuthal angle motion simultaneously and independently. Therefore, the chain actuator for the polar angle motion should be rotated in its entirety with respect to the sphere. A turret mechanism with an inner gear is a common way in which rotational motion can be provided independently of polar angle motion. The chain actuator is assembled on the inner gear, and the inner gear is rotated by an electric motor. Fig. 13 shows the turret mechanism for providing azimuthal angle motion to the end-effector.



(a) (b)

Fig. 13. Design of the turret mechanism for azimuthal angle motion: (a) top view; (b) isometric view of the turret mechanism including the open chain actuator.



(a) (b)

Fig. 14. Design of the gripper for grasping the member end; (a) closed; (b) opened and unlocked.

The gripper for grasping the member-end was designed to have minimal amount of functions. The gripper is planning to lock and unlock itself with one actuator. The member-end is placed on the gripper by another master node when the gripper is unlocked. After the member-end is placed on the gripper, the actuator of the gripper can lock itself. The member-end can then be freely released by unlocking the gripper. Fig. 14 depicts the design of the gripper. In the first prototype of the master node, the gripper was not equipped with an actuator. The locking and unlocking function was tested by turning the handle.

A prototype of the master node was fabricated to test its required functions. Most structural parts of the master node were fabricated using a 3 d printer. A polypropylene sphere was used as the sphere in the master node. The chain of the open chain actuator was made by assembling 3d-printed cover parts on a standard commercial chain. (Tsubaki Inc., RS25K-1-U.S.) Two electric motors were used for actuators, one for the open chain actuator and another for the turret mechanism. (Minebea, stepping motor PG42-17PM-F438CP06CA) The actuator of the gripper was neglected and will be added in the next version of prototype. The locking mechanism on the gripper was replaced with a handle in this version. Fig. 15(a) depicts the first prototype of the master node.

The required functions of the master node were tested using this prototype. At first, the master node was tested with the tip

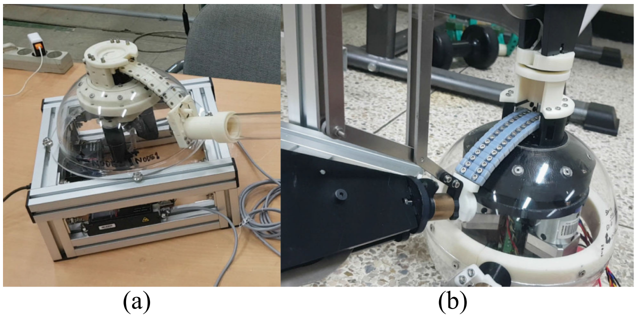


Fig. 15. Fabricated the master node prototype; (a) the master node prototype; (b) the assembled test bench for testing the reconfiguration process.

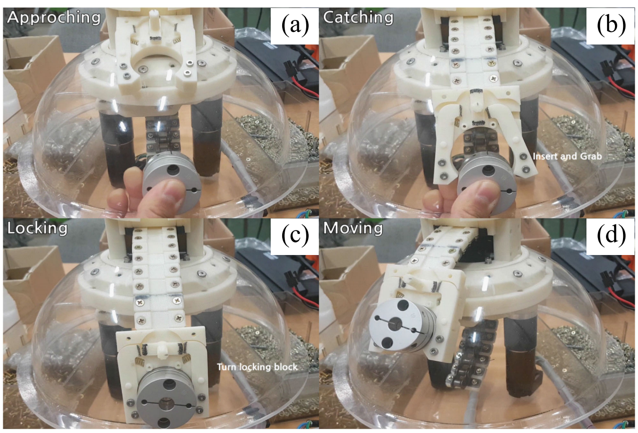


Fig. 16. Testing the required functions of the master node: (a) polar angle motion of the end-effector with the open chain actuator; (b) placing the member-end on the gripper; (c) locking of the gripper; (d) providing spherical motion to the member-end.

of the member end. Fig. 16 presents the functions of the master node with the tip of the member end. The master node could move its end-effector to the member-end and grasp it as depicted in Fig. 16(a) and (b). The gripper could be locked by turning the locking the handle as in Fig. 16(c). After grasping the member-end, the end-effector could be move on the spherical surface with two actuators of the master node.

Movement tests of the member were also conducted to verify the performance of the master node on that front. To test the extreme case, a replica of a fully-stretched member was used, and it was confirmed that the master node could move a fully-stretched member to any desired position. Fig. 17 depicts the movement test in the extreme case.

Finally, the fabricated member assembly was attached to the master node and the movement test was conducted. Fig. 15(b) and Fig. 18 depict the test bench of the master node with the two members. In the test, the spiral zipper (distance from sphere center is 0.7 m and mass of it is 0.9 kg) and the passive member-end (distance from sphere center is 0.25 m and mass of it is 0.4 kg) were attached to the gripper of the master node. The master node can move 0.125 RPM in polar direction and 0.31 RPM in azimuthal direction with the loads. The movement test of the master node have been summarized in the supplementary video.

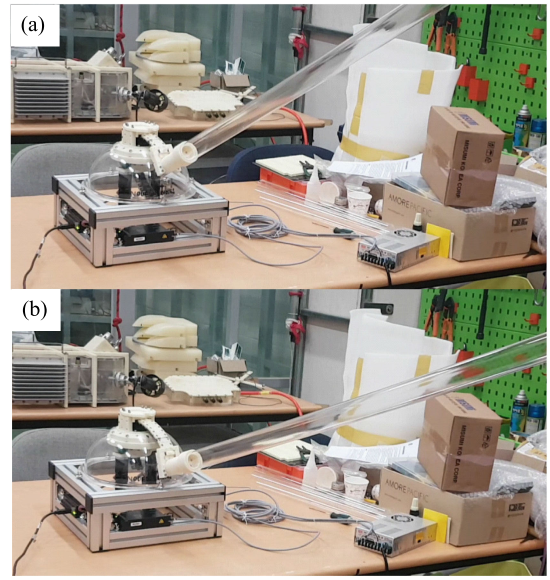


Fig. 17. Test of moving a fully-stretched member to the desired position. A replica of a fully-stretched member was attached to the master node.

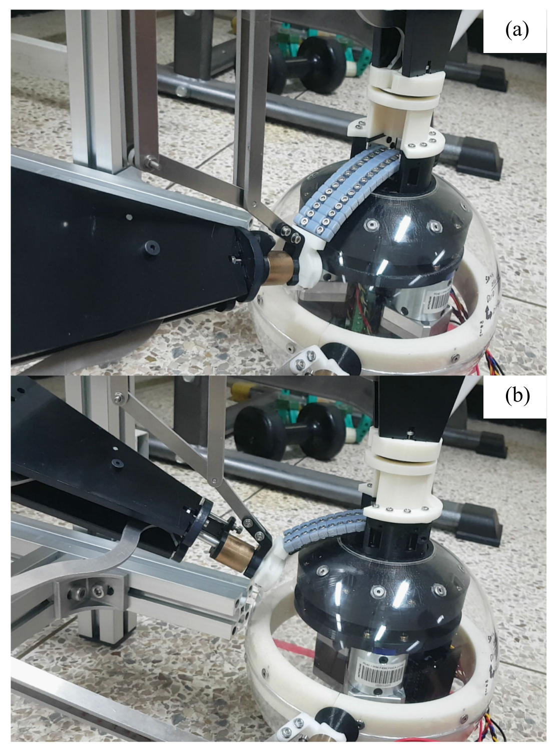


Fig. 18. Movement test of the master node on the VTT replica. Three fabricated members were connected to the master node and one member is moved by the master node.

V. Conclusion

In this letter, the master node for the VTT was designed and fabricated to execute the reconfiguration process. It was used to provide spherical motion to a target member without losing control of it. The master node significantly simplifies and stabilizes the reconfiguration process of the VTT. An open chain actuator and a turret mechanism were selected to provide polar and azimuthal angle motion around the sphere. A prototype of the master node was fabricated and its functions were tested via appropriate experiments. Reconfiguration of the real VTT system is planned to be conducted using the proposed master node in the future. Also, the final goal of the research is performing experiments of locomotion and shoring tasks with the reconfigurable VTT system.

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References

[1] K. Miura, H. Furuya, and K. Suzuki, "Variable geometry truss and its application to deployable truss and space crane arm," *Acta Astronaut.*, vol. 12, no. 7-8, pp. 599–607, 1985.
[2] P. C. Hughes, W. G. Sincarsin, and K. A. Carroll, "Trussarm-a variable-geometry-truss manipulator," *J. Intell. Mater. Syst. Struct.*, vol. 2, no. 2, pp. 148–160, 1991.
[3] G. J. Hamlin and A. C. Sanderson, "Tetrobot modular robotics: Prototype and experiments," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. IROS'96*, 1996, vol. 2, pp. 390–395.
[4] S. Curtis *et al.*, "Tetrahedral robotics for space exploration," in *Proc. IEEE Aerosp. Conf.*, 2007, pp. 1–9.
[5] T. Fukuda and S. Nakagawa, "Dynamically reconfigurable robotic system," in *Proc. IEEE Int. Conf. Robot. Autom.*, 1988, pp. 1581–1586.
[6] M. Yim, D. G. Duff, and K. D. Roufas, "Polybot: A modular reconfigurable robot," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2000, pp. 514–520.
[7] J. Davey, N. Kwok, and M. Yim, "Emulating self-reconfigurable robots-design of the smores system," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2012, pp. 4464–4469.
[8] J. Paulos *et al.*, "Automated self-assembly of large maritime structures by a team of robotic boats," *IEEE Trans. Autom. Sci. Eng.*, vol. 12, no. 3, pp. 958–968, Jul. 2015.
[9] D. Saldana, B. Gabrich, G. Li, M. Yim, and V. Kumar, "Modquad: The flying modular structure that self-assembles in midair," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2018, pp. 691–698.
[10] A. Spinos, D. Carroll, T. Kientz, and M. Yim, "Variable topology truss: Design and analysis," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2017, pp. 2717–2722.
[11] T. Kamegawa, T. Yarnasaki, H. Igarashi, and F. Matsuno, "Development of the snake-like rescue robot" kohga"," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2004, pp. 5081–5086.
[12] M. J. Micire, "Evolution and field performance of a rescue robot," *J. Field Robot.*, vol. 25, no. 1-2, pp. 17–30, 2008.
[13] W. Lee, Y. Lee, G. Park, S. Hong, and Y. Kang, "A whole-body rescue motion control with task-priority strategy for a rescue robot," *Auton. Robots*, vol. 41, no. 1, pp. 243–258, 2017.
[14] A. Spinos and M. Yim, "Towards a variable topology truss for shoring," in *Proc. 14th Int. Conf. Ubiquitous Robots Ambient Intell.*, 2017, pp. 244–249.
[15] F. Collins and M. Yim, "Design of a spherical robot arm with the spiral zipper prismatic joint," in *Proc. IEEE Int. Conf. Robot. Automat*, 2016, pp. 2137–2143.