Controlling a Variable Geometry Truss Tetrobot with an Isomporphic Puppet Controller

June 23, 2020

Abstract

Humans are skillful. By building a bio-inspired manipulable snake-like controller that can be molded into a wide variety of shapes, we allow a human controller to telepresently specify complex shapes and shape changes. We constructed a tetrahelix consisting of seven tetrahedron made of adjustable-length members connected via 3D printed Song-Kwon-Kim joints which allow manual changes to the shape of the controller. These changes in length are digitized and organized via an Arduino and transmitted to more power computers where they may specify a shape to be animated or control a robot of similar shape, or simply specify relative positions in Cartesian space. Although this research is basic, we hope it will eventually amplify human control of in vivo mechanical devices such as endoscopes, search-and-rescue robots weaseling into tight spaces, or general purpose tetrobots used for planetary space exploration as suggested by Prof. Sanderson and his students 20 years ago.

1 Introduction

The possibility of building a robot based on tetrahedra constructed of tensegrities has been well researched [6, 11, 12, 1]. It is possible to construct a variable geometry truss out of actuators using tetrahedra as a repeated module that might be expected to have an advantageous strength-to-weight ratio [9, 10]. The existence of the Boerdijk-Coxeter tetrahelix [2] has long been recognized [3, 4] as a geometric means of composing tetrahedra into long beam, which might combine the structural advanatages of a tetrahedral tensegrity with snake-like robot motion [7, 8].

By utilizing a 3D-printed jointing system which supports angular displacement of multiple members coming to central point extending previously patented work [14] and small-scale actuators and microcontrollers, the authors have constructed a relatively inexpensive tetrobot. Although some headway has been made in numerical control, this papers explores the fundamental idea of using a simulacrum controller. A controller which is isomporphic to the robot (but smaller) is constructed which can be manipulated by hand by an operated. The larger robots mimics the motion of the controller. This controller, called the *tetrocon*, has been used to develop a better hexapodal walking and turning gaits than previously possible for the tetrobot. Striking an object in space with the end effector is easy with the controller. The controller even allows, with some effort, locomotion around or over obstacles. This paper reports on the tetrocon and its usage.

Although developed to control the tetrobot, the controller could be used independently as a shape-input device. For example, it could control a tentacle animation or, more importantly, a surgical robot that had basically snake-like or tentacle-like properties, such as an advanced endoscope or arthroscope.

2 Design and Manufacture

All hardware and software the designs of the controller are free-libre open source [**anonymous**].

A tensegrity is a device in which each member only supports and has to support either tensile or compressive loads, or both. No member has to resist angular displacement. Tensegrities usually use cables for the tensile compoments and rods for the compessive components. Tensegrity robots vary the length of one or the other. Since a cable attached to a point can pull in any direction, the tensegrity condition is achieved by attaching rods only to cables, not other rods.

However, [5] produced a novel concentric multilink spherical joint based on parallelograms. Such joints allow the construction of tensegrities without cables (or, equivalently, where the cable length has shrunk to zero.)

2.1 The Song-Kwon-Kim Concentric Multimember Joint

Somewhat later [14] patented a modification of a ball-and-socket joint which is roughly similar. 3D printing makes the construction of Song-Kwon-Kim joint practical and inexpensive, though it is not necssarily superior.

Such joints allow multiple rods to be connected with spherical rotation around a single point, automatically forming a tensegrity. If those rods can change length on their own power, they form a machine or robot. If those rods can be changed by external forces, the form an input device. If you build both, you can have robot 4 which mimics a simulacrum or puppet controller **??** you can shape with your hands.

2.2 The Lock Component Designed for a Tetrahelix

In a Song-Kwon-Kim style joint, a spherical lock holds rotors in place. The placement of the holes for the rotors depends on the geometry of the robot one is trying to create. For tetrahedral tensegrities wherein the the ratio of the maximum length of an actuator to the minimum does not exceed the inverse of the golden ratio, the holes can be placed so that all configurations are possible. That is, the robot can never break itself by attempting to move into an unattainable configuration.

This relies on making the spherical part of the rotor in contact with the ball triangle. Making the the rotor trianglular lets the hole the shaft penetrates be made larger, allowing a greater angular displacement. So long as the rotors can revolve, then in the

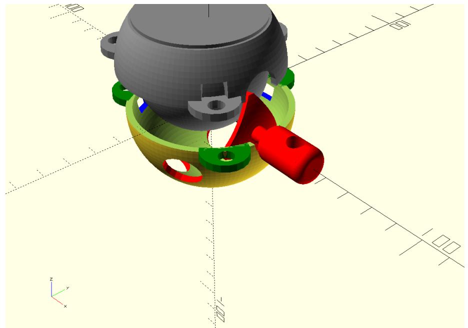

Figure 1: Exploded view of Song-Kwon-Kim Joint

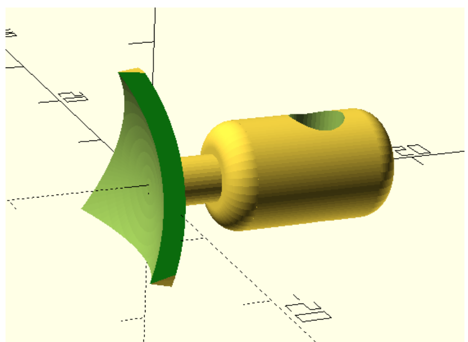

Figure 2: A Universal Rotor with a Triangular Face

tighter configuration the rotors meet edge-to-edge. This has the further advantage of strenthenging the points of contact with the lock when in tension.

2.3 A Universal Rotor

Early prototypes of our version of the joint connected the actuator to a rotor in a way that was difficult to disconnect. We have replaced this with a standard, or universal, rotor shape. The universal rotor has a hole which allows it to be detached from the sensor or actuator connected to it by removing a zip tie or a bolt.

The result is that the joint itself does not have to be taken apart to repair an actuator or displacement sensor. This has been a great help in the maintenance of the robot.

In our construction of the robot, we found it necessary to make some pieces of the joint out of metal, whereas on the smaller and less force-oriented scale of the controller the same parts were servicable when 3D printed in plastic.

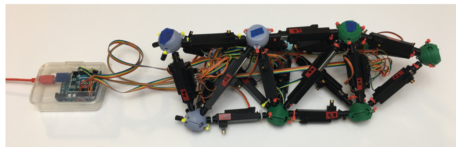

Figure 3: A 7-tetrahedron Controller

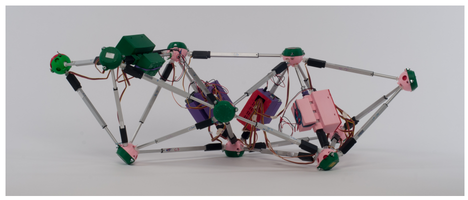

Figure 4: A 7-tetrahedron Tetrobot

2.4 The Controller

The tetrocon device uses 3D printed Song-Kwon-Kim joints. The holes in the locking shell of this joint are centered so as to mimic a tetrahelix (slightly different configuration would be needed for other configurations.) So long as the ratio of maximum to minimum displacement of a member does not exceed the golden ratio ($\frac{\sqrt{5}+1}{/}2$), the joint does moves freely and does not break.

Linear potentiometers serve as linear dispacement sensors. These sensors are held in snap-together 3D printed sleeves, which have female parts to receive our universal jointing system. The entire system is modular, in the sense that every joint and every member is precisely the same. It snaps apart easily but is easy to repair.

Because the controller is meant to be moved by hand through its range of operation with minial forces, we have found 3D-printed plastic parts acceptable, although occasional we have a layer sepration break with our rotors.

Electronically, each of six potentiometers (forming a two-tetrahedra modular extention) is connected to a multiplexer, which controllers which signal is sent to an Arduino Uno microcontroller. This allows the 24 displacment sensors in a 7-tetrahedron controller to be digitized. A simple program returns all values upon request in JSON.

A Python program implements a webserver, which allows other software to query the state of the 24 channels in the controller simply by making a web request.

2.5 The 7-Tet Tetrobot

The 7-Tet Tetrobot, hereinafter simply called the tetrobot, uses electromechanical actuators with a long lead screw driven by a small rotary motor. The can exert 50 Newtons (11 pounds) of force, while weighing only a few hundred grams.

The tetrobot consists of four modules independent, each having (and carrying) a 12V NiMH battery, by far the heaviest component of the robot. Thus in theory the tetrobot is expandable to any number of modules while remaining untethered. Each modules control six actuators, so the addition of a new module adds two more tetrahedra to the system. Each module has a Bluetooth radio on a custom Arduino Mega shield, along with three two-channel motor controllers. The Arduino runs code which accepts commands to change the length of members via Bluetooth. These commands are submitted by and Emacs electric lisp programmer, making it convenient for an operator to issue commands in an Emacs lisp buffer.

The case to hold the battery and controller for each module is 3D printed with an orifice allowing it to be mounted on the fixed part of an actuator.

In the tetrobot, the universal rotor is made by 3D printed steel ordered from Shapeways. Each end of an actuator is bolted to an universal rotor. We attempted to attach the pushrod to the universal rotor with a 3D printed plastic part, but found it necessary to move to an aluminum part. A local machinist made the threaded pushrod connectors for us. The other end of the actuator is larger and less prone to buckling forces, and we have so far been successful with plastic parts there.

The shell and ball of the Song-Kwon-Kim joint in fact is under very little force, and 3D printed plastic parts have been acceptable. However, our current design requires the shell to be bolted to a cap, and the bolts are prominent. When on the ground, they tend to catch and produce uneven forces. We intend to move to a low-profile design soon.

3 Use of Controller with Tetrobot

3.1 End-effector positioning

The simplest task for any robot that is capable of it is to position an end-effector in space. By orienting the tetrocon to match the physical position of the tetrobot, volunteers from an audience with zero experience can easily cause the first joint of the tetrobot to hit a positioned object after a few seconds of orientation.

In a sesne this is a simulation of a robot "arm" that does not support locomotion.

3.2 Locomotion

A variable geometry truss wherein each element can change length has high input dimensionality; the 7-tet tetrobot has 24 actuators. The authors have previously explored developing gaits using a a virtual model of the tetrobot. This system used the ammo physics engine to simulate gravity. The basic goal to position six joints on the ground and then move one joint at a time, similar to a hexapodal gait on a robot with legs. Although some progress was made, the complexity of the software and physics simulation had many limitations.

The controller, operating without the tetrobot, allowed us in a single hour to develop a set of thirteen positions which allows the robot to move forward on a smooth surface fairly effectively. As one might expect for a crawling robot, it was slow—approximately 4 inches per series of 13 poses, or approximately 4 inches per second (need to remeasuer precisely.)

We also were able to create a set of poses that accomplished a 45 degree turn with the same ease. The tetrobot turns 45°in TBD minutes.

However, when we were able to use the tetrobot with the tetrocon controller and see the effect of the robot position change directly within one or two seconds of changine the controller, we found we were much better able to intuitively develop motions for the robot. We discovered a more efficient "inchworming" gait which proved practical with two hours of experimentation. When recorded and replayed, this gait allows the tetrobot to move forward at TBD inches per minute.

3.3 Obstacle Confrontation

Unlike most wheeled vehicles and robots, the tetrobot might be able to climb over an obstacle of significant size compared to its own size. Operating in complex environments in a theoretic advantage of snake-like or tentacle-like robots.

After successfully developing inchworming and turning gaits on flat terrain, we attacked the problem of climbing over a simple rectangular obstacle. After practicing, we were able to manually control the tetrobot to climb over a 2"x2" obstacle in TBD minutes. We then tested climbing over a 4"x4" obstacle, and after TBD minutes of practice, were able to do it in TBD minutes. Finally, we attempted a 6"x6" obstacle, and found TBD.

3.4 Summary of Locomotions

Table 1: Locomotion Development

Locomotion	Practice Time	Motion Performance
Inchworm Gait	1.5 hours	X cm / minute
Turn CW	0.5 hours	X °/ minute
Turn CCW	0.5 hours	X °/ minute
Cross 2x2 board	TBD hours	TBD minutes
Cross 4x4 board	TBD hours	TBD minutes
Cross 6x6 board	TBD hours	TBD minutes

4 Future Work: Virtual Control

Because the shape of a tetrahedron is completely determined by the length of its sides, it is possible to completely reconstruct the shape of the controller from its input. Software to do so is available on our site [13].

Becasue a tetrahelix is basically cylindrical or tentacle-like in shape, one can use the tetrocon to define a wide variety of shapes in space. In fact the tetrocon supports a certain amount of size or thickenss information as well. However, if valuable, you could consider only the centroid of each tetrahedron and thereby have a hand-manipulated specifier of curves in 3D Cartesian space.

Thus any robot which is somewhat tentacle-like in shape could be controlled by the tetrocon. Since the tetrocon is modular, the length, in terms of the number of tetrahedra, is essentially unlimited. In practice, it becomes difficult to hold an object with too many tetrahedra. Our controller currently suffers from not offering enough resistance to change in displacemnt. That is, it is easy to move it into any position with the hands, but the potentiometers slide so easily that gravity may pull it back to the table of cause it to sag between your hands.

5 Conclusion

The use of a hand-manipulable controller that is the same shape as the controlled robot allowed a complex tetrobot to be effectively telepresently controlled to develop programmable gaits and allowed a human robot pilot to overcome obstacles with relative ease.

6 Gait Speeds

Inchworm: Trial 0: Node E begun on the starting line. Time: 32.99 s Travel: 12.5 cm

Trial 1: Configuration resting configuration from inchworm. Time: 34.17 s Travel: 11 cm

Trial 2: Time: 33.31 Travel: 11 cm

Conwalk: Trial 0: Node E begun on the starting line. Time: 57.65 Travel: 10 cm

Trial 1: Configuration resting configuration from inchworm. Time: 55.04 Travel: 12 cm

Trial 2: Time: 54.43 Travel: 6 cm : Note, locked against seam.

Tripod: Trial 0: Node E begun on the starting line. Time: 57.65 Travel: 10 cm

Trial 1: Configuration resting configuration from inchworm. Time: 55.04 Travel: 12 cm

Trial 2: Time: 54.43 Travel: 6 cm : Note, locked against seam.

Tripod: Trial 1: Time: 16.5 s Travel: 6.5 cm

Trial 2: Time: 16.85 Travel: 9 cm

6 steps 17.9 inches.

Acknowledgments

Some people will be thanked after the anonymous review period.

References

References

[1] Lee-Huang Chen et al. “Soft spherical tensegrity robot design using rod-centered actuation and control”. In: *Journal of Mechanisms and Robotics* 9.2 (2017), p. 025001.

[2] HSM Coxeter et al. “The simplicial helix and the equation tannt= ntant”. In: *Canad. Math. Bull* 28.4 (1985), pp. 385–393.

[3] R.B. Fuller and E.J. Applewhite. *Synergetics: explorations in the geometry of thinking*. Macmillan, 1982. ISBN: 9780025418707. URL: https://books.google.com/books?id=G8baAAAAMAAJ.

[4] R. W. Gray. *Tetrahelix Data*. http://www.rwgrayprojects.com/rbfnotes/helix/helix01.html. 2017. URL: http://www.rwgrayprojects.com/rbfnotes/helix/helix01.html.

[5] G. J. Hamlin and A. C. Sanderson. “A novel concentric multilink spherical joint with parallel robotics applications”. In: *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*. May 1994, 1267–1272 vol.2. DOI: 10.1109/ROBOT.1994.351313.

[6] Gregory J. Hamlin and Arthur C. Sanderson. *Tetrobot: A Modular Approach to Reconfigurable Parallel Robotics*. Springer Science & Business Media, 2013. ISBN: 9781461554714. URL: https://play.google.com/store/books/details?id=izrSBwAAQBAJ.

[7] S. Hirose. *Biologically inspired robots: snake-like locomotors and manipulators*. Oxford science publications. Oxford University Press, 1993. ISBN: 9780198562610. URL: https://books.google.com/books?id=TaIQAQAAMAAJ.

[8] P. Liljebäck et al. *Snake Robots: Modelling, Mechatronics, and Control*. Advances in Industrial Control. Springer London, 2012. ISBN: 9781447129967. URL: https://books.google.com/books?id=9knheIFml3IC.

[9] M.M. Mikulas and R.F. Crawford. *Sequentially deployable maneuverable tetrahedral beam*. US Patent 4,557,097. Dec. 1985. URL: https://www.google.com/patents/US4557097.

[10] Brian T. Mirletz et al. “Design and Control of Modular Spine-Like Tensgrity Structures”. In: *World Conference of the International Association for Structural Control and Monitoring (IACSM)*. IACSM. July 2014. URL: https://ntrs.nasa.gov/search.jsp?R=20160005274.

[11] *NTRT - NASA Tensegrity Robotics Toolkit*. https://ti.arc.nasa.gov/tech/asr/intelligent-robotics/tensegrity/ntrt/. Accessed: 2016-09-13. 2016.

[12] Chandan Paul, Francisco J. Valero-Cuevas, and Hod Lipson. “Design and Control of Tensegrity Robots for Locomotion”. In: *IEEE Transactions on Robotics* 22.5 (Oct. 2006), pp. 944–957.

[13] Robert L. Read. *The Tetrobot*. https://github.com/PubInv/tetrobot. June 12, 2020.

[14] S.K. Song, D.S. Kwon, and W.S. Kim. *Spherical joint for coupling three or more links together at one point*. US Patent 6,568,871. May 2003. URL: http://www.google.com/patents/US6568871.