The Design and Construction of a Novel Variable-Geometry Snake-like Input Device

Robert L. Read *email: read.robert@gmail.com
Avinash Baskaran †email: baskaran.avinash@gmail.com

Public Invention, an educational non-profit.

September 24, 2019

Abstract

The TetraCon represents a hand-held input mechanism for robotic control. Its biomimetic design is paralleled by its geometric simplicity, being comprised of a tetrahedrally arranged network of sensors. Its inherently modular design and construction makes it effective and intuitive to serve as a control mechanism in a variety of telerobotic applications. A modification of the TETROBOT[10, 7, 6, 4] concept, the TetraCon relies on an innovative spherical joint design[11] to provide connection between embedded sensors.

An innovative approach to modular robotics that is capable of both locomotion and exerting and withstanding structural forces is described. Extending the TETROBOT[10, 7, 6, 4] concept of a variable-geometry truss which is composed only of joints and linear actuators with a new 3D-printable embodiment of a spherical joint[11] produces a completely modular, mechanically strong, tentacle-like machine capable of independent locomotion.

1 Introduction

Snake-like robots are particularly advantageous due to their ability to adopt varying geometries to navigate curvilinear paths. They accomplish body undulation as a method of locomotion via . The design and construction of such objects relies on flexible actuation with respect to the field of motion.

*read.robert@gmail.com
†baskaran.avinash@gmail.com

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Between 1996 and 2002 years ago, Arthur C. Sanderson and his colleagues published a series of papers[10, 7, 6] on modular robots. The “TETROBOT” was a variable-geometry truss, in which motion was accomplished by the change in length of linear actuators, connected in a modular geometry based on the tetrahedron and octahedron. Such a system requires a special joint which allows the actuators to remain aimed at the center of joints while supporting a certain amount of rotation about this center.

This paper builds upon that work by introducing 3D-printable embodiments of a recently invented spherical joint[11], and gives some results related to the underlying geometry and math, as well as providing references to all of the open-source materials needed to duplicate and expand on this work. This is an open-source embodiment of the TETROBOT with physically smaller actuators which is more accessible to the hobbyist or researcher with a limited budget. The development of 3D printers, Bluetooth, microprocessors such as the Arduino, and inexpensive commercial actuators has made this possible. A very simple robot having only three tetrahedra is shown to be capable of locomotion.

5.1 Motivation

Imagine a strong, light, metamorphic material that can exert or resist force. You can command it to form any shape, limited only by its flexibility. Using that coformability you can get it to crawl across very rough terrain. You can command it to form into a bridge or to lift and move heavy objects, or to perform all the functions of a crane, a forklift, a backhoe and/or bulldozer.

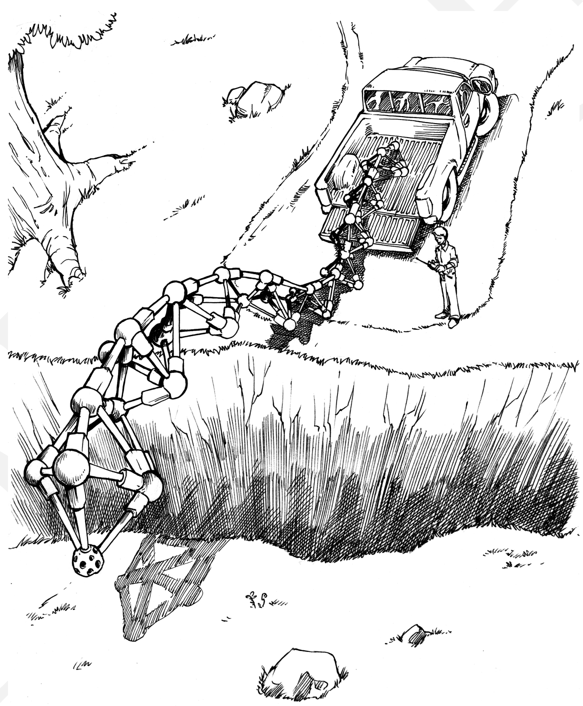

Figure 1: Concept art of GlussBot Spanning a Chasm

It is a truss that crawls like a slug—a *gluss*. If you need more of it, you buy it by the kilo and when it arrives you order it to crawl to your existing gluss. You easily join it there, creating larger, stronger, combined mass.

The advantages of snakebots have been widely recognized In general, these have been constructed with angular joints. In this paper we propose a different, truss-like approach to providing similar mobility that uses only linear actuators and spherical joints that eliminates non-axial forces so that only compressive and tensile forces act on the actuators. This potentially combines the advantages of forceful machines with snake-like mobility.

Other geometries, such as moving planes, are possible with the same material.

Additional videos at the YouTube channel, Public Invention, reachable from the above link, further motivate the *gluss* concept.

5.2 Concept: Gluss = Slug + Truss

Imagine a metamorphic or polymorphic machine that forcefully assumes a variety of shapes. It moves like a mollusc or amoeba, oozing into position as commanded. It is technically a "machine" because it can exert force reliably, but it may be thought of as a material, because unlike most robots its components are not differentiated.

Although someday an actual chemical substance may do this, today it can be constructed from commercial components and 3D-printable parts. This paper introduces the *gluss* approach to building metamorphic dynamic robots and static machines.[1]

Massively scalable robots have often been proposed. Our particular approach is to use linear actuators, which are rod-like machines that can make themselves shorter or longer. These are tied together using a relatively new joint [11] which allows, for example, as many as 12, but more realistically 4 or 6, members to be joined together sturdily at a single point. A 3-D printed embodiment presented here, called the *turret joint*, allows the change of angle required for the gluss to ooze about. Some gluss consists of some actuators joined together with some turret joints and whatever batteries and control microelectronics are needed.

1. Design concept
2. Control:
   (a) Sensors
      i. Mechanism
      ii. Housing
      iii. Wiring

[1] "Gluss" is a portmanteau of "Slug" and "Truss" because we are attempting to build a truss, or space frame, that is capable of moving like a slug or octopus. The word *gluss* should be used as a substantive noun in English, much like the word *clay* is used. The use of *glusses*, the plural of *gluss*, should be rare and refer to different kinds of metamorphic material, such as the expression "four clays" suggests four distinct types of clay without specifying how many kilograms of each one means.

    iv. Circuit analysis (needed?)

  (b) Signals

    i. Multiplexing

    ii. Wireless communication

3. Turret joint

  (a) Gluss-con scaling/proportions to the Gluss

  (b) Universal joint / modularity

4. Sleeves

  (a) Modularity

5. User-friendliness

  (a) (experimentation?)

6. Applications

  (a) Assistive

    i. Body-attached assistive / tertiary limb device

    ii. Pole mounted arm

    iii. Physically independent device

  (b) Medical

    i. Rehabilitation

      A. Motor skill development for learning imparied children

      B. Skeleto-muscular rehab

      C. Physiotherapy

    ii. Prosthetics / limb replacement

    iii. Medical casts / sleeves

    iv. Surgical assistant device

  (c) Future work

    i. Optical sensing

      A. Computer - vision based detection

6 The *Turret Joint*

6.1 The Need

The way to make something large, light, and strong is to make it inherently rigid by building it out of triangles. In a single plane, this is called a *truss* [2], and more generally is called a *space frame*. Space frames made completely from triangles tend to be rigid even if the joints that connect members allow motion, such as a pin joint or a ball-and-socket joint. This is an advantage because non-axial strain (that is, a slight change in the angular geometry of the frame) cannot cause the joint to fail, as it can with a welded joint.

But we seek a space frame that can change its shape dramatically. Imagine a radio tower in which each girder has been replaced with an actuator that can get longer or shorter. Such a tower could bend its top down to the ground, or even tie itself into a knot. To accomplish this, the joints must support significant but limited range of angular motion.

The spherical joint invented by Song, Kwon and Kim [11] is such a joint, the essence of which is rendered in their patent drawing, Figure 2. We name this joint the *Turret Joint*.

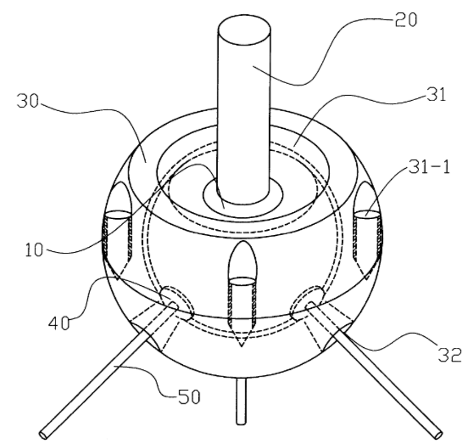

Figure 2: Song, Kwon, Kim, patent image.

When properly configured to support regular nets of actuators, it allows the gluss to be a moving space frame. It happens that the specific actuators we use are geared such that when no power is applied, they strongly resist outside forces that would change their length, essentially becoming rigid members. The resulting gluss can move into position and then be powered off to be a temporarily static space frame.

One could also use this joint with members which are not actuators. For example, we first constructed the joint with carbon fiber rods. In essence it is then a construction kit with continuously variable member lengths liberated from using a finite set of angles.

6.2 Geometry

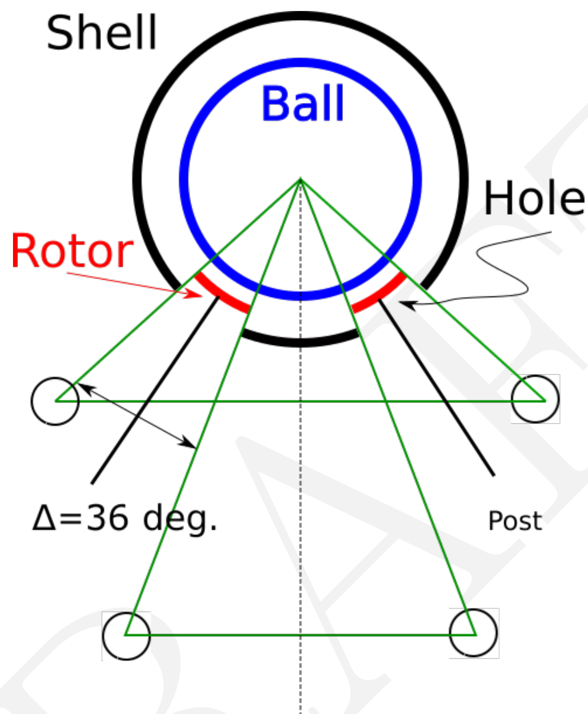

Figure 3: Turret Joint Planar Geometry

One way to approach this problem is to consider a single triangle formed by joints and actuators. The joint must support the most acute triangle that can be formed with the three actuators and the most obtuse triangle that can be formed with the actuators.

In fact it is a surprising result that we prove elsewhere [9] in Appendix A that the maximum Q which can be utilized by an ideal turret joint happens to be the famous golden ratio, $\varphi \equiv \frac{1+\sqrt{5}}{2} \approx 1.618...$, and the maximum deviation for any one member coming into the joint is 36°. Thus in Figure 3 the triangles drawn are in fact a Golden Triangle and a Golden Gnomon. A real-world joint, which will support less variation because the "post" must have a certain thickness and the "rotor" must have a lip slightly larger than the hole in order to remain locked in place. Furthermore, the joint adds a certain necessary thickness, the minimum length from joint-center to joint-center will be somewhat greater than from actuator tip to actuator tip.

However, the theoretical ideal result is a valuable approach to physical computation and makes a Q for a physical actuator of 1.5 seem quite appropriate.

6.3 Embodiment

Although the joint could be machined or formed in some other way, 3D Printers have made the construction of the Turret Joint far easier. We have designed a complete set of components needed to 3D print the joint and the rotors to attach to the linear actuators. These models are created with OpenSCAD, a functional parametric modeling program.

Our experience has been that the common plastics PLA and ABS are adequate for the Turret Joint, but have found that nylon, which is far tougher and less prone to cracking, is superior for the rotors which bolt directly to the actuators.

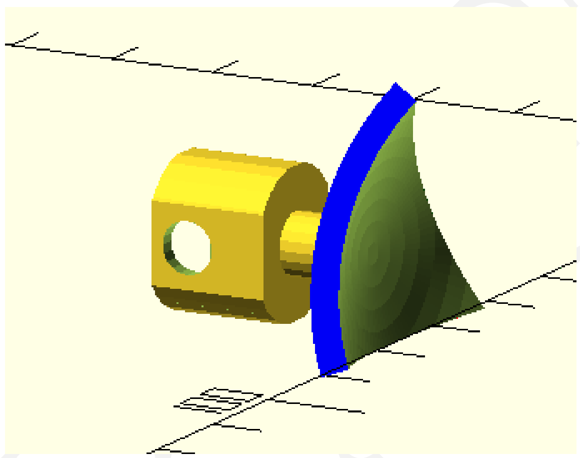

Figure 4: Triangular Rotor Model.

We have innovated the design of the rotor by using a triangular section of a sphere as the rotor rather than a circular section, as shown in Figure 4. Assuming that each actuator is free to rotate about its axis as well as revolve about the center of the ball joint, this shape does not limit motion even in the most pinched configurations. The triangular rotor provides greater extent of contact, which presumably makes the joint motion smoother and less likely to bind.

The Figure below shows most of the parts. The nylon triangular rotor is white and rests upon the red ball. The green part is a Tetrahelix lock, and the yellow parts are the locks for the Octet Truss geometry.

Figure 5: 3D Printed Parts

6.4 Open Source Realizations

7 Related Research

Between 1996 and 2002, Arthur C. Sanderson and his colleagues published a series of papers[10, 7, 6] on modular robots. The "TETROBOT" was a variable-geometry truss, in which motion was accomplished but the change in length of linear actuators, connected in a modular geometry based on the tetrahedron and octahedron. A quadrupedal robot was constructed completely out of the tetrahedral/octahedral geometry. The TETROBOT robots successfully walked and even rolled. The TETROBOT hardware was significantly heavier and more powerful that then hardware used here. The glussbots have so far demonstrated no greater functionality, although we have demonstrated that very simple robots consisting of only 3 tetrahedra can locomote.

The technology presented in this article has drastically lowered the cost, thus making the glussbot/TETROBOT concept accessible to hobbyists and researchers on a limited budget.

The TETROBOT used a joint called the CMS joint. Although possibly superior in not allowing an extra degree or rotational freedom, it would be a challenge to use the CMS joint with the Actuonix actuators because the pushrod must fully retract, or the length of the pushrod would be have to be extended with an attachment. Sanderson's students used actuators that extended from the middle, avoiding this problem. If the Gluss Project ever develops its own actuators, it should explore using this joint.

If you read the introduction of the brilliant book by Shigoe Hirose[5] substituting "even simpler soft squiggly thing that might not be as cylindrical as a snake" for the word "snake", you will have an excellent motivation for the gluss concept. More generally, much of the work developed for snakebot locomotion is directly reusable, in the sense that a long enough tetrahelix can model a snake, and further inspires the idea of using simpler models mapped into a gluss model to perform complex movements.

Buckminster Fuller also promoted *tensegrity*, and some research on Tensegrity Robots has been done, the work of Paul, Valero-Cuevas, and Lipson[8] being a good starting point. This work has developed into a serious effort[1] by NASA to explore tensegrity robots for extraterrestrial exploration.

Tensegrities are closely related to the gluss concept, more researched, and potentially more performant. In fact a gluss could be considered a special case of a tensegrity, using vanishingly short cables and, in the terminology of [8], *strut-collocated actuation*. It has been reasonable to produce a static gait for the 3TetGlussBot and 5TetGlussBot because its behavior is not very dynamic: it is so slow and strong that velocity is irrelevant at the current scale. Reported tensegrity robots have focused on dynamic, "hopping" and rolling gaits.

It is possible that gluss is easier to work with for an actual human being on the ground. Although of course both systems will use computer control systems, one can imagine a large robot crawling into place imperfectly, and some workperson making a manual adjustment: "Actuator #37, get shorter!" This is intellectually more difficult for a tensegrity, wherein changing a cable length has less predictable impact on the tensegrity geometry. However, many of the future steps outlined in Section 9 apply to both gluss and tensegrity robots.

This paper presents the gluss as a "machine", rather than a "mechanism". That is, it motivates gluss by asserting it can exert and resist force, yet currently treats gluss positioning as a purely kinematic, rather than dynamic problem. The actuators currently in use are geared such that they are so slow and powerful that the behavior is not really dynamic. If static analysis of a resulting geometry is needed, for example to ask if structure used as a bridge will bear a load, a finite element approach[**?**] will be adequate.

If one chooses to attempt to exert a high enough force or to move more quickly, classic robot control theory which models forces and velocities based on Lagrangian mechanics will be required.

8 Placeholder for Photos

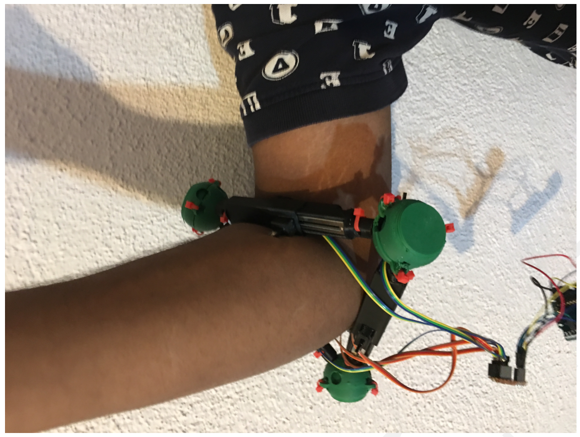

Figure 6: One-tet controller fitting an elbow

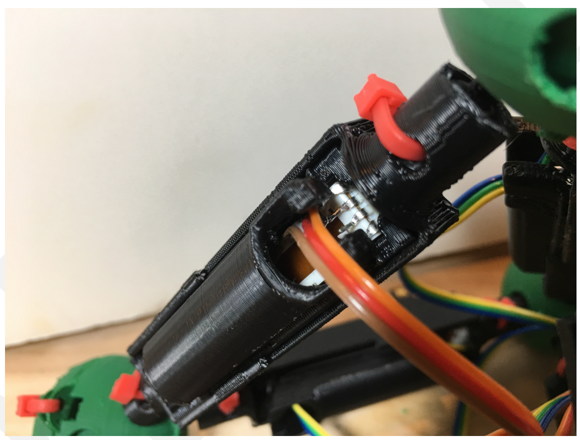

Figure 7: Close-up of Potentiometer Connection

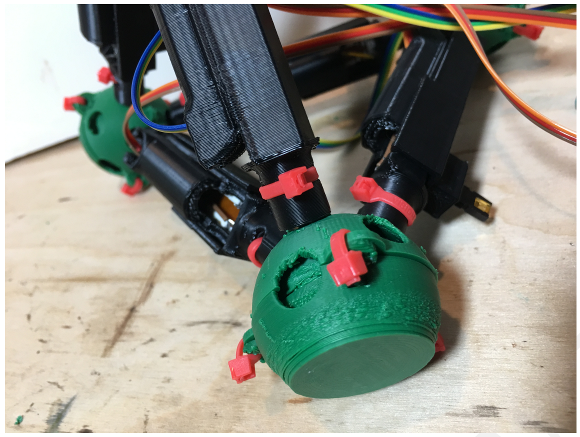

Figure 8: Joint Close Up

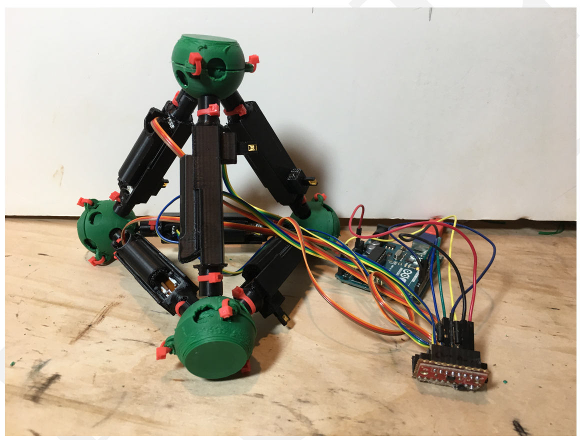

Figure 9: Basic One-Tet Controller

9 Future Steps

10 Contact and Getting Involved

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