

# Mechanical Design and Locomotion of Modular-Expanding Robots

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## Introduction

Modular robots are a class of robotic systems composed of many identical, physically connected, programmable modules that can coordinate to change the shape of the overall robot. By transforming its shape, a modular robot can achieve many tasks, such as locomotion in complex terrains. An interesting question is how to design these relatively simple modules such that they can be combined to achieve a variety of locomotion mechanisms such as rolling, crawling, and climbing. Modular locomoting robots have the potential of being more adaptive to their environments, and may thus prove useful in applications such as space exploration or search and rescue.

One recent area of interest has been the design of “expandable” modular robots. In 2004, NASA developed a proposal, along with a conceptual video, for a modular robot composed of many expandable links, capable of moving in complex ways: sliding, rolling, climbing, etc [2]. They also constructed a physical version of a 4-link tetrahedral expandable robot, called the *4Tet Walker*, capable of conducting a rolling motion; this design was later expanded to a 12-link robot, however the design was quite large and difficult to scale due to the significant weight. Nevertheless it demonstrated an interesting concept for the design of a modular robot. More recently, at the University of Southern Denmark, Lyder et al [1] developed *Odin*, a fully modular deformable robot based on a similar concept of expandable links with compliant joints; the group demonstrated modular electronics and communication, and also showed how passive expandable links could be introduced in addition to the active links. Our group also explored the design of deformable modular robots, and developed several sensing-based control algorithms, including one for rolling locomotion using the Tetrapod robot with pressure and light sensors [3,4].

One of the main difficulties in the implementation of these expandable modular robots is the mechanical design. The proposed locomotion techniques require large changes in actuation length and significant compliance at the joints during locomotion, but also require rigidity in order for the robot to hold its shape. These conflicting requirements make it difficult to design even the simple rolling tetrahedral walker. For example, the *4Tet Walker* telescoping links were hand-crafted and quite heavy, the *Odin* robot so far has demonstrated only sliding motion rather than rolling motion due to the limited range of both the expandable links and the joints, and the pressure-sensitive Tetrapod design by Yu *et al* frequently failed due to joint breaks.

In this paper we explore some of the design challenges involved in constructing expandable modular robots. We present the mechanical design of a modular-expandable robot that is capable of multiple configurations and locomotion styles: tetrahedral rolling, 2D sliding, and simple climbing. In addition the modules are easy to manufacture, using only 3d printing and off-the-shelf actuators, and have proven to be robust to repeated use and reassembly. We believe that these mechanical design principles can be incorporated into other similar robots, and move us closer to the types of complex locomotion envisioned by the original NASA project.

## Mechanical Design of the Modules

Our expanding modules were first designed to be used in a tetrahedral walker robot. The general configuration and motion of the tetrahedral walker is described in Figure 1, based on the design and algorithms developed in [1,4].

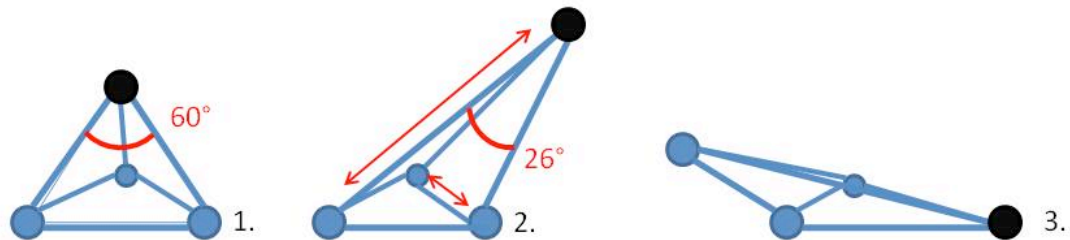


FIGURE 1: DIAGRAM OF TETRAHEDRAL WALKER MOVEMENT. FROM ORIGINAL POSITION (1) USES LINEAR ACTUATION TO CHANGE SHAPE (2) AND MOVE CENTER OF MASS UNTIL STRUCTURE FLOPS OVER (3).

The tetrahedral walker is composed of 6 active links and 4 joints. The walker moves by shifting its center of mass through expansion (linear actuation) of the active links. The body of the walker begins in a pyramidal position and is then contorted until it reaches a critical position causing it to fall over. The structure then returns to its original pyramidal position. During this movement cycle the tetrahedral robot takes on significantly different shapes, changing from a 60° angle between limbs to a 26° angle. The links also require a significant expansion ratio. One of the main challenges to this design is the balance between rigidity and deformability. The modules need to be capable of deformation, both elongating and changing their connection angle, while retaining a rigid form.

The primary requirement in our design was to develop modules capable of the expansion, compliance, and rigidity necessary for this locomotion. In addition we had several secondary requirements. The design needed to be easy to manufacture, using only 3d printed parts and off-the-shelf components, and not require the machining of special metal parts. It also needed to be robust and reusable for long-periods of time, in spite of the manufacturing restrictions and high stresses caused by the rolling locomotion. Finally it needed to be easy to reassemble in new configurations, since the long-term goal was to explore multiple locomotion styles.

These requirements were considered when designing each of the components. There are three main components of the design: the joint, the connector, and the linear actuators with housings. The assembly of the connectors, actuators and housings constitute one module; the joints allow us to combine multiple modules into a larger structure. The assembled parts can be seen in Figure 2. All of the components were designed in Solidworks and printed out of ABS using Fused Deposition Modeling (FDM). Design decisions for each of the components are described in more detail next.

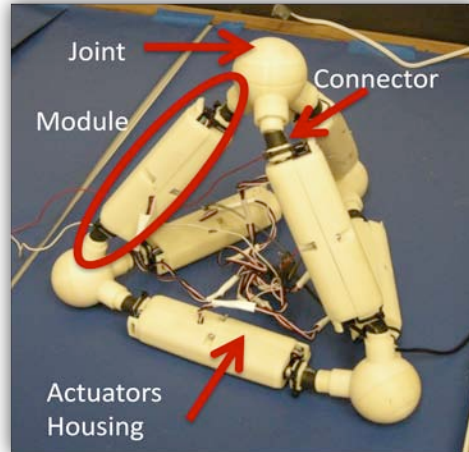


FIGURE 2: DIAGRAM OF VARIOUS COMPONENTS OF THE MODULAR-EXPANDABLE TETRAHEDRAL WALKER.

- CONNECTOR DESIGN

The connectors provide the interface between the joint and the active link (linear actuators). The connectors have the unique responsibilities of supplying the compliance in the structure as well as taking the majority of the load when the structure flops over. Thus, when designing the connectors a part was created which would provide secure connections, create compliance, and be able to withstand significant loading.

The connector is attached securely to the linear actuator using screws, since this connection is meant to be permanent over many structures. To interface the connector with the joint several different options were considered and were evaluated for the security of the connection as well as their ease of assembly and disassembly. Two different sizes of threads (20mm X 1.25 and 20mm X 1.67) were tested as well as a design utilizing tabs (Figure 3L), all of which were directly printed in ABS plastic. The smaller threads were seen to be too thin to be reliable thus the tabbed design and the larger thread design were selected for use. To achieve sufficient compliance in the connector, a ball joint was used having a swivel angle of 80°. This is highlighted in Figure 3Ra.

Finally, the connector was designed to repeatedly handle the force of the walker tumbling. Stress concentrations were thus avoided by reducing the number of sharp corners. Also, a stiff black tube was placed around the connector, which serves to damp loading without limiting the motion of the connector. This can be seen in Figure 3Rb.

- JOINT DESIGN

The joints are responsible for connecting the different modules together. In the case of the tetrahedral walker this involves holding three modules each 60° from each other. To hold the modules the joints were designed to interface with the connectors. A joint to interface with the tabbed connector (figure 4a) as well as a joint designed to interface with the connector with larger threads (figure 4b) were developed. These two joints can be seen in Figure 4. The smooth rolling surface allows the tetrahedral walker to easily roll over the joints. While the original design was focused on the tetrahedral configuration, several aspects were designed with the long-term goals in mind. For example, the ball unscrews into two halves to allow the easy design of joints with more connections. In addition this provides access to the hollow interior, which can be used to store components such as additional weight or sensors.

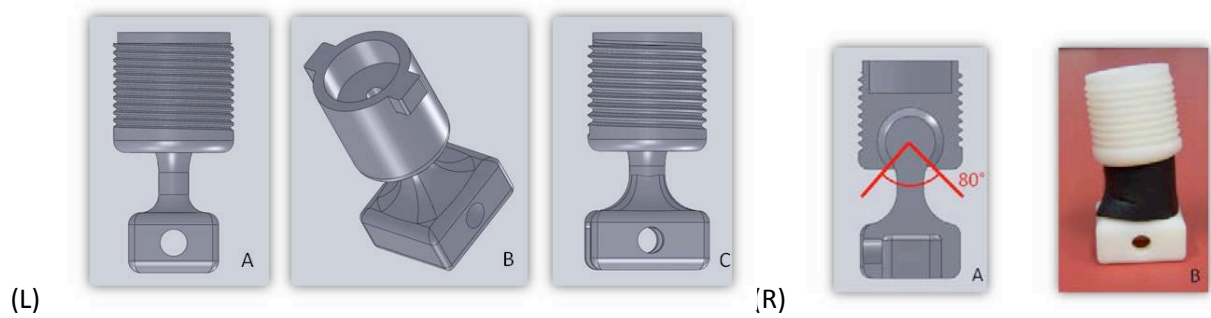


FIGURE 3: (L) THREE INITIAL CONNECTOR DESIGNS. DESIGN A. UTILIZES SMALL THREADS, DESIGN B. UTILIZED TABS, AND DESIGN C. WAS THE MOST SUCCESSFUL UTILIZING LARGER THREADS. (R) CONNECTOR FEATURES INCLUDING A BALL JOINT WITH 80° OF SWIVEL (A) AND STIFF TUBING TO DAMPEN LOADING (B).

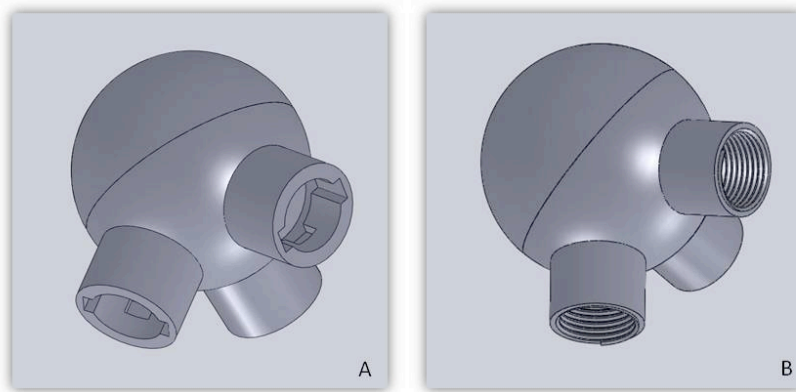


FIGURE 4: TWO JOINT DESIGNS FOR THE TETRAHEDRAL ROBOT. DESIGN A INTEGRATES WITH TABBED CONNECTORS AND DESIGN B WITH THREADED CONNECTORS.

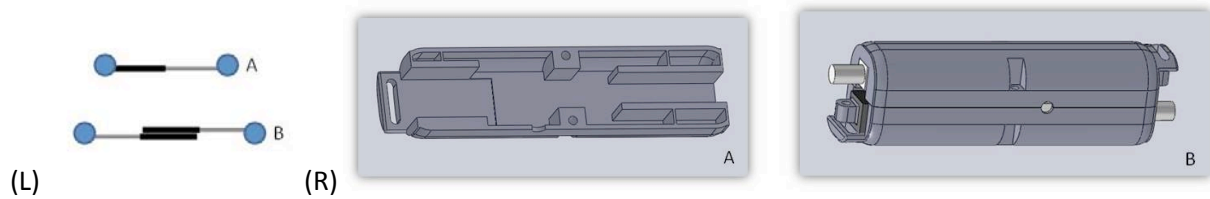


FIGURE 5: LINEAR ACTUATOR ASSEMBLY. (L) VIEW A SHOWS THE OLD CONFIGURATION WITH A SINGLE LINEAR ACTUATOR. VIEW B SHOWS THE NEW DESIGN PROVIDING ADDITIONAL EXPANSION BY 1:3 EXPANSION BY ATTACHING TWO LINEAR ACTUATORS. (R) VIEW A IS THE INTERIOR OF ONE SIDE OF THE HOUSING. VIEW B SHOWS FULL LINEAR ACTUATOR AND HOUSING ASSEMBLY.

- **LINEAR ACTUATORS WITH HOUSINGS**

The active links, composed of linear actuators, drive the motion in the tetrahedral walker. In order for the tetrahedral robot to locomote by rolling it needs to shift its center of mass significantly; this requires significant expansion of the linear actuators. In previous designs of the walker the configuration of the single linear actuator did not supply sufficient expansion for locomotion. Thus twice the number of actuators were used and arranged to provide a 3:1 expansion of the structure. This change is described in Figure 5L. With this new design utilizing two linear actuators (produced by Firgelli), housings were needed to securely hold the actuators together. The housings were designed to prevent sliding of the actuators as well as provide smooth rolling surface for the walker (Figure 5R).

### **Different Configurations and Locomotion**

After being fabricated the modules were assembled into the tetrahedral configuration. The robot was put through many gait cycles. The result can be seen in Figure 8 and movies are available at [5]. These results illustrate that the tetrahedral robot was capable of rolling locomotion. It was able to maintain a rigid pyramidal shape while at the same time deforming its body to shift its center of mass, thus satisfying the requirement of compliance and rigidity. In the process of testing the robot was disassembled, reassembled and tested for multiple hours suggesting the parts are robust.

The modules were next rearranged into a square formation. This new formation allows for a variety of different motions including crawling (Figure 7) and climbing (Figure 8). The crawling locomotion is based on a central-pattern-generator (CPG) style movement described in more detail in [6], where we show that the same control algorithm allows locomotion for more complex, and asymmetric, configurations of the square linkages. The climbing robot uses a similar periodic motion, and in open-loop form can robustly climb the padded tube at 45 to 90 degree angles with only occasional slippage. A more redundant design (more active links) and the use of pressure sensors could potentially make this locomotion even more robust.

In addition to demonstrating each locomotion technique multiple times, this modular robot design has been assembled and reassembled many times, and has been transported and demonstrated at robot exhibitions. The modules have proven to be very robust, and to date no joint breaks have occurred (a sharp contrast from the implementation in [4]); the robot has also proven to be easy to disassemble, reassemble and transport. One of the areas for future improvement is in the design of passive telescoping or spring-based modules, to allow a wider range of flexible structures and potentially easier locomotion algorithms. Another area for improvement is in the design of pressure sensors that interface well with the joints; this requires flexible sensors that can wrap around the joints and current low-cost pressure sensors are not reliable enough.

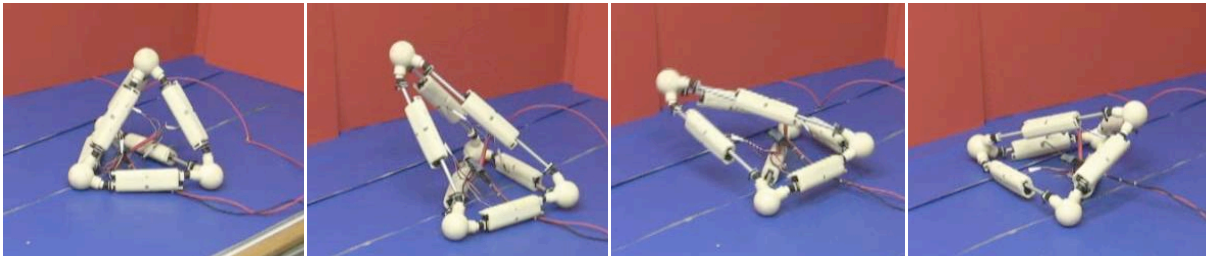


FIGURE 6: TETRAHEDRAL ROBOT IN MOTION, SINGLE GAIT CYCLE: 1. STRUCTURE AT REST 2. STRUCTURE EXTENDING 3. STRUCTURE FLOPS OVER 4. STRUCTURE LANDS AND RIGHTS ITSELF.



FIGURE 7: 2-SQUARE ROBOT IN MOTION: THROUGH LINEAR ACTUATION THE ROBOT IS ABLE TO SHIFT ITS WEIGHT AND CRAWL FORWARD.

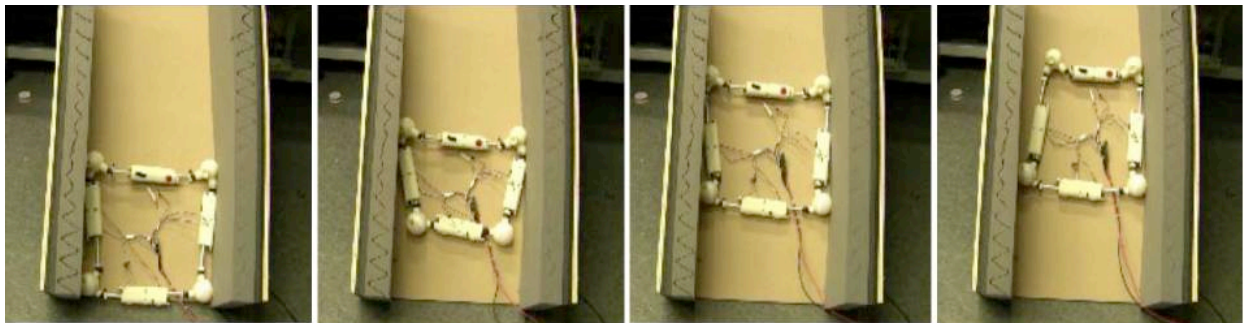


FIGURE 8: 1-SQUARE ROBOT CLIMBING: BY USING LINEAR ACTUATION TO APPLY PRESSURE TO THE WALLS THE SQUARE ASSEMBLY IS CAPABLE OF CLIMBING UP A CHIMNEY-LIKE STRUCTURE.

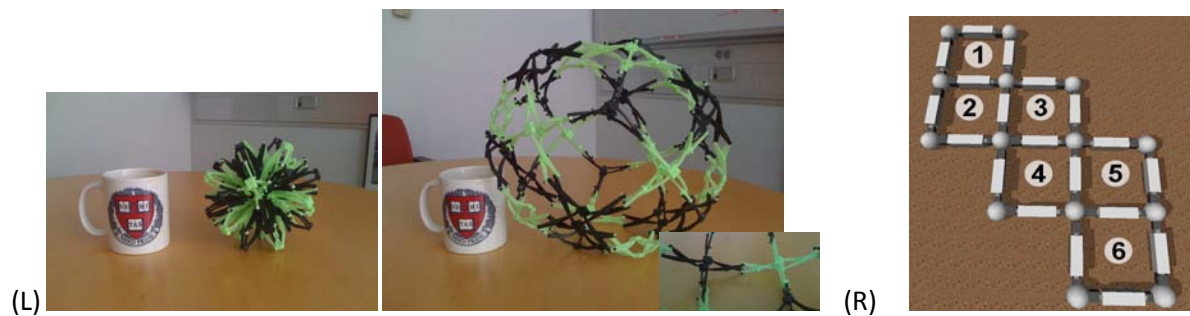


FIGURE 9: OTHER POTENTIAL EXPANDABLE STRUCTURES: (L) HOBERMAN™ SPHERE, WHERE THE SCISSOR-LIKE LINKS BEHAVE SIMILAR TO AN ACTIVE LINK THAT CHANGES LENGTH. (2) AMORPHOUS 2D ROBOT COMPOSED OF SQUARE UNITS [6].

Through these different locomotion examples, we have demonstrated some of the potential for modular-expandable robots. We have successfully implemented three different forms of locomotion using the same modular hardware, which brings us significantly closer to realizing the behavior suggested in the original NASA concept video for an expandable robot. The possibility of linear actuation in expandable modules also has potential outside of the arrangements presented here. For example, other expanding modules such as the Hoberman Sphere could be deployed using linear actuation.

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