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Passive Legged, Multi-Segmented, Robotic Vehicle

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Abstract

The Passive-legged, Multi-segmented, Robotic Vehicle concept is a **simple** legged vehicle that is **modular** and **scaleable,** and can be sized to fit through confined areas that are slightly larger than the size of the vehicle. A specific goal of this project was to be able to fit through the opening in the fabric of a chain link fence. This terrain agile robotic platform will be composed of multiple segments that are each equipped with **appendages** (legs) that resemble oars extending from a boat. Motion is achieved by pushing with these legs that can also flex to fold next to the body when passing through a constricted area. Each segment is attached to another segment using an actuated joint. This joint represents the only actuation required for mobility. The major feature of this type of mobility is that the terrain agility advantage of legs can be attained without the complexity of the multiple-actuation normally required for the many joints of an active leg. The minimum number of segments is two, but some concepts require three or more segments. This report discusses several concepts for achieving this type of mobility, their design, and the results obtained for each.

Acknowledgements

Several persons contributed to this project and their work and imagination has contributed to the progress that has been made. Paul Klarer and Dave Shirey performed the design and analysis on some of the early concepts. Daniel Cde Baca, and Jim Buttz performed mechanical design and assembly and electrical assembly on the various concepts. David Yao contributed a design for the final concept explored here, the Push/Pull Concept (Linear Actuator Concept Two). And, Mark Reineke contributed many valuable comments and suggestions in his capacity as project mentor.

Introduction

The utility of robotic vehicles is limited by many factors, including the inability of many existing vehicle platforms to traverse terrain populated with both natural and manmade obstacles. To mitigate this limitation, much emphasis has been placed on autonomous behaviors, obstacle detection, and path planning, and navigation. These methods tend to be computationally intensive, and require significant complexity and power. Simple terrain features can still present an insurmountable obstacle to these systems. Some of these terrain features include; dense foliage, small ditches, sewer and drain-pipes, street curbs, and especially fences. In fact, manmade obstacles can be more significant than natural obstacles in many cases.

Most existing robotic vehicle platforms are wheeled or tracked. Wheels are a very efficient mode of mobility, but they are limited in the roughness of terrain that they can traverse and they lose their effectiveness as the vehicle scale is reduced. Using tracks can increase rough terrain mobility over that attained by wheeled vehicles, but drive complexity and inefficiencies are penalties. Legged vehicles can increase rough terrain mobility even more. Most legged vehicles have active legs, with multiple actuated joints. This makes them much more complex systems that require more processing, more actuators, more wiring, more power, and results in reduced reliability, less fault tolerance, and they are generally heavy and large. This project proposes to develop a simple, small, legged robotic vehicle that is very terrain agile and is small enough to gain access to normally denied areas by passing through chainlink fence fabric or other small natural and manmade openings. The discriminating feature of a Passive Legged Vehicle is that the **legs are not actuated**. They are only passive elements of the body that function to enhance the motion generated by a joint or actuator in body. Figure 1 is a drawing of a Passive Legged Vehicle. It shows four modules connected by a single axis of rotation joint and simple legs that are rigidly attached to the modules. Mobility is achieved by actuation of the joint causing the legs to push against whatever surface they are contacting, and, forward motion is dependent on differential friction. The leg must slide easier when pulled forward than it does when pushing backwards. Again, mobility is not generated by actuated joints in the legs, but by joints in or between body segments and is enhanced by the legs. In this concept, legs are any feature that is not actuated and functions to enhance motion.

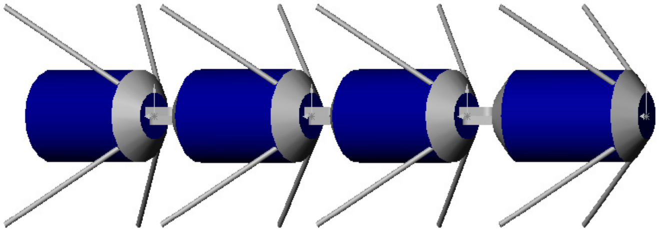


Figure 1.
A Four-Segmented Passive Legged Vehicle

Rotational Actuation Concept

Initially, two basic mobility concepts for the Passive Legged Vehicle were explored. Both of these involved the same modules but had different mechanisms to produce the relative module motion required. The first method was *single axis of motion*, in either the vertical or horizontal plane. Imagine an impulse traveling down a rope as the expected motion to produce mobility. The second method involved a *conical motion* that was essentially a combination of the motion in the horizontal and vertical plane. Here, each joint between the bodies would move in a manner to swing the module, immediately in front, in a circle. The *conical motion* seemed the simplest to implement, allowed easy control of direction, and was immune to vehicle orientation. Since the motion of one joint affected two modules, it was expected that all the joint motions would have to be sequenced in a coordinated manner to produce meaningful mobility.

The design conceived for the modules was two-inch diameter cylinders that are four inches long. This size and shape were selected primarily due to the symmetry of the shape, the smoothness (to not catch on obstacles), the small diameter (to pass through a chain link fence), and the length (needed for components that are primarily long and narrow). The joint motion for the modules was selected to be +/- 20 degrees from center. This was based on the motion specification of available spherical bearings, and on module volume, spacing, and interference considerations.

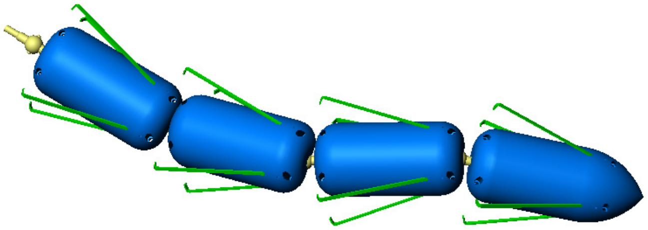


Figure 2.
Rotational Actuation Conceptual Design

Figure 2. is a representation of the Passive Legged Vehicle Rotational Actuation conceptual design. There are three traction modules and one lead module in the figure. The traction modules contain; a motor, batteries, control circuit board, inner-module communication electronics, and drive mechanism. The lead module is free to contain batteries, a control circuit board, sensors, or remote communication electronics. Actuator-linkage arms connect the modules in the figure. One of these arms is visible protruding from the rear module. The rear unit will not have this arm (as there is nothing to attach it to), but appears due to the software assembly of the vehicle, by simply adding copies. This does illustrate that to perform the analysis, some design detail was involved prior to subjecting the model to dynamic analysis.

Concepts, and Analysis

SolidWorks was used to develop the solid models for the dynamic analysis. The models were made with as much detail as possible to provide accurate mates for the adjoining parts. This was required for accurate relative motion and interaction of the models for Dynamic Designer. Changes were easily made to the models and the analysis was repeated as needed for each concept. A rough estimate of the weight and weight distribution of the modules was made to allow analysis to begin. Then, components were designed or selected, and the estimate was refined. Therefore, analysis was performed on solid models that were also basic functional designs (although unproven) for the two concepts of motion; *conical* and *single axis*. The two concepts contained the same basic components, with the exception of a axis of motion limitation device in the *single axis* concept.

Dynamic Designer was employed on the solid models using different constraints to produce results for several different scenarios. The analysis was intended to determine the sequencing of actuation required to produce meaningful motion for both concepts. It was determined that some actuation sequences failed to produce forward motion and some produced slight reverse or sideways motion. But, the results of the analysis predict that joint motion, sequenced 90 degrees out of phase from the previous modules joint, will produce meaningful forward motion for both horizontal and vertical *single axis* planes of motion. The analysis for the *conical motion* concept has not revealed a successful method for producing forward motion. The analysis indicated a sideways bias to the motion produced. It could be the result of the lead module's nose touching the surface and adding a nonsymmetrical frictional force, or the effect of the same rotation direction of all the traction modules. Also, only three modules were assembled into the model for the analysis. Four were used for the *single axis* analysis. Further *conical motion* analysis is needed to determine a sequence of motion that will produce forward motion without the sideways bias. Dynamic Designer *.avi files were made of the analysis to document the results.

Design and Construction

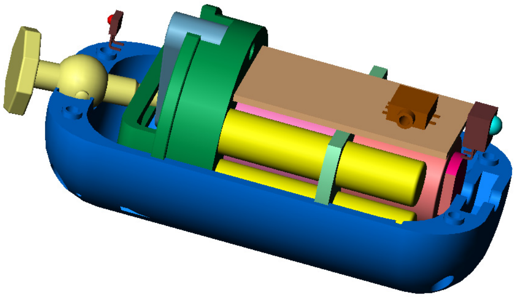


Figure 3.
SolidWorks Assembly Model

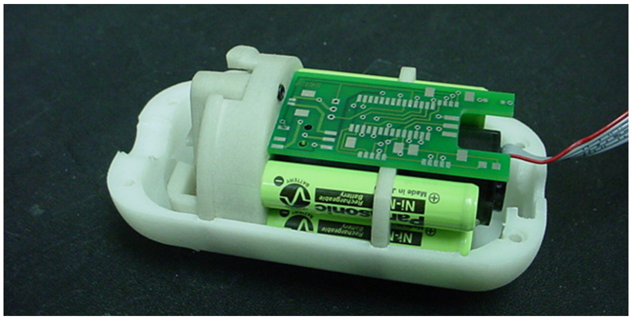


Figure 4.
Prototype Assembly

Figure 3. is a SolidWorks assembly model showing most of the internal components. The assembly is made by drawing the individual parts in 3D and mating them together to form the assembly. In this case the batteries and motor are drawn to scale and mounting and actuation components are designed to match. This allows for efficient packaging of the components and for interference check of the rotating components. After dynamic analysis indicated how to achieve successful coordinated motion, the part files were sent to a shop that uses the files with a laser sintering process to rapidly and inexpensively produce the individual parts. Figure 4. shows actual assembled parts for comparison to the SolidWorks assembly of Figure 3. Figure 5. shows some of the laser sintered prototype parts prior to assembly.

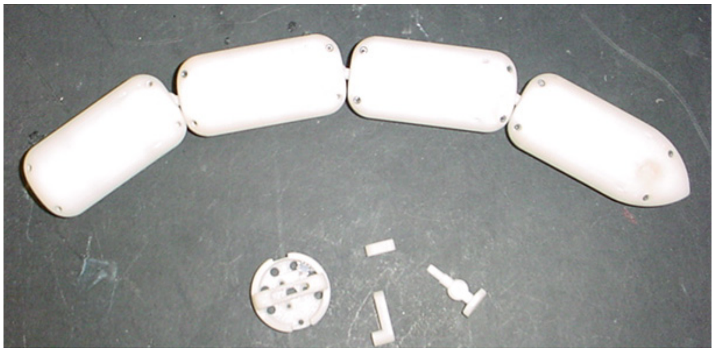


Figure 5.
Laser Sintered Prototype Parts

Electrical design was completed for the control electronics of the traction modules and a printed circuit board was designed. A smart charging circuit was designed for the NiMH batteries, and a printed circuit board was populated and tested. Infrared was selected for the inter-module communication, required to sequence each module to the others. With these details determined, the plan was to conclude final assembly of all mechanical components, perform electrical assembly of the electronics, write the microprocessor software, and conduct operational testing of all of the subsystems. The goal was to achieve the coordinated motion needed to produce forward mobility and to demonstrate penetration of a chainlink fence, using the single axis of motion concept. Then for the conical motion concept, further analysis would be conducted to determine if a method could be found to generate meaningful motion.

Results and Conclusions

It was concluded, that based on the analysis performed, that the *single axis motion* would work in either the vertical or horizontal axis, with joint motion sequenced 90 degrees out of phase, using at least four modules linked together. Although analysis has not confirmed that conical motion will produce purposeful locomotion, ideas have been developed that need to be analyzed prior to proceeding with or discarding the concept.

Before proceeding, attention was directed to leg and foot design. It had become more evident that the design of the leg and the foot for these two concepts was very important. There are several design characteristics important for the design of the legs and feet. The legs must fold along the body to allow penetrating a two-inch opening (chainlink), yet the legs must not collapse when pushing. The foot needs to augment motion on all types of soils and surfaces, yet the foot cannot impede passing through the two-inch opening. There were questions such as: How many legs? At what angle? How stiff? How attached to the body?

After thinking about the problem of the legs and trying to determine an analytical method to answer these design questions, it became quite apparent just how important the design of the legs was to the mobility and operation of these concepts. Another concern was that the use of legs that are angled backwards (probably needed for any meaningful functionality) could inhibit the vehicle from going backwards. This would be a serious concern for some missions.

These musings prompted an overall reevaluation of these concepts prior to committing further to their development. In contrast to the simple design envisioned for the Passive Legged Vehicle, this design was becoming complex. There was a need for a controller in each traction unit to control the phase of the actuation of that unit relative to the other ones. There was a need for communication between the units. **Each traction unit (every one but the lead unit) required a controller, inter-unit communication, batteries, motor, switches, encoder, and drive mechanisms. They were full and heavy! There was no room for payload except in the lead unit. And, the design of the legs and feet was critical for these concepts.**

By considering each of the serious concerns of these two concepts (**serious impact of leg and foot design, payload space, inter-unit communication, weight of each module, and the general design complexity)**, other concepts were conceived that could mitigate these concerns. In the time left to the project, it was felt that it was of primary importance to develop a mobility concept that would be simpler and would have a better chance of success. This redirection is discussed in the remainder of this report.

Push Pull Concept

The new concepts involved expanding and contracting the space between modules (**push**ing them apart and **pull**ing them together). One of these concepts involved having a motor only in the rear unit that pulled a cable strung through the center of the other units and terminated in the lead unit. The spaces between the units would have a spring between them. The motor would contract the string of units by compressing the springs between them and the springs would increase the length of the string when the motor released the tension.

Another concept also had the motor in the rear unit and a reciprocating push rod connected to a lever in the next unit. The other side of the lever was connected to the lever of the following unit and so on. The purpose of the lever was to amplify the motion to make up for the distance lost in expanding the distance between multiple units. To summarize, the rear unit generated a push/pull motion of a rod that actuated a lever in the next unit to expand and contract the distance between the units.

The idea of distributing rotational motion from one unit to all the others was also considered. This rotational motion would be used the same as if a motor were in each unit to actuate a mechanism to produce compression and expansion of the string of units or to produce the sequenced back and forth motion needed for the original concepts.

All of these concepts addressed the weight and volume concerns of having a motor in each unit, and therefore provided increased payload fraction. They also eliminated the need for communication between the units and the need for rotational sensors to synchronize the relative motion of the units. But, they still depended on legs with feet, to varying degrees, to generate differential friction for motion. Therefore, the complexity of designing legs and feet to achieve adequate mobility remained.

Our efforts to address the leg and foot analysis and design issues were stalled. Either design tools and methods needed to be identified and applied, or other mobility methods that did not depend on the legs for differential friction for motion had to be conceived. A concept was developed that indeed is not strongly dependent on legs for motion. This concept is based on equal friction between the units and the surface resulting in equal frictional forces from each unit, and sequentially moving only one unit at a time to generate forward motion. The vehicle can also go in reverse by reversing the sequence.

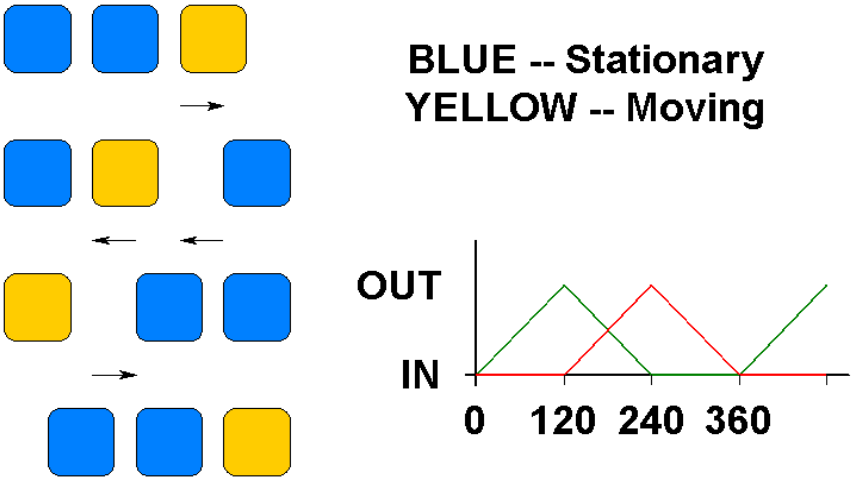


Figure 6.
Leg Independent Concept

Figure 6. depicts a concept for motion that does not depend on the legs to provide different friction for different module motion directions. It is based on having the same frictional forces from each module and increasing module separation in a manner where only one module at a time is in motion while the other modules remain stationary. Expanding and contracting the distance in the proper sequence will result in meaningful motion. In Figure 6. the arrows show what joint is in motion relative to the center module. And the graph on the right shows the motion (IN or OUT *versus* phase angle, or simply time) of the two joints of the three modules on the left. Three modules are the minimum for this concept of motion. But the motion depends on equal friction produced by each module, and the side with the fewer modules should move relative to the others. There are questions about different friction encountered during transition from one surface to another. Ways to address this concern include linking more than three modules together or designing legs that will augment the frictional bias. But the design of these legs will not be as critical because the legs will only augment or equalize the friction independent of the surface, and are not vital to the motion.

Another point addressed by this concept was the complexity of the previous designs. To produce the proper phasing of the joint motion, they required a processor in each module, a method to sense the position of each joint, and a method to communicate this information to each module’s processor. A method of sequencing the joint motions mechanically could simplify the design. Also, centralizing the motion generation of two joints in one body would allow a three-module system with two of the modules available for payload or other functions. This reduced the complexity and the weight of the system and increased payload fraction at the same time. Generating the motion mechanically allowed the mechanical design to be decoupled from the electrical/software design, and therefore provided faster testing and evolution of the motion generation mechanism.

With the new concept, there is no longer a need to lift the preceding module and its battery. This reduced the size of motor required and allowed the battery selection to be revisited, resulting in a smaller battery pack being selected. This further reduced the module's weight and the volume required for the components.

Cam Actuator Concept

Figure 7. illustrates the key components of a mechanical method to generate the sequenced push/pull motion. This method is based on a two-lobe cam with two double acting cam followers. As the cam turned, it would push one inner surface of the cam follower. As the lobe of the cam passed, the cam engaged the other surface and began pushing in the other direction. Then the lobe would enter into the notched portion of the cam follower, and there would be no contact with the cam follower, and the cam follower would remain in its current location. The lobes of the dual cams were 120 degrees out of phase to provide the action depicted in the graph of Figure 6.

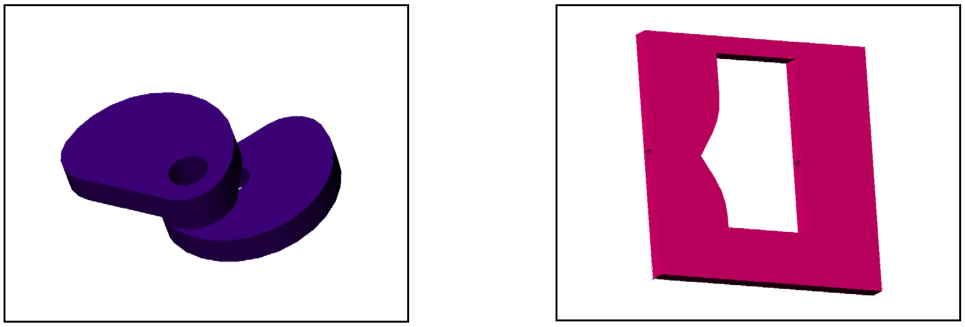


Figure 7.
Cam and Cam Follower

Design and Construction

Figure 8 shows the top and bottom half of a SolidWorks model of the body for the traction module. On the left is the battery with one of the cam followers and on the right are the motor (seen through partially transparent body), the cam, and a cam follower. The method of actuation is a rod that attaches to the cam follower and is anchored in the forward and rear modules. The action is a push/pull motion of the modules, verses a rotating or back and forth motion of the earlier concepts.

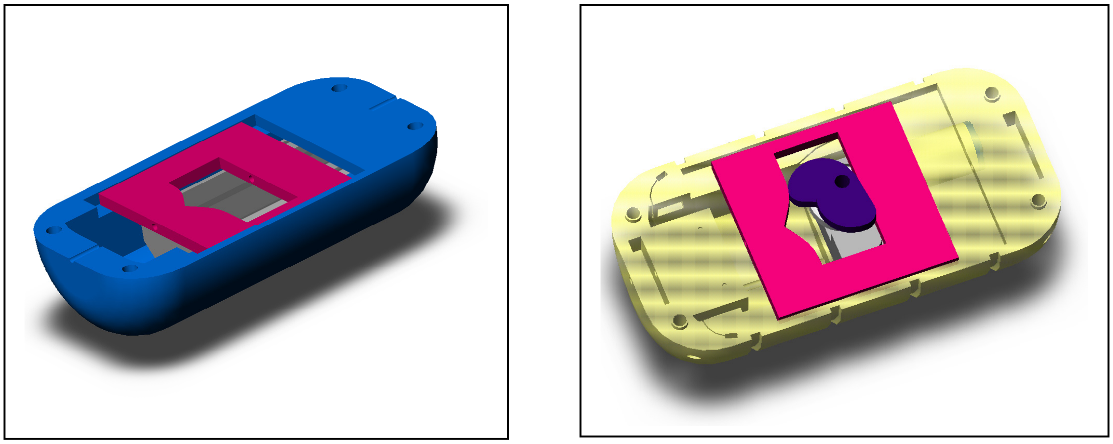


Figure 8.
Body Assemblies

The detailed design of all of the mechanical parts was completed using SolidWorks, and rapid prototype parts were ordered. Steering, although not addressed in the test model, was considered. Actuator rods were included in the design for that purpose. Figure 9 is a SolidWorks assembly model of the Push-Pull concept vehicle. The center rod is the rod attached to the cam followers that produce the sequenced back and forth motion, and the two side rods are for future steering capability.

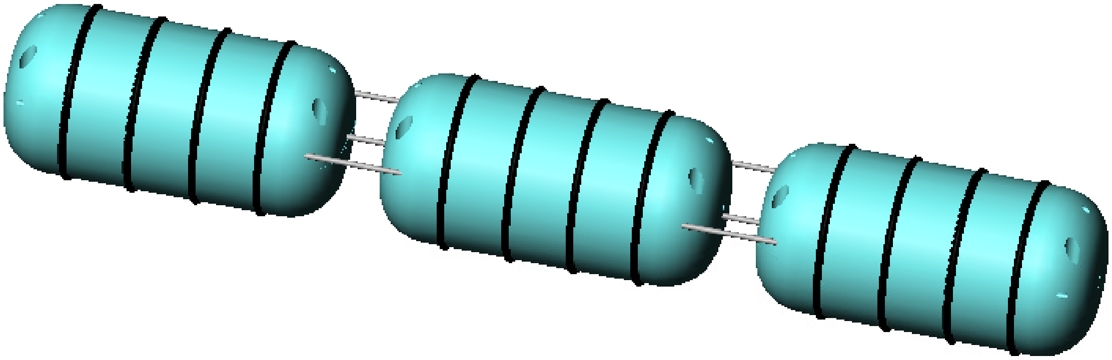


Figure 9.
Cam Actuated Push-Pull Concept Vehicle

The vehicle was assembled and tested to verify that locomotion could be achieved. Figure 10. is a photograph of the assembled vehicle. Note that the body has black rings installed. These are O-rings that were installed to augment the friction for operation on smooth slick surfaces.

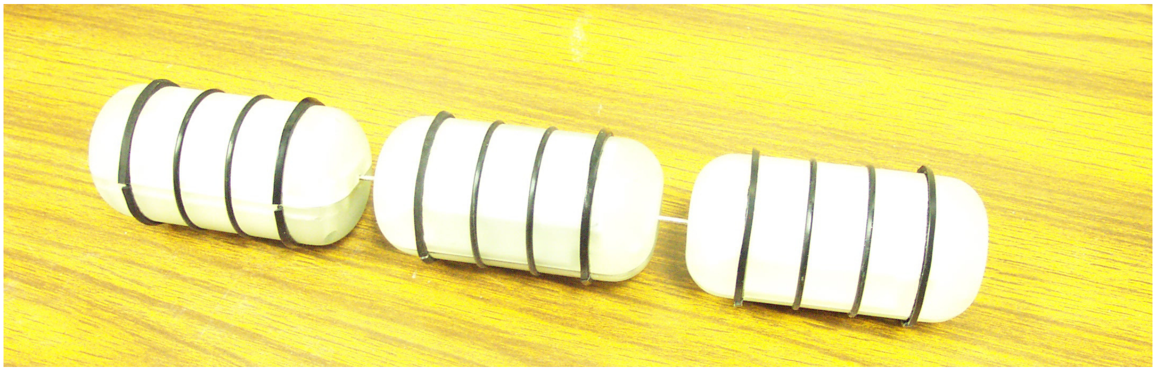


Figure 10.
Cam Actuated Push-Pull Vehicle

Results and Conclusions

The testing confirmed that the vehicle does produce the expected forward locomotion. There were characteristics revealed that need to be addressed. The stroke **length** of the cam actuator is on the order of **¼ inch**. This results in **very slow progress**. At 7.4 volts, the current required was about 125 mA. The battery that was selected that fits in half of one of the bodies is a 7.4V at 700 mAh. This means the vehicle would operate for about eight hours and travel a maximum total distance of about 600 feet on one battery.

Finding a method to increase the stroke length will increase the vehicle speed. Also, the concern about uneven friction from different surfaces was proven to be valid. If one of the modules encountered an obstacle (even a small stone), it would upset the differential friction required and forward motion would cease. This directs the development toward solving these two main concerns. The stroke length must be increased to provide a usable operating velocity, and a method of countering the problem of obstacles and uneven friction must be found. Nevertheless, *successful forward motion was achieved,* and this concept has resulted in a simpler design, with increased payload space.

Linear Actuator Concept One

A lead screw or linear actuator can be used to produce a significant distance of travel. It was decided to search for available linear actuators, and to conceive methods to design linear actuators if they could no be found. In discussions with the team, the idea arose to attempt to combine the forward motion and the steering actuation into a single mechanism for space efficiency. If all the actuation mechanism were kept in a single unit and if steering were incorporated, four individual actuators could be used to provide both steering and forward motion. Two actuators were for the front module, and two for the rear. If the actuators extended and contracted equally, the vehicle would go straight. Note that the actuators are attached to what were the steering rods seen in figure 9, and there is no center rod. Steering could be achieved by shortening the stroke on the side of the intended steering direction. It was felt that this concept using four actuators would be capable of producing a force of several ounces and a stroke of about one inch.

Design and Construction

No source for an acceptably small actuator could be found. Therefore a miniature linear actuator was designed. Figure 11. shows the assembly model of a dual miniature actuator. The actuator assembly consists of two motors and gears that drive a threaded rod. A follower is threaded to match the rod and moves the push/pull rod attached to the next module. Two of these fit back to back in one half of the center module. Figure 12. shows the mount for this arrangement.

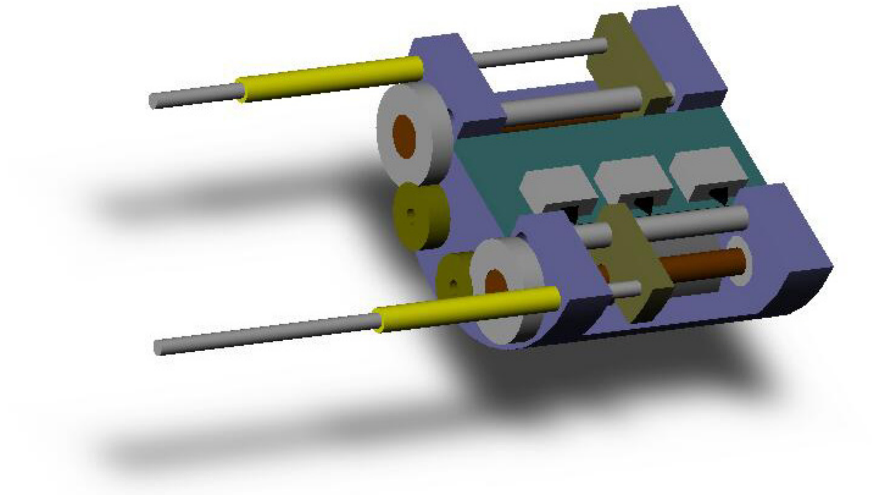


Figure 11.
Dual Miniature Linear Actuator

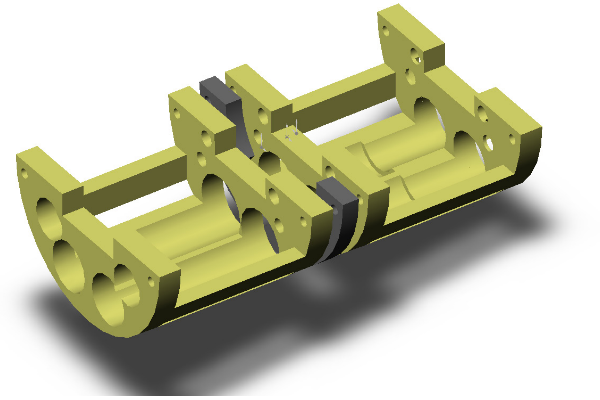


Figure 12.
Back-to-Back Dual Actuator Mount

Using linear actuators brings other requirements: limit sensing, controller, and motor driver. Notice the three limit switches in the middle of the assembly of Figure 11. Only one side's switches are shown, but there are three more switches that are not shown on the other side. The switches are used to provide an indication of the extension and retraction limits and the middle switch can be used to sense mid-stroke for steering limits.

Figure 13 is a photo of the center module with the actuators exposed, showing the four motors and associated hardware. The control board and mated limit-switch board can also be seen. Also notice the brass, threaded followers that are connected to the actuator rods that move the adjacent modules in or out. In Figure 14, the control board and the limit-switch board are shown separately for clarity. The control board contains the microprocessor, motor drivers, and voltage regulation circuits. The two long tabs on the right side of the board are contacts for the battery. The limit-switch board has provision for the mid position sensing switches, but they are not installed because steering was not implemented at that time. The two boards were designed to connect together as seen in Figure 13. This provided a compact unit that seated in the middle of the actuator. The only wiring required was to the motors. The actuator was assembled and tested, and it was determined that it provided about 0.8 inches of stroke and greater than one pound of force.

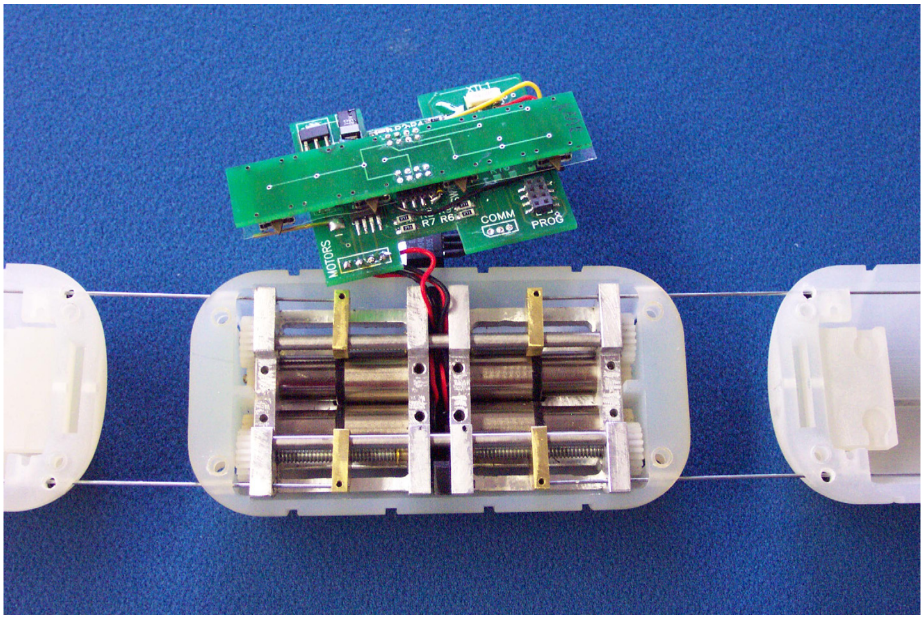


Figure 13.
Actuators With Control and Limit Switch Boards Removed

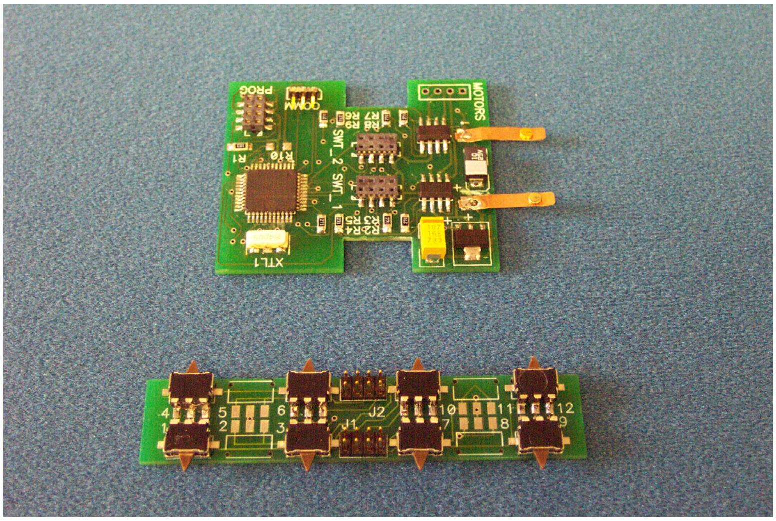


Figure 14.
Control Board (top) and Limit Switch Board (bottom)

Results and Conclusions

As seen in the above figures, the parts for this concept were designed and built and a prototype was assembled. The electronics was tested and code was written for the microprocessor. The first design was meant to address the forward mobility only, and then the steering features (middle switches of the switch board, the steering code, and a way to command steering) would be added. There some difficulties in packaging that were overcome by leaving the battery out and using external power. Using the same O-rings to augment friction, the vehicle was tested to confirm mobility. Mobility was achieved in a limited fashion. A major problem was the different speeds of the actuators pairs that were driven by the same motor amplifier. Only two motor amplifiers were included to simplify the design and were to be added later when steering was included. The different speeds of the actuators could have been solved with individual motor amplifiers. But, the vehicle would only operated a few strokes before the mismatch of the actuators was too great to produce mobility. The stroke length was initially as expected and if the design were refined, this method of mobility could be the basis for a vehicle of this type.

Linear Actuator Concept Two

Another method of increasing the stroke length has the potential of providing about two inches of stroke. Figure 15. illustrates the detailed mechanical layout of this concept. It includes two linear actuators facing opposite directions. The actuators consist of a motor driving a capstan that pinches a rod against an idler wheel. The rod is driven, by friction, in and out of the module. This method also requires limit sensing, a controller, and motor drivers. (Schematics and microprocessor code are located in the appendix). This actuation method does not incorporate steering. But, one of the dual actuators of Figure 11. mounted in the rear module could perform this function.

All of the mechanical details were designed using SolidWorks and rapid prototype parts were procured. The battery and controller/motor driver board is located in the other half of the module. This method also incorporates the advantage of having all the actuation and control in a single module, leaving the front and rear module available for payload. Although steering actuation will be located in one of these modules, this only presents a minor increase to the complexity of this concept as compared to the previous concept (Linear Actuator Concept One), yet it has the potential of doubling the actuation stroke. And area of concern is the friction drive of the actuator rod. A coating or gear teeth on the rod and driven wheel may be needed. The project ended prior to complete assembly and testing of this concept.

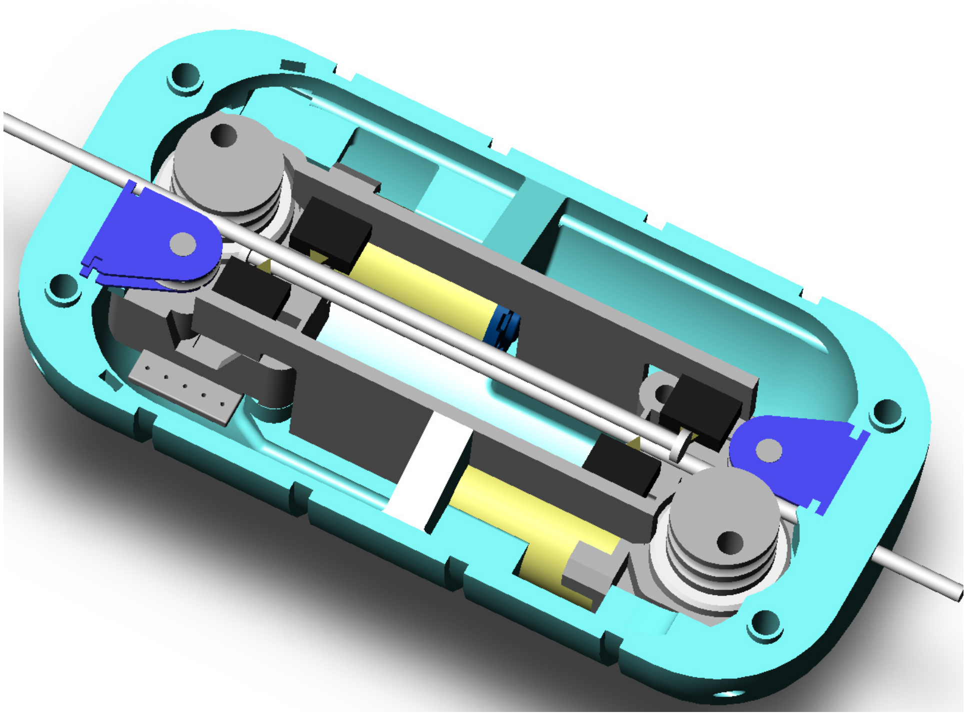


Figure 15.
Linear Actuator Concept Two

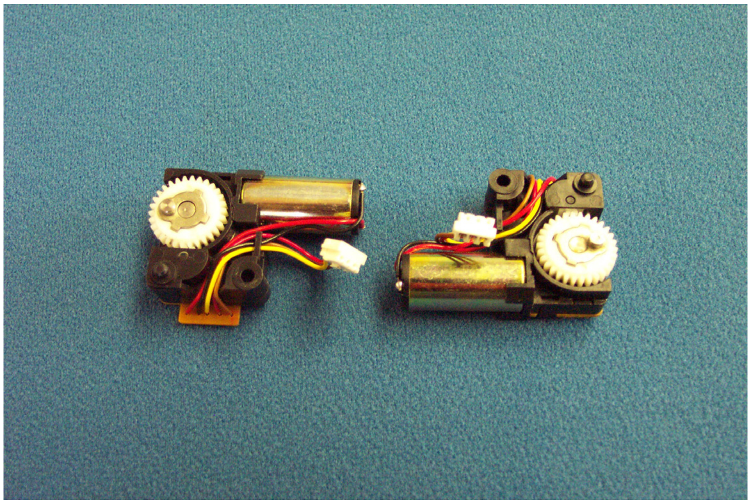
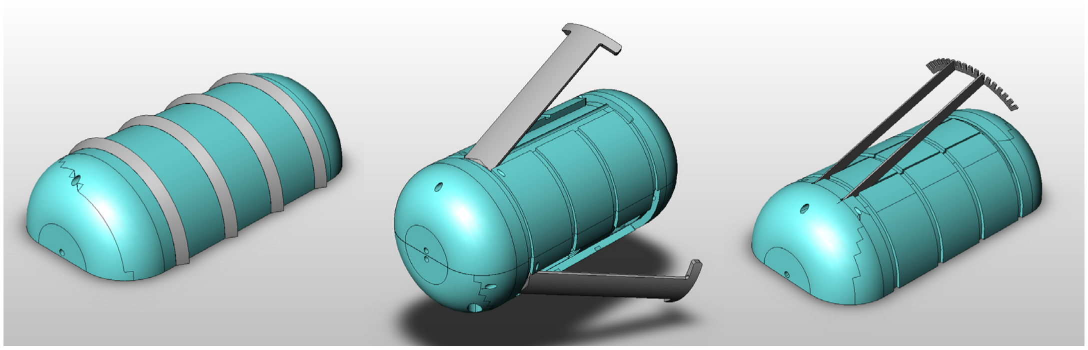


Figure 16.
Two Motors used in Linear Actuator

Leg Development

Leg design has varying importance for the different concepts. The initial concepts using *Single Axis* or *Conical* actuation depended strongly on the leg design. For these concepts the legs were the design feature that produced differential friction or traction force. The effectiveness of their design had a strong impact on the mobility of the vehicle. Internet searches seeking similar endeavors, yielded several entries regarding similar principles. However, these all described “snake” and/or “worm” characteristic motion, but they were only similar in that they moved without driven wheels or limbs. Due to the limited time left in the project and facing the complexity of the design of the legs and for other previously mentioned reasons, other concepts that did not have strong dependence on the leg design were explored.

A number of leg concepts were considered, but as previously mentioned, the leg development was deferred in preference to striving for success in the development of a method of mobility. The purpose of legs in this type of vehicle is to augment mobility. And in this project, a leg was any method to accomplish this. The simplest method to augment mobility would be to apply a friction coating as a skin to the body segments. This would lend adhesive traction, and aid the device in both forward and reverse movement. Alternately, passive rings can be applied around the circumference of the bodies (Figure 17. A) to improve mechanical traction. Adding both complexity and perhaps capability, would be appendages (legs) that had mechanical traction aids such as small feet or rakes (Figure 17. B & C).



(Fig. A) (Fig. B) (Fig. C)

Figure 17.
Leg Concepts

The method illustrated in Figure 17. (A) was used and can be seen in some of the previous figures. Two variations of this concept were tried; one used simple O-rings and another use a seal that had a wiper that would fold in one direction and remain open in the other. This produced a frictional bias in one direction, whereas the O-ring just functioned to produce more friction without a bias. Both yielded increased friction, but it was not clear that the seal was better for all surfaces.

Moving through sand presents other issues for leg design. The semi-fluid nature of sand renders a friction coating largely ineffectual. Cleats or rakes (see Figure 17 (B&C) at the end of longer appendages likely would prove more capable. Additionally, legs could be used to maintain orientation or for self-righting.

Final Conclusions and Recommendations

The *single-axis* concept, that was originally pursued, was shown in dynamic simulations to produce forward motion when the module joints were sequenced in the proper manner. That version was not pursued to demonstration due to recognized problems with weight, complexity, and lack of payload volume. A motion sequence for efficient forward motion for the *conical* concept was not found, but a solution was not pursued because this concept suffered from the same problems. The Push/Pull concepts showed promise for producing simple mobility and addressed the payload, weight and complexity issues. Several versions were designed and some were built. **Forward motion has been demonstrated for the *push-pull* concept**.

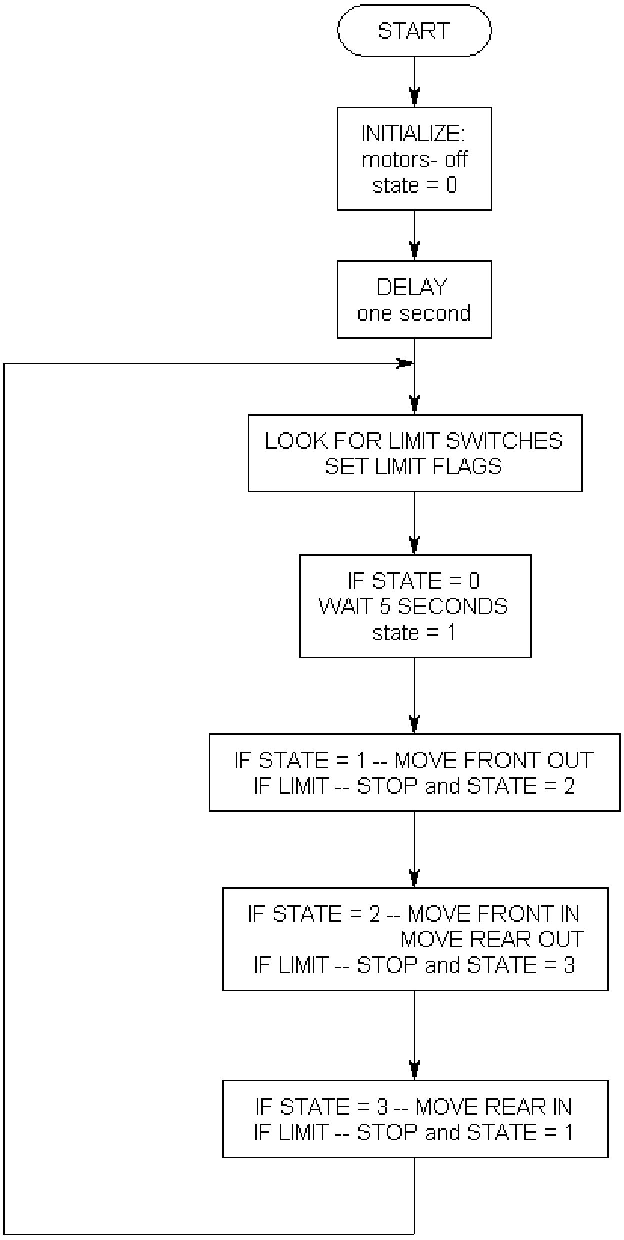
As the project ended, the design for the Linear Actuator Concept Two was not completely built and tested. Therefore, no confirmed conclusions can be stated about its performance. It does have of the promise of producing the longest stroke of the concepts that have been conceived, and therefore may be very effective at producing mobility. But, as with most designs, it is expected that design iterations would be required to arrive at a mission ready design.

The Linear Actuator Concept One was built and initially tested during the final days of the project. The electrical schematic, and microprocessor code can be found in the appendix. It does indeed produce the expected linear actuation stroke, but improvements are need in its design. The initial control electronics only included two motor h-bridges. This was done for simplicity and for space savings. The actuators exhibited different internal friction and therefore different actuation rates. And since they were driven in pairs, one would reach full extension (or retraction) and trip a limit switch before the other could reach full extension or retraction. This caused a bias in the direction of traveled and finally resulted in a very short stroke as the pair became further separated in stroke. In retrospect, it would have been wiser to have taken the time and addressed the steering issue at the same time as the forward mobility issue and included the additional h-bridges.

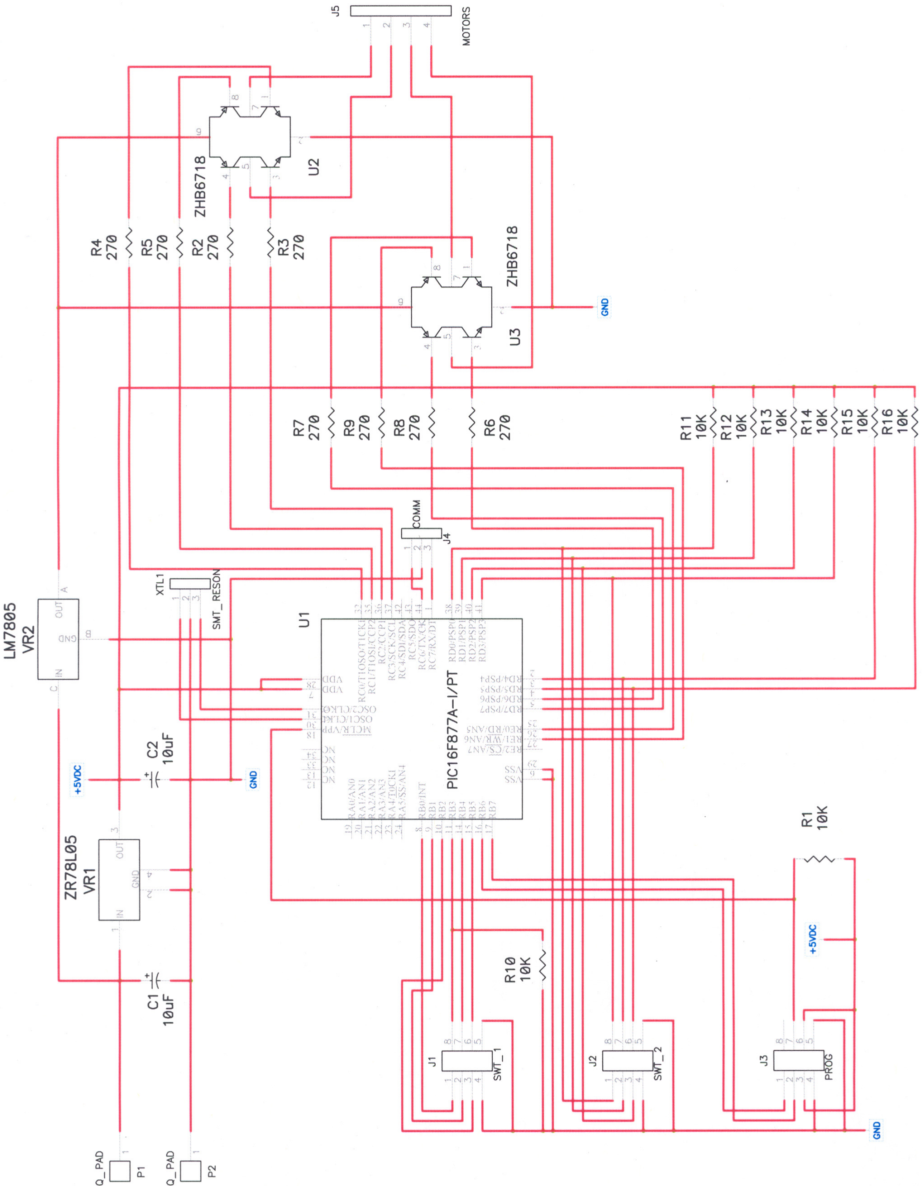
The Push/Pull concept does work, and the new concepts show promise in improving their functionality. Dependence on equal friction for mobility does have issues that need to be addressed. Either leg concepts need to be developed, or ganging more than three units together and coordinating their movement need to be explored. Although the goal of crawling through a chain link fence was not demonstrated, it is felt that the goal was close and could be attained with minor refinements of this concept.

Appendix

Block Diagram of Microprocessor Control Code:



Schematic Diagram of Linear Actuator Control Board:



Microprocessor Code Listing:

```
/////////////////////////////////////////////////////////////////////////
////                             PLV.C                               ////
////                            16F877A                              ////
////                                                                 ////
////  This is the control program for the two linear actuator based  ////
////  Passive Legged Vehicles.                                       ////
////                                                                 ////
////                       D. HAYWARD                                ////
////                       LAST CHANGE: 09/05/2003                   ////
////  PIO:                                 CONN-PIN                  ////
////     RB0   SWT9 OUT-RR      INPUT      SWT_1-1                   ////
////     RB1   SWT11 MID-RR     INPUT      SWT_1-2                   ////
////     RB2   SWT10 IN-RR      INPUT      SWT_1-3                   ////
////     RB3   SWT7 IN-LR       INPUT      SWT_1-8                   ////
////     RB4   SWT8 MID-LR      INPUT      SWT_1-7                   ////
////     RB5   SWT9 OUT-LR      INPUT      SWT_1-6                   ////
////     RB6   PROGRAM PIN      INPUT      PROG-1                    ////
////     RB7   PROGRAM PIN      INPUT      PROG-2                    ////
////                                                                 ////
////     RC0   F_MOTOR_D        OUTPUT    H-BRIDGE PIN 1             ////
////     RC1   F_MOTOR_B        OUTPUT    H-BRIDGE PIN 8             ////
////     RC2   F_MOTOR_A        OUTPUT    H-BRIDGE PIN 4             ////
////     RC3   F_MOTOR_C        OUTPUT    H-BRIDGE PIN 3             ////
////     RC4                                                         ////
////     RC5                                                         ////
////     RC6   RS232_TX         OUTPUT     COMM-1                    ////
////     RC7   RS232_RX         INPUT      COMM-3                    ////
////                                                                 ////
////     RD0   SWT6 IN-RF       INPUT     SWT_2-1                    ////
////     RD1   SWT5 MID-RF      INPUT     SWT_2-2                    ////
////     RD2   SWT4 OUT-RF      INPUT     SWT_2-3                    ////
////     RD3   SWT1 OUT-LF      INPUT     SWT_2-8                    ////
////     RD4   SWT2 MID-LF      INPUT     SWT_2-7                    ////
////     RD5   SWT3 IN-LF       INPUT     SWT_2-6                    ////
////     RD6   R_MOTOR_C        OUTPUT    H-BRIDGE PIN 3             ////
////     RD7   R_MOTOR_A        OUTPUT    H-BRIDGE PIN 4             ////
////                                                                 ////
////     RE0   R_MOTOR_D        OUTPUT    H-BRIDGE PIN 1             ////
////     RE1   R_MOTOR_B        OUTPUT    H-BRIDGE PIN 8             ////
////                                                                 ////
////                    MOTOR CONTROL MATRIX                         ////
////              A    B    C    D       ACTION          COMMENT     ////
////              0    0    0    0        STOP      VOLTAGE ON MOTOR ////
////              0    1    0    1        CW                         ////
////              1    0    1    0        CCW                        ////
////              1    1    1    1        STOP      GND ON MOTOR     ////
////              1    1    0    0        STOP     MOTOR FLOATING    ////
////              X    0    X    1        NEVER    WILL SHORT DRIVER ////
////              0    X    1    X        NEVER    WILL SHORT DRIVER ////
////        NOTE: TURN OFF C (LOW) BEFORE TURNING ON A (LOW)         ////
////              TURN OFF D (LOW) BEFORE TURNING ON B (LOW)         ////
////                                                                 ////
////  clock: 4MHz  cycle time: 1us                                   ////
////                                                                 ////
////  flags: XT,WDT-OFF,PUT,CP-OFF                                   ////
////                                                                 ////
////  COMPILED WITH CCS VER 3.170 (ccsinfo.com)                      ////
/////////////////////////////////////////////////////////////////////////




#include <16F877A.H>
```

```
#use Delay(Clock=4000000)


#use rs232(baud=19200,xmit=PIN_C6,rcv=PIN_C7)

// function prototypes
void r_motor_in(void);
void r_motor_out(void);
void r_motor_stop(void);
void f_motor_in(void);
void f_motor_out(void);
void f_motor_stop(void);

main()
{
   char     f_in_flag;
   char     f_out_flag;
   char     r_in_flag;
   char     r_out_flag;
   char     state;
            //
            // state    action
            //    0     STOP
            //    1     FORWARD OUT
            //    2     FORWARD IN & REAR OUT
            //    3     REAR IN


   state = 0;
   port_b_pullups(TRUE);
   output_high(PIN_C2);    //F_motor A OFF
   output_high(PIN_C1);    //F_motor B OFF  ---- STOP front motor
   output_low(PIN_C3);     //F_motor C OFF
   output_low(PIN_C0);     //F_motor D OFF
   output_high(PIN_D7);    //R_motor A OFF  ---- STOP rear motor
   output_high(PIN_E1);    //R_motor B OFF
   output_low(PIN_D6);     //R_motor C OFF
   output_low(PIN_E0);     //R_motor D OFF
 printf("PLV PROGRAM STARTED\n");
 delay_ms(1000);

// The following generates the sequence of module motion to produce
// forward motion:
//    forward module OUT
//    forward module IN AND rear module OUT
//    rear module IN

 While(TRUE)
 {
  r_out_flag = 0;
  if((!input(PIN_B0)) || (!input(PIN_B5)))
  {
   printf("\nREAR_OUT");
   r_out_flag = 1;
  }
  r_in_flag = 0;
  if((!input(PIN_B2)) || (!input(PIN_B3)))
  {
   printf("\nREAR_IN");
   r_in_flag = 1;
  }
  f_out_flag = 0;
  if((!input(PIN_D2)) || (!input(PIN_D3)))
  {
   printf("\nFRONT_OUT");
   f_out_flag = 1;
  }
  f_in_flag = 0;
  if((!input(PIN_D0)) || (!input(PIN_D5)))
  {
```

```
   printf("\nFRONT_IN");
   f_in_flag = 1;
  }
  switch (state)
  {
   case 0:
      f_motor_stop();
      r_motor_stop();
      state = 1;
      delay_ms(5000);
      break;
   case 1:
      if(f_out_flag != 1)
      {
        f_motor_out();
      }
      else
      {
        f_motor_stop();
        state = 2;
        delay_ms(500);
      }
      break;
   case 2:
      if((f_in_flag != 1) && (r_out_flag != 1))
      {
       if(f_in_flag != 1)
         f_motor_in();
       else
         f_motor_stop();
       if(r_out_flag != 1)
         r_motor_out();
       else
         r_motor_stop();
      }
      else
      {
       f_motor_stop();
       r_motor_stop();
       state = 3;
       delay_ms(500);
      }
      break;
   case 3:
      if(r_in_flag != 1)
      {
       r_motor_in();
      }
      else
      {
       r_motor_stop();
       state = 1;
       delay_ms(500);
      }
      break;
  }//end switch
 }//end while
}// end MAIN

r_motor_in()
{
   output_low(PIN_D7);     //R_motor A ON
   output_high(PIN_E1);    //R_motor B OFF
   output_low(PIN_D6);     //R_motor C OFF
   output_high(PIN_E0);    //R_motor D ON
}

r_motor_out()
{
   output_high(PIN_D7);     //R_motor A OFF
   output_low(PIN_E1);      //R_motor B ON
```

```
   output_high(PIN_D6);      //R_motor C ON
   output_low(PIN_E0);       //R_motor D OFF
}

r_motor_stop()
{
   output_low(PIN_D6);      //R_motor C OFF
   output_low(PIN_E0);      //R_motor D OFF
   output_high(PIN_D7);     //R_motor A OFF
   output_high(PIN_E1);     //R_motor B OFF
}

f_motor_in()
{
   output_low(PIN_C2);      //F_motor A ON
   output_high(PIN_C1);     //F_motor B OFF
   output_low(PIN_C3);      //F_motor C OFF
   output_high(PIN_C0);     //F_motor D ON
}

f_motor_out()
{
   output_high(PIN_C2);     //F_motor A OFF
   output_low(PIN_C1);      //F_motor B ON
   output_high(PIN_C3);     //F_motor C ON
   output_low(PIN_C0);      //F_motor D OFF
}

f_motor_stop()
{
   output_low(PIN_C3);      //F_motor C OFF
   output_low(PIN_C0);      //F_motor D OFF
   output_high(PIN_C2);     //F_motor A OFF
   output_high(PIN_C1);     //F_motor B OFF
}
```

Parts List for Control Board:

DESIGNATION	DESCRIPTION	PART NUMBER	MANUFACTURER
C1,C2	10uF, 16 V, TANT., CAP	ECS-T1CX106R	PANASONIC
J1,J2,J3	8-PIN, 2mm CONN	87340-0822	MOLEX
R1,R10-R15	10K,1206 SMT RES.		
R2-R9	270 OHM, 1206 SMT, RES		
U1	MICROPROCESSOR	PIC16F877-I/PT	MICROCHIP
U2,U3	H-BRIDGE	ZHB6718	ZETEX
VR1	5 VOLT REG., 200mA	ZR78L05	ZETEX
VR2	5 VOLT REG., 1A	LM7805	
XTL1	4 MHz RESONATOR	EFO-S4004ES	PANASONIC

Distribution:

1	MS0323	LDRD Office (01011)
1	MS1125	Bennett, Phil (15252)
1	MS1207	Reineke, Mark (05922)
1	MS1125	Hayward, David (15252)
1	MS1125	Buttz, Jim (15252)
1	MS1125	Cde Baca, Daniel (15252)
1	MS1125	Yao, David (15252)
3	MS1004	ISRC Library (15221)
1	MS9018	Central Technical File (8945-1)
2	MS0899	Technical Library (9616)