Simulation of an All Terrain Hexapod using Lego Mindstorms

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Abstract

Last year one of Graceland University's students did a project on the control of a hydraulic electro solenoid valve by a computer system. He set up the interface needed for a computer to run a hydraulic valve. The long term goal on which this project was based, was to build an all-terrain vehicle that doesn't use wheels. This vehicle would consist of a pick-up truck body sitting on a metal frame. The frame would be propelled by a remote control held by the driver and by 6 legs instead of wheels. Each leg would be a backhoe arm and each arm would be controlled by 4 hydraulic cylinders. That student established the interface, but did not have time to create or implement any algorithms for the control over the interface. He only had a single hydraulic valve for materials. This paper discusses the algorithms needed to propel a hexapod in 10 directions.

1.0 Overview

The goal on which this project is based is to produce a full sized vehicle that has the functionality of an insect. Last year one of my classmates designed the interface for a single hydraulic valve, one small piece of that larger goal. His project involved controlling hydraulic fluid so as to move in and out of a valve in the appropriate directions for one part of one leg in the overall design. This section introduces my project, involving Legos instead of full sized materials. [3]

1.1 Definitions

Pneumatic - of or relating to air or other gases.
Hexapod - having six legs or feet
Hydraulic - of, involving, moved by, or operated by a fluid, especially water, under pressure
Neutral - when all legs are perpendicular to the base and on the ground
Tripod – grouping of three legs represented by triangles in the diagrams of this paper

1.2 Introduction

Where would you go if you had a vehicle that could take you anywhere on land? Want to turn off the main road and take a short cut across the countryside? A hexapod vehicle could do just that.

Imagine a pick-up truck with backhoe arms, minus the shovel, in place of all four wheels with one under each door totaling six legs. It should look more like a gigantic insect than a pick-up truck. In this paper I illustrate 10 directional movements, outline the key action sequences, and briefly discuss my simulation of what can be accomplished by a hexapod using hydraulics.

How do the hydraulic cylinders move with a valve? If fluid is put in either the top or bottom end of the cylinder the piston will move out or in. As fluid is forced in one end, it must be forced out the other. This can also be done with pressurized air which is what I settled on for a Legos miniature prototype. The key idea is pressure.

The transfer of pressure in sequence will produce movement from several cylinders. Each cylinder must be synchronized to enable coordinated and stable movement. For this paper I watched video of other moving hexapods. I recorded what I observed in the leg movements and translated that as to how it would be represented in a 24 cylinder environment for a hexapod. [4]

1.3 Primitive Movements

Each leg movement can be described by two triangles. The corners of a triangle represent three different feet, both triangles for all six feet. Thus each movement of a triangle, or tripod, moves three feet in unison. In all figures that follow, the base lines of the triangles are all vertical. The left vertical line is the base of the left triangle. In some diagrams there is a blue triangle (these figures are in color) which denotes a set of legs in the air. Each seven stage diagram depicts a seven step cycle of motion. A pair of seven stage diagrams in a figure (like figure 1.3.1) illustrates related counter motions of one full step. Each stage 0 in every diagram is a neutral state. Neutral will be discussed later in this paper.

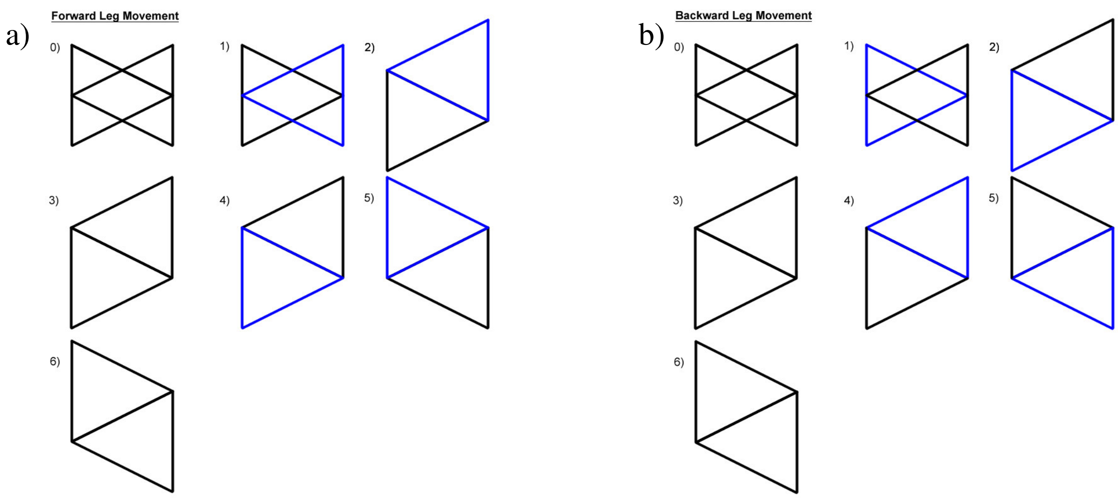


Figure 1.3.1: a) Forward, b) Backward

First you see the triangles sitting in neutral, stage 0. Next, one tripod is lifted off the ground and moved forward making a rhombus, stages 1 and 2. The lifted triangle is put down and the other is lifted off the ground, stages 3 and 4. It is moved forward and then placed back on the ground, stages 5 and 6. When moving forward or backward, it does not matter which triangle is selected to go airborne.

The triangle diagram for backward movement is similar to the forward one except that the opposite triangle is colored blue. The tripods will go through the same motions, but switching which one is raised will change the direction.

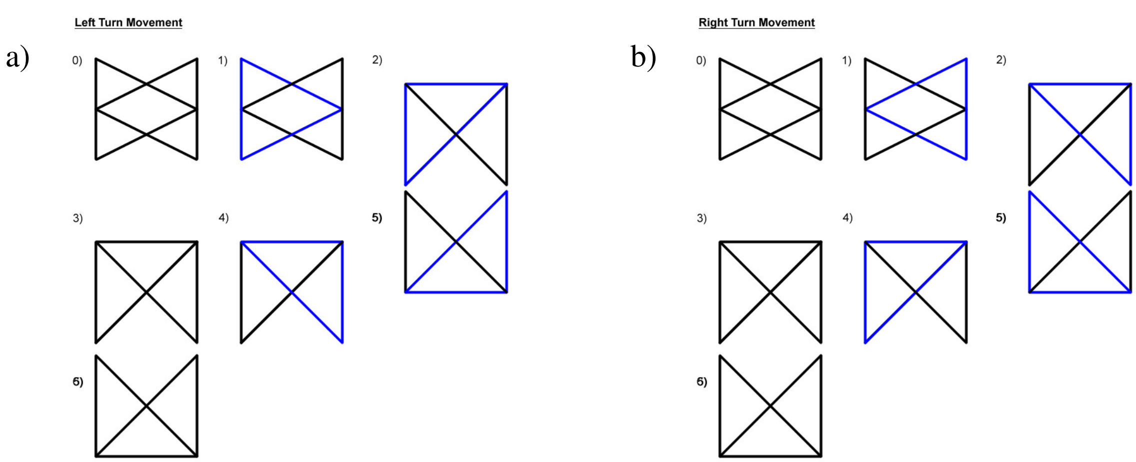


Fig 1.3.2: a) Left Turn, b) Right Turn

Figure 1.3.2 is harder to imagine than the simple forward and backward movement of Figure 1.3.1. First, the left tripod is lifted off the ground, as seen by the coloring in stage 1. Then the outside legs are moved backwards, and the inside legs are moved forward, as shown in stage 2. The outside legs of the neutral triangles, stage 0, are the base angles. The inside legs are the vertices. The movements change the equilateral triangles to more of an isosceles.

At stage 3 all legs have been placed back on the ground. Next, the right tripod is lifted and all the outside legs are moved forward while the inside legs are moved backwards, for stages 4 and 5. Finally, the legs are returned to the ground and the cycle repeats at stage 0.

As with forward and backward movements of figure 1.3.1, the left turn movements are the same as the right with one difference, switch which legs are airborne.

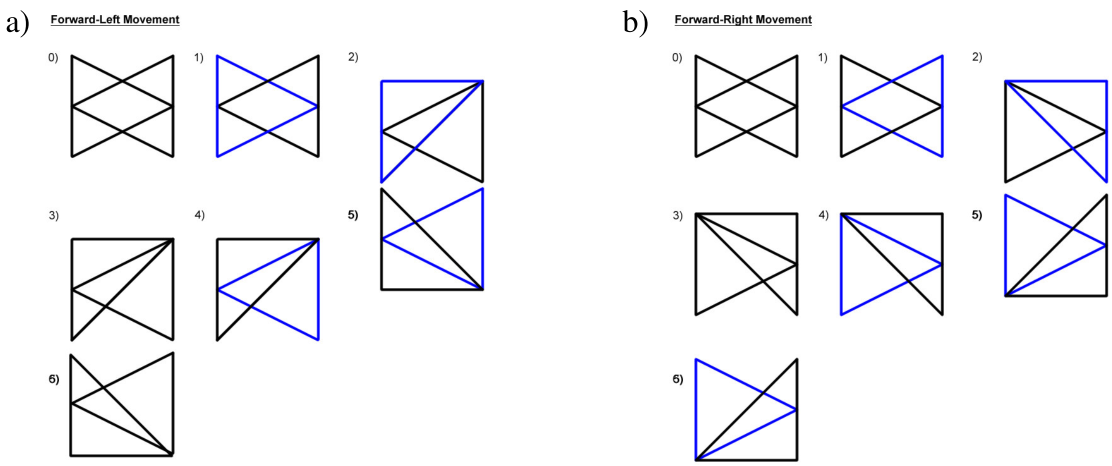


Figure 1.3.3: a) Forward Left, b) Forward Right

Figure 1.3.3a is an illustration of forward left movement. Like all movements, it starts in stage 0 at neutral. The left triangle is picked up, its base is moved down, and its vertex is moved up. The right triangle is completely moved down, stages 1 and 2.

All legs are returned to the ground and then the right triangle is picked up, stage 3 and 4. In stage 5 the right triangle is moved forward, the left base is moved forward and the left vertex is moved backward. When all legs are put down it is ready to repeat the cycle.

As the name suggests forward left movement is a combination of the forward and left movements. The corresponding triangle is selected and put through its directional movement. In this case the left triangle is selected, since it is forward left, and moved through left type movements. The opposite triangle is then put through forward movements. The right triangle is moving forward and the left triangle is moving left, thus forward left movement.

Figure 1.3.3 is a representation of forward right movement. Again, as with forward left movement, the right triangle is moving right while the left triangle is moving forward. To move the vehicle backward right or backward left simply switch which triangle is off the ground.

These triangles really helped me picture which leg was supposed to be where. Visually they help explain the simple differences in opposing directions.

The six legs allow the hexapod a variety of movement. If turning or moving diagonally does not achieve the desired affect the system enables strafing, sideways walking.

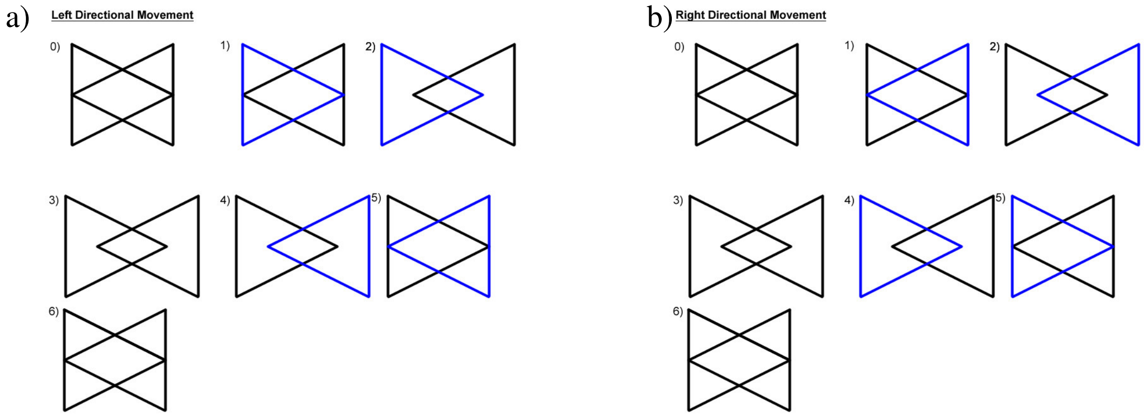


Figure 1.3.5: a) Left Directional, b) Right Directional

Figure 1.3.5 shows the leg states during a left strafe. The left triangle is picked up off the ground and moved to the left. The right triangle is moved to the right, stages 1 and 2. All legs are returned to the ground and then the right triangle is picked up, stages 3 and 4. The left triangle is moved in, or to the right, and the right triangle is moved to the left and then put down, stages 5 and 6. As with every previous movement, strafing right requires only a switch of which leg is in the air. [4]

1.4 Structural Dependencies

Ideally each cylinder should be capable of end-range motion. In other words, each cylinder is engineered to fully contract and retract at a given pressure. If a cylinder is still contracting and is impaired by the body material, eventually it will pull free from its fastenings. With Legos that would be merely a minor set back, but with a larger metal system it could mean time in the hospital and weeks of setback.

Though each cylinder is allowed end-range motion, limiting the range of movement is also important. In order to have efficient use of force, the lifting cylinder must not break the horizontal plane of its connection to the body.

Figure 1.5.1a shows the leg's position and each thin line, whether horizontal or diagonal, represents a plane that should not be broken. Figure 1.5.1a has two parts. The top part is how the legs should look. The lower part shows the legs breaking the described plane.

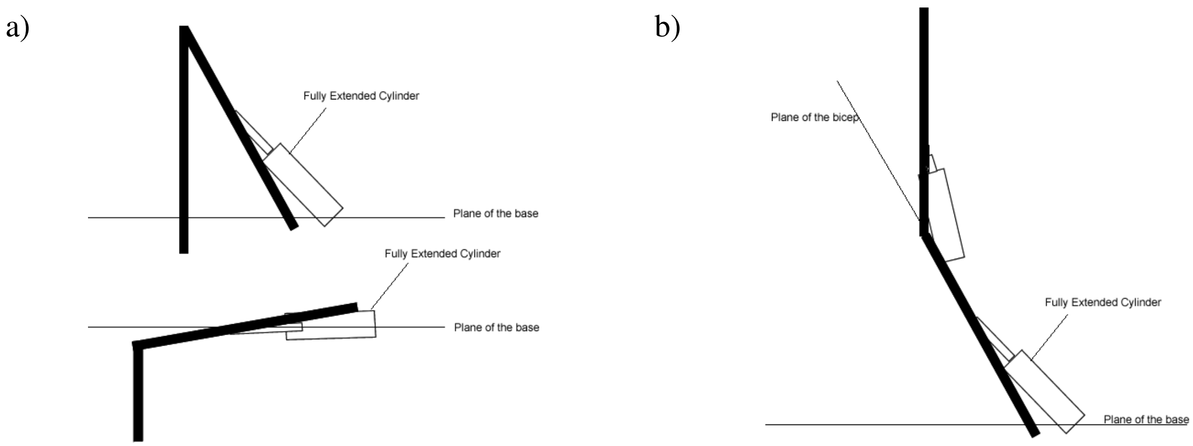


Figure 1.5.1: a) Horizontal Plane, b) Bicep Plane

If the leg is allowed to break the planes, the cylinder will require more force to return than it does to extend. The cylinder loosely locks into position and runs the risk of pulling free from its fastenings. As the pressure builds up, it could exceed the force of the stress for the fastening materials.

It is best advised to prevent the elbow cylinder from breaking the plane of the bicep, Figure 1.5.1b. It will take more force to open the cylinder than it did to close it. In the end it depends on how you want the legs to function. You can design it for the legs to be entirely below the body but you would have to configure each cylinder's actions differently than described in this paper.

The rest of the cylinders can move as far as the user would like. The forward/backward movement cylinders turn horizontally and don't have extra influences due to the force of gravity on its position.

2.0 Design

Before I discuss what the system does it is best to have an understanding of how it does it. It would be far more difficult to just make assumptions while building. My goal was not only to make a prototype but also to outline what needs to be done in the system as a whole. This section entails the numbering layout and how cylinders work in conjunction with each other to enable motion.

2.1 Cylinder and Leg Layouts

Typically a backhoe has 5 cylinders. One controls the up and down movement, one for forwards, one for backwards, one to move the elbow in and out, and one to move the shovel.
The shovel is not practical to the full sized version of this project. It is replaced by a foot that is not powered. The four other cylinders, however, are still essential.

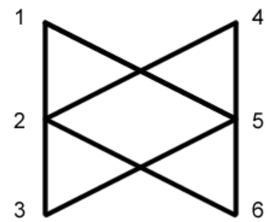


Figure 2.1.1: Leg Number Layout

I developed a numbering and lettering system. When looking down on the layout with the front facing up, start at the top-left corner and, numbering down the one side, assign 1, 2, and 3 for the leg numbers. From the top-right corner, again numbering down, assign those 3 legs 4, 5, and 6. Figure 2.1.1 shows the leg numbers on neutral from the triangle diagrams.

The cylinders are not leg specific, but rather each leg has all the same cylinders. Legs 1 and 4 are the front and legs 3 and 6 are the back. The front cylinder on each leg is 1 and the back is 2. Each lift cylinder is 3. The elbow cylinder is 4.

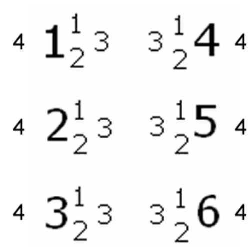


Figure 2.1.2: Leg and Cylinder Number Layout

Figure 2.1.2 shows the cylinder numbers as they appear in relation to each leg number. The number is located generally where the cylinder appears on the body.

Further in this document I will make references to the odd or even numbered legs. As the reference implies the odd number legs are 1, 3, and 5 and the even legs are 2, 4, and 6. [5]

2.2 System States

For all images in this section, N stands for neutral, R stands for relax, and C stands for contract. All of these are actions applied to the specified cylinders where N is a state in itself. In general, if the cylinder number appears by itself without an R or C following it, it will be contracted. All cylinders remain selected until the opposite cylinder is selected.

L stands for leg and H stands for hydraulic. If there is a reference to L.1.H.3.C, it means leg 1 is contracting hydraulic 3. When cylinder 1 is contracted, it should be understood that cylinder 2 is relaxing and vice versa unless specified otherwise. Contract refers to closing the cylinder, while relax refers to extending the cylinder.

The pictures in this section are meant to represent a finite state, with concurrent actions, that must complete each step of each action and can only exit the state if the conditional expression is met. Boxes at the same level must be completed at the same time. The diamonds are the conditional question “Is it still receiving this movement?” If so, continue, if not, return to neutral.

Neutral is defined to be the waiting state. When in neutral the system is waiting for an interrupt to occur. This interrupt can be defined by the user and should be specific to the movement. Therefore the system would work best if implemented in an interrupt-driven environment.

While in neutral the legs should be positioned to easily transition into any of the other states. By being in this “ideal” position, the legs perform minimal motion to transition. Basically, the robot doesn’t have to move from one end range movement to the next in order to achieve its goal, and the body can easily maintain its balance when waiting.

The robot should be in neutral when it is turned on/off and should return to neutral after each movement. First it lifts a tripod off the ground, contracts cylinder 3, and relaxes both of its forward and backward cylinders, numbers 1 and 2.

For neutral, cylinders 1 and 2 should be equally extended and then the selected tripod should be returned to the ground, relaxing cylinder 3. Next select the other tripod and contract cylinder 3. Relax its 1 and 2 cylinders and then relax cylinder 3. Each leg is now in its neutral position and is ready for any movement.

In order to move forward the odd legs contract cylinder 3. The odd tripod moves forward, contracting cylinder number 1, while the even tripod moves backward, contracting cylinder number 2. Once the lifted tripod is completely forward, it is dropped to the ground and moved backwards. When the odd tripod is dropped the even legs are lifted into the air and moved forward.

a)

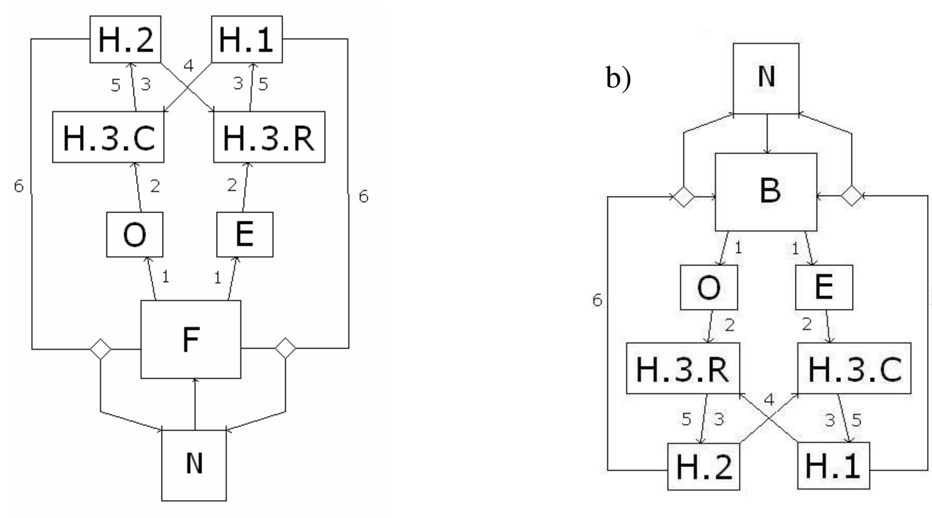


Figure 2.2.1: a) Forward, b) Backward

In Figure 2.2.1a, the diagram shows the selection starting with the forward movement. Both the even and the odd numbered legs are selected and remain selected until the conditional expression.

Each arrow is numbered in order of execution and, unless specified otherwise, the same legs remain selected throughout the arrow's track. For instance in Figure 2.2.1a, the left side arrow selects the odd legs and the odd legs stay selected through arrows 3, 4, and 5.

From the forward state box, the 1 arrow goes to the odd and even legs. Following the path of the odd legs, arrow 2 runs to cylinder 3 contract, arrow 3 goes to cylinder 2 and implies contraction, and arrow 4 selects the odd leg's cylinder 3 but this time it's for relaxing. Arrow 5 selects cylinder 1 and then arrow 6 runs to the conditional diamond.

Other than the picture being upside down, Figure 2.1.2.1b is the same as in Figure 2.2.1a with one difference, the even legs are the first to contract cylinder 3.

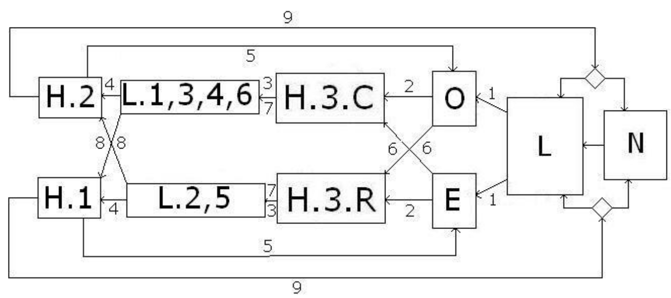


Figure 2.2.2: Left Turn

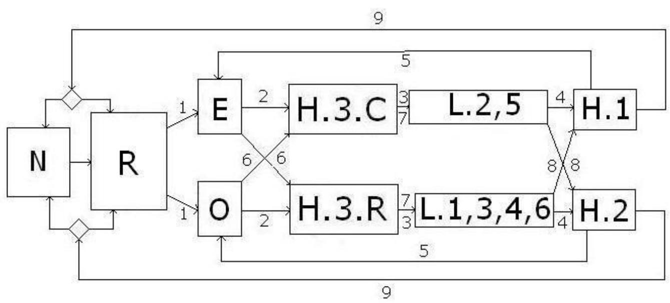


Figure 2.2.3: Right Turn

Figure 2.2.2 is for left turning. From the diagram you see both even and odd legs are selected and H.3 is contracted for the even legs and relaxed for the odd legs. From there the legs 2 and 5 are selected in their own group and the rest of the legs, 1, 3, 4, and 6, are in their own group.

L.2, 5 contracts H.2 and the other legs contract H.1. This is easier to imagine in conjunction with Figure 1.3.2a. The odd and even groups are reselected. The odd legs were in the air and are now put on the ground and the evens are raised, shown by arrow 6. Arrow 7 shows the selection of the groups from earlier, L.2, 5 and L. 1, 3, 4, 6. Next H.1 is contracted for L.2, 5, and H.2 for L.1, 3, 4, 6. Then go to the conditional expression.

Figure 2.2.3 is for right turning and the only difference, other than orientation, between it and Figure 2.2.2 is that the L.E.H.3 is contracted first.

The triangle diagrams depict the spatial state of the legs, while all the figures in this section show what cylinders are moving to achieve those spatial motions.

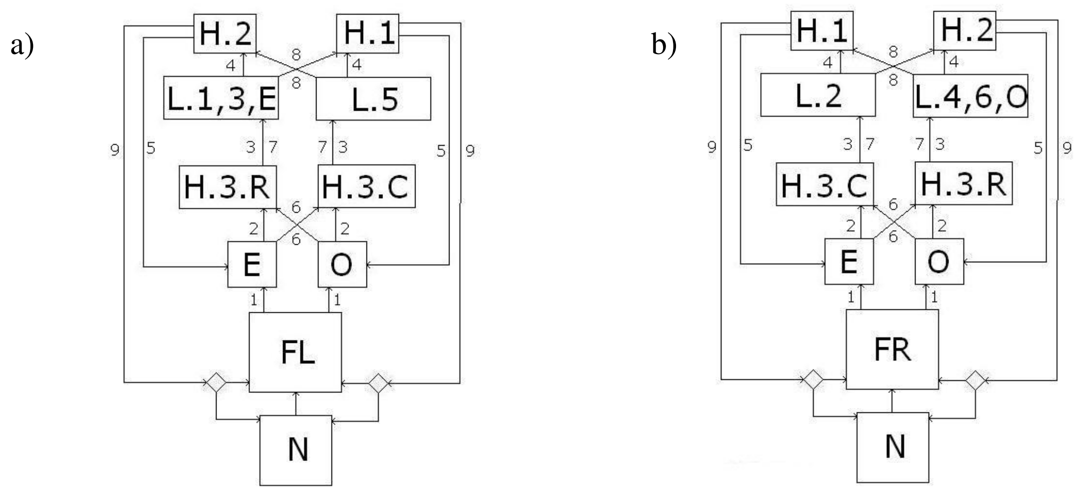


Figure 2.2.4: a) Forward Left, b) Forward Right

Figure 2.2.4 is a depiction of forward left and right movement. From staring at my previous diagrams, these should be a little easier to follow. Nonetheless I will describe the actions of Figure 2.2.4a.

Both the even and odd legs are selected. The L.O.H.3 is contracted and L.E.H.3 is relaxed. Next all the even legs and L.1, 3 are selected in a group and contract H.2. As you can see, L.5 is in a group by itself and has H.1 contracted. The second half of the state is the opposite of the first half, as with every previous movement. To move backwards and to the left simply switch things in figure 2.2.4a so that L.E.H.3 is contracted first.

By now these pictures should make some sense and Figure 2.2.4b should explain itself. [5]

2.3 Cylinder Grouping

There are a total of 24 cylinders. The 24 can be simplified into 12 groups. Cylinders that do the same thing through each movement can be put into the same group.

Forward and backward movements are the only actions capable of using the simple odd and even cylinder grouping.

Every other action manipulates the legs differently. Each cylinder could be the only member of its respective group but it would be more difficult to implement. By inspection several legs do the same or opposite things in any of the discussed motions.

L.O.H.3 is a group of cylinders residing on the odd numbered legs. This group is observed in every action. By grouping these cylinders all legs in the odd set are lifted off the ground at the same time. The opposite group is L.E.H.3. By opposite I mean if L.O.H.3.C then L.E.H.3.R. The selected cylinders are doing the opposite. When the odd tripod is in the air it only makes sense to have the even tripod on the ground, otherwise the hexapod would fall on its stomach.

L.O.H.4 can be put into a group by itself as well. The only action H.4 is used for is the strafing movements. As with H.3, L.E.H.4 is the opposite group of L.O.H.4.

That is as simple as the groups get. In all movements it is observed that L.1 and L.3 do the exact same thing. So L.1,3.H.1 is in a group and L.1,3.H.2 is in the opposite group. Similarly L.4,6.H.1 always do the same thing and its opposite group is L.4,6.H.2.

L.2 and L.5 are in groups by themselves. L.2 and L.5 do different things in different movements. They cannot be characterized with other legs and get grouped by themselves. Grouping them by themselves generates 4 additional groups for L.2,5.H.1 and L.2,5.H.2. [5]

2.4 Implementation

Legos is the easiest building material. I was playing with Legos when I was a kid, before I took time off to grow up. When I discovered it was possible to build such a thing with Legos, it was my natural choice.

Since I chose Legos as my medium, some intricacies are not immediately available. Nonetheless, with over a thousand pieces, including many Technics pieces, 24 Legos cylinders, 4 pumps, 2 tanks, and a hybrid Powerade bottle/tank, I have built a Legos robot that can move in 2 directions.

It only moves forward and backward, but it shows how the system works in unison. Pressure is produced by the 4 pumps, and is stored in the tanks. The compressor is made out of Legos. It dispenses pressure to each cylinder via rubber hose and switches. There are 2 kinds of switch.

One kind of switch is Legos brand, and is as simple as most Legos pieces. There's a bar and when the bar is flipped air pressure is exhausted from one place and moved to other. The other kind of switch is actually an air solenoid.

The solenoid was made by Techno-Stuff and works with the Legos Mindstorm RCX brick as any other motor does. Unlike the Legos switch, this solenoid runs directly off the RCX. A motor must flip the Legos switch.

The system design, not the construction, will change significantly as more movements are added. There will be more switches, more hose, and more pressure. Such change will require new functions. As of right now there is not enough pressure to sustain ceaseless movement, and I have yet to implement all cylinder groups.

As it works now I observed only the groups associated with each tripod. L.O.H.1, L.O.H.2, L.O.H.3, L.E.H.1, L.E.H.2, and L.E.H.3 are the only groups so far. I added a buffer group for the in and out movement of the support cylinder. The rest will come later.

a) 

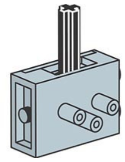
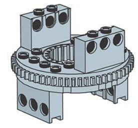
b) 
c) 
d) 

Figure 2.4.1: a) Air solenoid, b) Cylinder, c) Legos Switch, d) Turn table

Figure 2.4.1 pictures some of the specialty pieces used to build the robot. These are not the only pieces used, but as a whole they are the most important. The turn table is the base of each leg and allows free turning from side to side. It has gear teeth, so other gears could be used to manipulate it.

The air solenoid, figure 2.4.1a, is what was discussed earlier and had to be purchased from a specialty store. In order to obtain 24 cylinders, figure 2.4.1b, from a single vendor, they had to be imported from the United Kingdom.

The turn tables, figure 2.4.1d, come in packages of two from the Lego Education Store. The Legos switches, figure 2.4.1c, are also available at the Lego Education Store in packages of five. [1][2][4]

3.0 Conclusions

Several difficulties were encountered, lessons were learned, and there is more than enough work left to further the project. Some of these are outlined below.

3.1 Problems

Originally my construction was too heavy and flimsy to work. The base was built out of an assortment of Lego brick and plates. When the cylinders were attached to the body, many connections fell apart because of the weight.

It was back to the drawing board. I was able to minimize the number of pieces used. To reduce the weight I replaced the bricks with beams and axles. The axles are what actually hold the body together, give it strength, and reduce the weight.

Rubber bands are used on each foot to provide traction that the smooth Legos do not have. The legs would move but they would not catch on the surface and propel the body.

To start with I used two pumps. They are rather small and did not produce enough force to pick the body up. Once the body was up they did produce enough force to move either forward or backwards. I needed to add an additional pump to push the middle of the body up.

That was not enough pressure to keep the body in the air for long. With more pumps it should work better, but the best approach would be to have an outside source of compressed air. That would relieve some weight and yield more pressure.

3.2 Lessons Learned

I have never been someone to over plan or over research. Planning just enough to get by has always worked in the past but not in this case.

When reviewing my first designs and diagrams from the start of this project, it became apparent they did not accurately reflect what a hexapod does in every necessary movement. If I had done an earlier review, I would have addressed those things sooner, and avoided excessive changes diagrams and pseudo code in the development phase. When one thing needed to be changed then everything seemed to change. More thorough planning at the front end would have alleviated these complications.

Instead of researching much of what others might have done in this area, I watched video of other hexapods. I went as far as to take note of what a crab was doing on the Discovery Channel and stared at an ant in a jar. If I had researched more of what others had done, it might not have taken as much time to determine the sequences.

3.3 Future Work

Some modifications may need to be made to the structure of the robot. My system functionality is solid, but the implementation may not work as well for all movements with the current structure. More time is needed to explore these issues.

There are still eight movements that need to be implemented and tested. I have not worked out the actions of a squat. The squat is tied to a jump, since it is conceivable that it could return from the squat with enough force to lift every leg off the ground.

It would be nice to see a model built out of metal and circuit boards. That would require more research, specialty parts, and more expense.

Of course, building that full-sized all-terrain truck is many years, thousands of dollars, and far removed from my little Legos robot.

4.0 References

[1] "Air Solenoid." Air Solenoid. 09 Mar 2005 < http://www.techno-stuff.com/AirSol.htm >

[2] Bagnall, Brian. Core Lego Mindstorms Programming. New Jersey: Prentice Hall PTR, 2002

[3] Gonzalez, Miguel. "Control of a Hydraulic Electro Solenoid Valve by a Computer System." Graceland University. 10 May 2004

[4] Lego Education Store, 09 Mar 05. Legos Education < http://www.legoeducationstore.com/ >

[5] Stewart, Mikael. "Mhex: Hexapod Robot Project." 16 July 2004. New Zealand, 09 Mar 05 < http://www.geocities.com/viasc/mhex/mhex.htm >