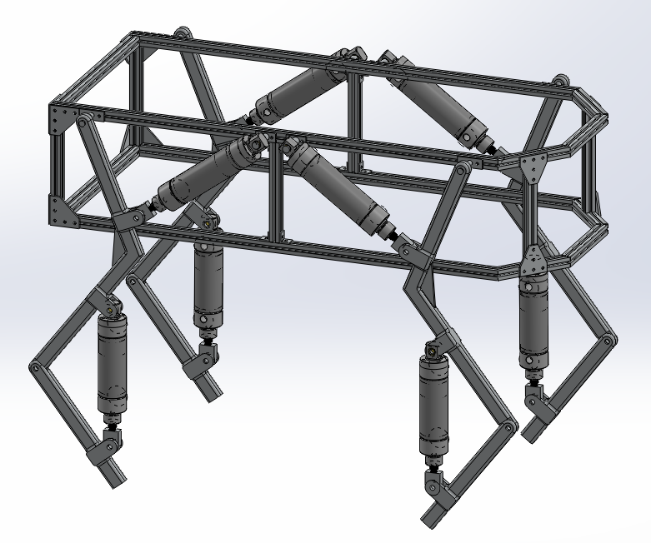
http://www.joyglobal.com/clientCSS/images/logo_JoyGlobal.png

**Development of an Agile Educational Robot**

Team A.R.C. – Design Report



**March 8, 2015**

Logan Beaver

Justin Campbell

Tyler Paddock

Ronald Shipman

***Advisor***: Dr. Luis A. Rodriguez

Contents

[Table of Figures 3](#_Toc412466389)

[Table of Tables 3](#_Toc412466390)

[Executive Summary 4](#_Toc412466391)

[Dynamics 6](#_Toc412466392)

[Mechanical Design 15](#_Toc412466393)

[**Pneumatic Components** 17](#_Toc412466394)

[**Double Acting Air Cylinders** 18](#_Toc412466395)

[**Compressor** 20](#_Toc412466396)

[**Valves** 20](#_Toc412466397)

[Electrical System 23](#_Toc412466398)

[Control Algorithms 24](#_Toc412466399)

[State Machine 25](#_Toc412466400)

[Conclusion 25](#_Toc412466401)

[Environmental Report 26](#_Toc412466402)

[A. Materials Contained in Design 26](#_Toc412466403)

[B. Materials Contained in Prototype 27](#_Toc412466404)

[C. Special Handling Instructions 27](#_Toc412466405)

[D. Special Storage Instructions 27](#_Toc412466406)

[E. Disposal Instructions 28](#_Toc412466407)

[References 29](#_Toc412466408)

[Appendix I – Dynamic Simulation MATLAB Code 31](#_Toc412466409)

# Table of Figures

[Figure 1: Mathematical notation for the robot model 6](file:///D:\MyDocs\Documents\Senior\Fall\Senior%20Design%201\AgileRoboticControls\Documentation\Design%20Report\Design%20Report%20Agile%20Quadruped%20Project.docx#_Toc412466943)

[Figure 2: Free body diagrams for the shank (left) and thigh (right) 7](#_Toc412466944)

[Figure 3: Free body diagram of the chassis at an arbitrary angle 7](#_Toc412466945)

[Figure 4: Length definitions for the front right robot leg 9](file:///D:\MyDocs\Documents\Senior\Fall\Senior%20Design%201\AgileRoboticControls\Documentation\Design%20Report\Design%20Report%20Agile%20Quadruped%20Project.docx#_Toc412466946)

[Figure 5: Kinematic step simulation for a single robot leg 11](#_Toc412466947)

[Figure 6: Free body diagram for the drag portion of the gait 13](#_Toc412466948)

[Figure 7: FEA result for Shank 17](#_Toc412466949)

[Figure 8: FEA result for Thigh 17](#_Toc412466950)

[Figure 9: FEA result for Chassis 18](#_Toc412466951)

[Figure 10: Bimba Original Line® Air cylinder w/ Adjustable Cushions 19](#_Toc412466952)

[Figure 11: Cylinder Cross-Section View 19](#_Toc412466953)

[Figure 12: Speedaire Air Compressor, 0.9 HP, 120V, 115 psi 21](#_Toc412466954)

[Figure 13: 12v DC 4mm 1/4" NPT Brass NBR 2-Way Solenoid Valve 21](#_Toc412466955)

[Figure 14: Electric Solenoid Valve – Cutaway 22](#_Toc412466956)

[Figure 15: Numatics Mark 3, SPA 3, and PA 3 Series Valve 22](#_Toc412466957)

[Figure 16: 4/2 Directional Control Valve 22](#_Toc412466958)

[Figure 17: Belimo B208B : 2-Way 1/2" Brass .46 Cv Control Valv 23](#_Toc412466959)

[Figure 18: Sample pneumatic circuit for motion actuation 24](#_Toc412466960)

[Figure 19: PID model for a single leg 25](#_Toc412466961)

[Figure 20: Flowchart representation of the state machine architecture. 26](#_Toc412466962)

[Figure 21: Gantt chart for project lifetime 27](#_Toc412466963)

# Table of Tables

[Table 1: Advantages and disadvantages of legged versus wheeled locomotion. 5](#_Toc412471335)

[Table 2: Simulation results for the Swing, Drag, and Impulse phases of the simulation 14](#_Toc412471336)

[Table 3: Relationship between Cv to SCFM at pressures between 40 and 100 psi 23](#_Toc412471337)

# Executive Summary

The Milwaukee School of Engineering (MSOE) participates in Science Technology Engineering and Mathematics (STEM) outreach events for prospective students. The school will benefit greatly from having a sophisticated robotic control system to build excitement about STEM as well as sparking interest in fluid power, automation, and the controls fields. An agile pneumatic robot is not only a complicated control system that can be used to get young people excited about STEM, but it will also increase the prestige of MSOE knowing that a group of seniors attending the school were able to design and build the system from the ground up. In addition it also provides an exciting opportunity for future groups to iterate on the design and integrate new and exciting features.

To fulfill the needs of the project existing robot designs were researched to help determine the initial objectives and constraints for the project. Existing walking robots such as Boston Dynamics Big Dog and Little Dog, the Swiss Federal Institute of Technology (EPFL) Cheetah Cub, and various robots from the Massachusetts Institute of Technology Computer Science and Artificial Intelligence (CSAIL) laboratory were examined. These robots were used as a baseline comparison for the design specifications and constraints. From these robots a list of constraints and criteria were developed. The most critical of these are given below:

* A maximum weight of 35 kg for portability
* Maximum size of 0.75 m x 0.75 m x 1.0 m box for portability
* Custom debug panel creation to facilitate troubleshooting
* MATLAB and Simulink model support to allow mechanical engineering students to update control algorithms without knowledge of C/C++
* Electronic fuses and shielding to protect the robot and operator during use and maintenance
* Mechanical protection to reduce the risk of pinching and self-collision damage to the robot
* An easy to access emergency stop to quickly depower the robot
* A pressure relief valve to reduce the risk of overloading and damaging pneumatic components

The work done on this project is a continuation of the work done by Kevin Lee during the Research Experience for Undergraduates (REU) at MSOE. His work involved deriving a dynamic model for a simplified quadruped robot. This work is continued by the agile robotics controls team in deriving a full dynamic model for the physical robot and integrating it with control algorithms to manipulate the robot. This resulting robot design will be implemented in actual hardware by the end of the project.

Pneumatic power was chosen over electronic and hydraulic power for a variety of reasons. Pneumatics were chosen over hydraulics due to the weight and maintenance needs associated with hydraulic systems. Hydraulic systems are also dirtier than pneumatic systems and pneumatic working fluid is freely available. Pneumatics were chosen over electronic systems due to their higher power density. Electrical systems have lower power density due to the inefficiencies in converting electrical energy to mechanical work. In addition fluid power systems are compliant, meaning that if a large force is applied to the pneumatic actuators the fluid can compress and absorb the shock whereas electronic actuators will experience an increased stress.

The robot locomotion utilizes a quadruped design. Four legs were selected because of the inherent static stability of a four legged design coupled with the decreased control complexity compared to robots with five or more legs. This will allow the robot to initially actuate a slow one legged gait as the software architecture is developed, and it will eventually lead to more sophisticated gaits being developed without the need for additional hardware. The following table summarizes the advantages of legged locomotion over wheeled locomotion:

Table 1: Advantages and disadvantages of legged versus wheeled locomotion.

|  |  |  |
| --- | --- | --- |
|  | **Advantages** | **Disadvantages** |
| **Wheeled Locomotion** | -Less complex motion  -Fastest on flat ground | -Bad for rough terrain (uneven, sloped, rocky) |
| **Legged Locomotion** | -Better for rough terrain (uneven, sloped, rocky)  -Good obstacle avoidance  -Precise feet positioning | -More complex motion  -High control complexity |
| **1 Legged** | -Lower cost due to fewer components | -Complexity in controls due to static instability  -Can only hop |
| **2 Legged** | -Marginal static stability  -More achievable gaits (walk, run) | -Complex balance control |
| **4 Legged** | -Statically Stable | -Complicated leg synchronization controls |
| **More than 4 Legged** | -Statically Stable | -Very complicated leg synchronization controls  -Very high cost for additional components |
| **Hydraulic Power Source** | -Highest achievable power density | -High maintenance  -Heavy  -Dirty |
| **Electric Power Source** | -Accurate positioning | -Lowest achievable power density  -Noncompliant |
| **Pneumatic Power Source** | -Higher power density than electric power  -Low Maintenance  -Compliant action from fluid compression | -Compressible fluid causes inaccuracy in positioning |

During the previous design phase four design alternatives were drafted which fulfill the design requirements. The design alternatives were *Arachnia*, *Hexabox*, *Boxxy*, and *DogeBot*. After scoring each robot with a design matrix, *DogeBot* was chosen as the design to be continued, with a score of **96.19** out of 100.

During the current design phase mathematical models of the robot were developed to assist in determining component specifications. Initially a dynamic simulation was constructed which output the internal forces and applied torques at each joint of the robot during motion. These results were then used with a finite elements simulation to update the design of the legs and chassis.

In addition the dynamic model output was used with a motion study to determine the pneumatic cylinder bore diameter and stroke length. These values were then used to specify the maximum pressure of the pneumatic circuit, which allowed the remaining pneumatic components to be selected.

In the final design phase the selected components will be ordered and assembled by the team. The control architecture will be rapidly tested and iterated using a single leg prototype while the robot chassis and subsystems are wired and assembled. The legs will then be attached to the completed chassis to test simple gaits such as the drag. Finally, if time permits, more complicated gaits will be implemented on the robot.

# Dynamics

To determine the internal forces felt in the joints and the required torques for locomotion a dynamic mathematical model of the robot was constructed. From the specifications the robot was known to have four legs with two links each all attached to a main chassis. Summing the force and torque around each link of the robot resulted in 27 simultaneous equations used to calculate the state of the robot. To simplify the calculations it was assumed that the robot exhibited purely planar motion and all leg torque is applied purely at the hip and knee. A diagram of the mathematical notation used in the model is shown below:

X

Y

Θthigh

Θbody

Θshank

Leg 1

Leg 2

Leg 3

Leg 4

Thigh

Shank

Figure : Mathematical notation for the robot model. The body angle is measured relative to the horizontal, the thigh angle is measured relative to the body, and the shank angle is measured relative to the thigh.

To determine the equations of motion for the overall system free body diagrams were developed for the shanks, thighs, and bodies. This resulted in a system of 27 equations with 32 unknowns. The free body diagrams are given below for a single leg and the chassis:

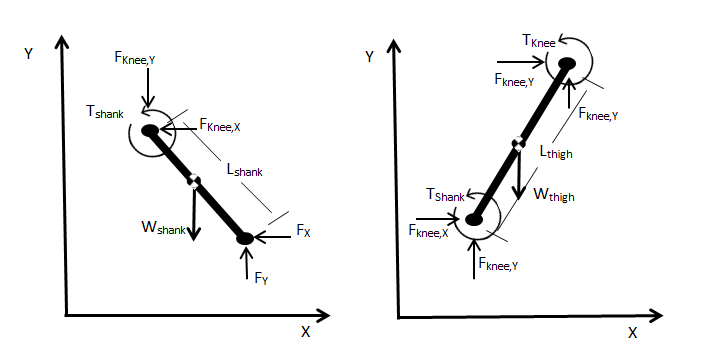


Figure 2: Free body diagrams for the shank (left) and thigh (right). Summing forces and masses on the legs generates 24 equations and 32 unknowns.

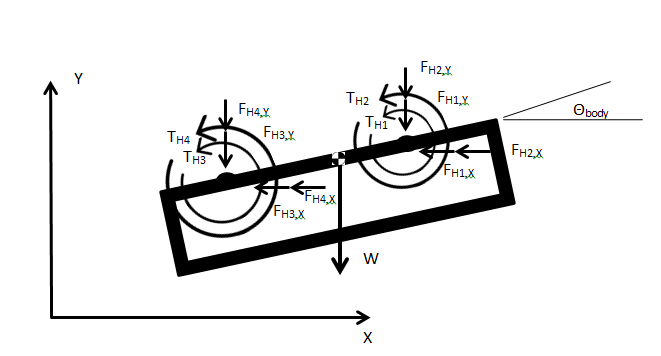


Figure 3: Free body diagram of the chassis at an arbitrary angle. The body brings the system to 27 equations and 32 unknowns.

To simplify the model into a solvable form it was assumed that the reactionary forces of the feet were known, and equations of motion for the body were discarded. This reduced the simulation to a system of 24 equations and unknowns, which could be solved to find the torque applied and internal force felt at each joint.

The final step in developing a solvable model for the robot is to deal with the non-inertial reference frame of the robot. Due to the robot’s acceleration during motion, taking a force and moment sum of each joint will neglect inertial forces acting on the robot. The coriolis and centrifugal forces are two examples of inertial forces that need to be accounted for when doing a force sum in a non-inertial reference frame [1].

There are three main ways to deal with dynamics in non-inertial reference frames. The most common way is to simply add in the inertial forces to make newton’s laws of motion valid. Adding in the inertial forces is the most conceptually straight forward and the simplest to solve mathematically. However without a physical system to test it would be very intensive to determine the extent that non inertial forces are affecting a system as complicated as ours.

The second method is to use lagrangian mechanics to solve the system in an arbitrary coordinate system. Due to the general energy based nature of lagrangian mechanics inertial forces are accounted for during equation derivation [2]. Unfortunately the core curriculum at MSOE does not mention lagrangian mechanics and it would be too time intensive to learn an additional dynamic system on top of constructing the senior design project.

The final method is to have an arbitrary ground point as the reference for the system. This eliminates the inertial forces acting on the robot while also allowing newton’s laws of motion to be used for the dynamical analysis. After giving the robot an arbitrary ground location the sum of the torque equation needed to be modified using relative motion. A subset of the developed equations is given below:

(1)

(2)

(3)

(4)

(5)

(6)

Where *r* is a distance vector to the arbitrary ground point, *Fhip* and *Fknee* are the internal forces on the hip and knee joints, *Thip* and *Tknee* are the torques applied to the hip and knee joints, and *Tequivalent* is calculated as follows [3]:

(7)

Where *Izz* is the moment of inertia of the link about the z axis.

The torque and force equations can then be put into the following matrix forms:

(8)

(9)

Where T is an 8x1 matrix of torques, A is an 8x8 matrix of 1’s and 0’s, and B is an 8x1matrix containing the other torque equation elements such as distances and equivalent torques. F is a 16x1 matrix of internal joint forces, C is a 16x16 matrix of 1’s and 0’s, and D is a 16x1 matrix containing masses, accelerations, and weights.

Equations 8 and 9 can then be solved by inverting the A and C matrices to get the following solution form:

(10)

(11)

This creates a system of equations where the torques and forces are dependent on the robot link’s mass and inertia, the angular position, velocity, and acceleration of each joint, and the Cartesian acceleration of each joint. The mass and inertial values for the robot were taken from the SolidWorks model developed during the previous design phase and a kinematic model was developed to calculate the required position, velocity, and acceleration values during motion.

To determine the position of the hip, knee, foot, and thigh CGs a kinematic model for the robot was developed. The kinematic model assumed each leg is a serial manipulator grounded at the CG of the robot at a position (x, y) relative to the arbitrary ground. A diagram for the front right leg is given below:

LH1

LK1

LF1

LT1

LS1

Figure : Length definitions for the front right robot leg. All positions are measured with polar notation using a series of angles and distances from the point (x,y) at the CG of the robot chassis. For the kinematic equations the leg is considered a serial manipulator consisting of revolute joints connected to a ground reference at point (x, y). All angles use the earlier notation.

From the above diagram it is easy to perform a serial manipulator analysis to determine the position of any point on the robot leg. The position of the foot in terms of the body, hip, and knee angles is given below:

(12)

Where F is the Cartesian foot position. All angles follow the convention given earlier.

The equations were then symbolically stored in a MATLAB script and derived with the following generic function[4]:

(13)

Which is equivalent to:

(14)

Where *J(f)* is the Jacobian matrix of function *f*. This approach allows rapid iteration of design versions without changing the differentiation of the joint velocity and accelerations. The partial derivative of the position is multiplied by the position Jacobian to acquire the velocity function, and the velocity function is multiplied by the velocity Jacobian to achieve the acceleration. A simplified form of the kinematics which assumed *LH1 =* θ*body = 0* was hand derived and matched exactly with the MATLAB differentiation.

In addition a static case close form solution was created for the torques and forces at each joint in a single leg. After modifying the simulation parameters to fit a single static leg the identical equations were output by the simulation. Although having a correct static case doesn’t verify the entire dynamical derivation, it is useful to spot any fundamental errors in the simulation.

After deriving the dynamic and kinematic equations the required torques and resultant forces at each joint are functions of the following 11 x 1 state vector q and its two time derivatives:

(15)

To calculate q and its time derivatives for the robot a second kinematic simulation was constructed with some simplifications. The simulation was simplified to a single leg with the foot following an arbitrary path at a constant speed. This allows the angles and their derivatives to be calculated for a single leg. The values of the other legs could then be approximated either as constant values or values based on from the simulation.

A semi-ellipse was selected as the initial foot path. The path was selected due to its mathematical simplicity and the ease of changing the step length and height parameters. It is also a similar shape to the more complicated pear-shaped quartic, which is the path many organic creature’s feet follow during motion. A constant speed was selected to simplify the step analysis. A plot of the simulation in action is given below:



Figure 5: Kinematic step simulation for a single robot leg. The leg follows the elliptical path with a constant velocity.

To get a close approximation of the maximum stresses and torques felt by the robot a 0.5 m long step was selected to be completed in 1 second which satisfies the specification of moving a maximum of 0.5 m/s.

After a close inspection of the step it should be clear that there is a corner at 0.25 m, which causes an unrealistically large spike in acceleration and therefore force and torques felt. To correct this error the step was split into three phases. The first two phases, swinging and dragging, were calculated as described above. The third phase, impulse, used the velocity of the leg to calculate the foot force which was then used to calculate internal forces and torques in the joints. The impulse method was derived as follows from the conversion of linear momentum[3]:

(16)

Where *m* and *v* are the mass and velocity of their respective bodies, and *f(t)* is the impulse force applied to the foot. Assuming *f(t)* is constant and *vfloor* = *vtotal* = *0* the following equation results:

(17)

Which calculates the force applied to the foot. This force can then be used in conjunction with the other simulations to determine the impulse force felt by the robot joints.

After running the simulation for the swing and drag phase the vector *q* is also known for a single leg. In order to find the torques required and internal forces at each joint some simplifying assumptions were made about the robot’s gait to determine the remaining values in *q* and the foot forces.

The first simplification made was that the robot performed a drag gait to move. This means the robot locks three of its legs and uses the fourth to drag itself along the ground. It was also assumed that the robot chassis is moving at a constant velocity of 0.5 m/s forward. These simplifications don’t capture the entirety of the dynamical motion, but it is accurate enough to get a rough idea of the expected dynamic forces without spending months doing only dynamical analyses of the system.

To finish defining the state vector *q* a value of 90 degrees was selected for the remaining hip angles, and a value of zero degrees was selected for the body and knee angles. The derivatives of these values were also set to zero due to the static nature of this gait. Finally the foot force values were calculated for the swing and drag phases of the elliptical step. For the drag portion of the step the following free body diagram was used to calculate foot force values:

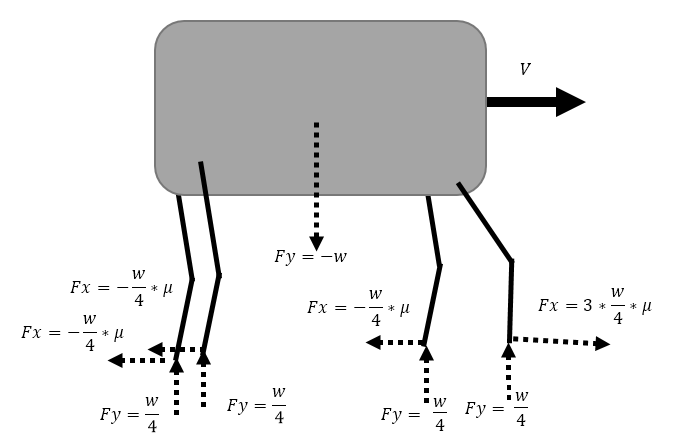


Figure 6: Free body diagram for the drag portion of the gait. All four legs are assumed to be on the ground of the robot while travelling at a constant velocity V.

Where μ is the dynamic friction coefficient of the feet. This resulted in the following equations:

(18)

(19)

Which, when simplified, leads to the following:

(20)

(21)

Equation 20 simplifies to weight divided by four because the rotational acceleration of the body was assumed to be zero. Thus to prevent an unbalanced tipping moment the force of each foot in the y direction must be equal. For the simulation a value of 0.5 was used for the coefficient of friction. This is a common value for rubber sliding across a hard surface [5].

Finally the foot forces during the swing phase were calculated. To simplify the calculations it was assumed that the robot body was completely static as the foot swung out. There are a few inaccuracies in this assumption, but the amount of time it would take to determine a foot reaction force model for the robot would exceed the time allotted for the project. With this simplification and leg geometry setup it is trivial to calculate that the x and y components of force acting on the swinging leg is zero. Additionally because the legs are completely vertical it is trivial to conclude the x component of the other foot forces are zero as well, while the y direction is one third of the robot weight.

After performing all of the derivations a MATLAB script was developed to run the simulations and output the state of the robot at the maximum torque and maximum internal forces. The script can be seen in Appendix 1. The maximum values output from the script are tabulated in the figure below:

Table 2: Simulation results for the Swing, Drag, and Impulse phases of the simulation. Values are labeled as [Type][Location][Leg], so TK1 is the Torque applied at the Knee on Leg 1, and FH2x is the Force felt by at the Hip on Leg 2 in the X direction.

|  |  |  |  |
| --- | --- | --- | --- |
| *Value* | *Swing* | *Drag* | *Impulse* |
| TH1 [N-m] | 383.2008 | 67.082 | 0 |
| TH2 [N-m] | 2.9008 | -3.1367 | 0 |
| TH3 [N-m] | -0.7823 | -1.3573 | 0 |
| TH4 [N-m] | 2.9008 | -3.1367 | 0 |
| TK1 [N-m] | 1.3135 | 99.3253 | 0 |
| TK2 [N-m] | 17.5289 | 6.8914 | 0 |
| TK3 [N-m] | -13.2918 | -9.8418 | 0 |
| TK4 [N-m] | 17.5289 | 6.8914 | 0 |
| FK1x [N] | 557.6 | 33.7092 | 12.3869 |
| FH1x [N] | 911 | 91.9408 | 0 |
| FK2x [N] | 0 | 17.25 | 0 |
| FH2x [N] | 0 | 17.25 | 0 |
| FK3x [N] | 0 | 17.25 | 0 |
| FH3x [N] | 0 | 17.25 | 0 |
| FK4x [N] | 0 | 17.25 | 0 |
| FH4x [N] | 0 | 17.25 | 0 |
| FK1y [N] | 789.9 | 145.8055 | 50.3962 |
| FH1y [N] | 1321.2 | 199.8142 | 34.5 |
| FK2y [N] | -42.4 | 30.8703 | 34.5 |
| FH2y [N] | -38.2 | 26.652 | 34.5 |
| FK3y [N] | -42.4 | 30.8703 | 34.5 |
| FH3y [N] | -38.2 | 26.652 | 34.5 |
| FK4y [N] | -42.4 | 30.8703 | 34.5 |
| FH4y [N] | -38.2 | 26.652 | 34.5 |

It can be seen from the above table that the forces and torques are an order of magnitude higher during the swing phase compared to the other two. At first this may seem unintuitive, but it does make sense. The drag and impulse columns represent forces that are being used to either stop or maintain a velocity, whereas the swing column includes forces used to achieve high accelerations due to the motion of the foot.

With these simulation results the pneumatic cylinders and legs can be sized to fit the walking specifications. The results were used with a motion study and cost analysis to determine the maximum force output and therefore pressure required by the pneumatic system. This allowed the other components of the pneumatic circuit to be sized. Additionally the worst case scenario forces for the legs were determined allowing their design to be iterated and ensured they did not fail.

# Mechanical Design

The major mechanical components of the robot are the legs and the chassis. The legs are further broken down into the thigh and the shank. The constraints placed on the mechanical design include the overall dimensions, weight, and carrying capacity of the robot.

The chassis of the robot is designed to support the legs while in motion, as well as serve as the housing for the pneumatic and electrical components. The choice to use 6105 –T5 T-Slotted Aluminum framing for the chassis was due to the simplicity of construction. With a number of connection plates and brackets available, a simple chassis would be easy to construct. In addition to its simplicity, the Aluminum framing is lightweight, fulfilling the robot’s weight constraint, and strong enough to support the forces exerted by the pneumatics during operation. Custom hip joints will need to be designed to be able to easily attach the legs to the outside of the frame. Additionally, mounts for the pistons will need to be created in a similar fashion.

The design of the legs is based on the anatomy of quadruped mammals, more specifically dogs. In order to reduce the robots complexity, the number of joints in the legs was reduced from three to two. In order to compensate for the loss in range of motion, the thigh was designed with a bend in it. The bend allows for a shorter stroke length for the pneumatic cylinder. This in turn, means that the cylinder can be attached closer to the hip joint on both the body and the thigh. The bend in the thigh is also beneficial in that it prevents the piston controlling the rotation of the knee joint from reaching a singularity point and possibly seizing. The design of the shank is much simpler. One factor that helped to determine the lengths of the thigh and shank was the desired step length. Similar to the body, the legs will most likely be constructed using an Aluminum alloy. 6061 Aluminum will used to create the legs due to its high strength relative to its weight as well as its relatively easy machinability.

An important design consideration focused on in this phase of the project was the design of the robot’s feet. The foot will provide the necessary friction required to prevent the robot from slipping on its walking surface. Options for feet of the robot include rubber, either spheres or rectangular sleeves, in which the lower shank is inserted and liquid rubber that can be applied to the bottom of the shank and allowed to cure. The rubber sphere feet allow the foot to contact the ground at any orientation, while still providing the necessary friction, however if the shank cannot be securely inserted, the effectiveness of the foot during the leg’s motion becomes a major concern. Rubber sleeves face the same considerations as rubber spheres in that the shank must be inserted securely, so for both options methods for ensuring a sound connection must be looked into. If appropriate sizes of the rubber spheres or sleeves are not available, custom making the appropriate feet is then required. When considering the need of custom manufacturing the feet of the robot, ultimately the use of a liquid rubber substance, such as urethane, that can be cured into the necessary shape, as an option for the feet of the robot becomes the most attractive. By cutting a hole into the bottom of the shank and dipping the shank into the liquid rubber, the appropriate shape of the leg is formed and, as liquid rubber flows through the hole in the shank and cures, a connection point between the foot and the shank is formed. By repeating this dipping process, an appropriate layer of rubber can be applied to the lower portion of the shank, generating an effective foot for the robot. Initial testing of the chosen liquid rubber substance will be conducted to confirm desired mechanical properties.

As a means to ensure the design would be handle the forces due to the weight and pistons, an initial FEA analysis was run. Each component (shank, thigh, and body) was tested separately, using the worst case scenario as an upper limit test of the structures: Trying to move at maximum velocity using the slowest gait with the joints seized. Due to the simplicity of the geometry, it was determined that a surface mesh would be sufficient to accurately model the reactions within the material. Tet10 was used for the element shape to allow for the system to predict how the material might bend under the applied forces. With the system parameters set the simulations were run and the results show that even under the worst case scenarios, the design should hold up. Figure 7- Figure 9 show the resulting ANSYS models and the maximum stress endured by the component.

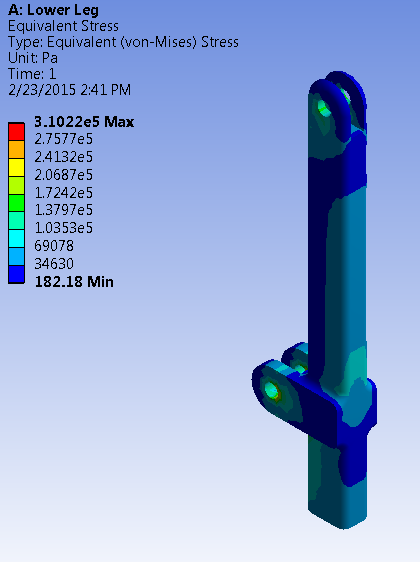


Figure 7: FEA result for Shank

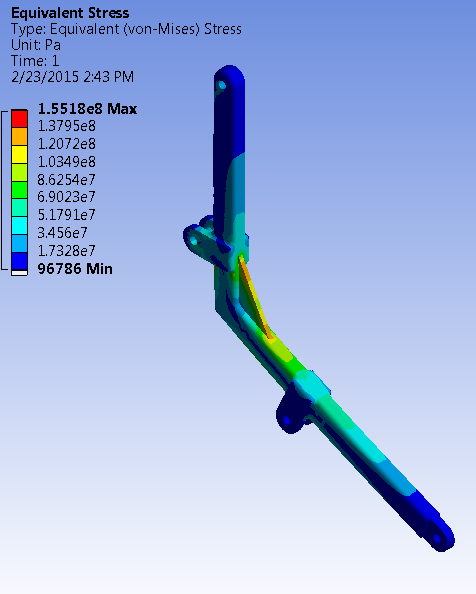


Figure 8: FEA result for Thigh

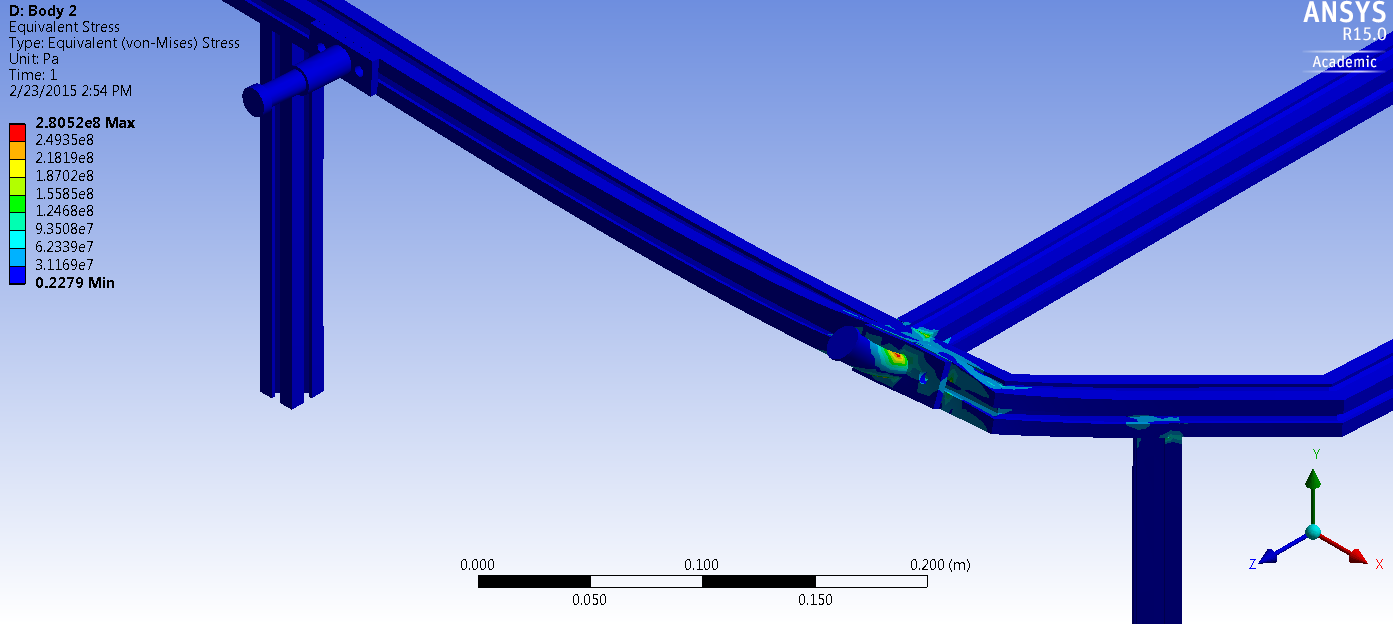


Figure 9: FEA result for Chassis

For the thigh, a small rib needed to be added at the bend to help alleviate some of the stress on the bend. Similarly, it was determined that a cross brace would need to be applied on the chassis near the hip joint to add stability to the frame as well as prevent the frame from twisting as a result of the moment created by the hip forces. The large stress seen in Figure 9 is only present on the placeholder for the hip joint and will need to be accounted for when the final design for the joint is considered.

### **Pneumatic Components**

In order to successfully design a user controlled, pneumatic powered quadruped robot, various electrical and fluid power components must be utilized. These components make up the subsystems that eventually are combined to make up the robot itself. Fluid power components include the air supply tank, the air compressor, the tubing, the double acting air cylinders, the reservoir tank, solenoid valve, and control valves. Initial specifications of pneumatic components were made after determining the forces required by the air cylinders using the dynamic simulation of the robots walking gait.

### **Double Acting Air Cylinders**

Unlike with single action air cylinders, double acting air cylinders are able to receive pressurized air to both extend and contract. Without utilizing a double acting air cylinder, controlled contraction of the legs of the robot would not be possible. Retraction through some forcing mechanism such as a spring would provide contraction of the leg, however the retraction would not be controllable, as the spring would tend to return to its un-stretched length as fast as possible, thus varying walking patterns would be challenging. An image of a cylinder is shown in Figure 10 and the functional cross sectional view is shown in Figure 11.



Figure 10: Bimba Original Line® Air cylinder w/ Adjustable Cushions – Reprinted From [6]

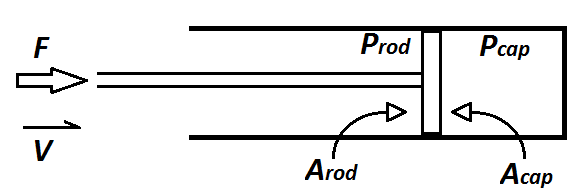


Figure 11: Cylinder Cross-Section View

The equation to find the amount of force produced by the pneumatic circuit is shown in equation 22.

 (22)

From equation 1 Pcap is the pressure on the cap side of the cylinder, Acap is the area of the piston head, Prod is the pressure on the rod side of the cylinder, and Arod is the surface area of the piston head on the rod end. In addition to finding the possible force output of the cylinder, it is also important to be aware of its efficiency. The cylinders efficiency can be influenced by a number of factors such as seal friction, viscous friction, leakages, and fluid compressibility, which can all contribute to the cylinders energy losses. The efficiency of the cylinder is determined using equation 23.

 (23)

For the efficiency equation, Pin and Pout are the power into and out of the system, respectively, Qin is the volumetric flow rate into the system, and V is the velocity of the cylinder.

After determining the torque forces necessary to generate motion in the legs of the robot, the air cylinders providing those forces can be specified. In order to specify the air cylinders, a desired bore diameter of the air cylinders must be chosen. After determining the forces necessary to generate the required torques, the pressures required to generate those forces is also determined. The relationship between the forces output by an air cylinder and the pressure-area differential within the cylinder is given by Equation 22.

After determining a possible bore diameter of the cylinder and the output forces desired, the required pressures must be considered. If the pressures required to produce the necessary output forces in the air cylinders exceeds the pressures attainable by the air compressor, either the bore diameter must be increased to lower the necessary pressure, or the design of the robot must be altered to lower the torques required and thus the air cylinder’s necessary output forces.

After determining a suitable bore diameter with considerations of the pressures required, the flow required by the air cylinders is to then be determined. The flow required by the air cylinders can be determined using Equation 24.

(24)

where Q is the required volumetric flow in a minute, Ap is the surface area of the piston, DT is the total distance traveled by the piston in 1 cycle, N is the number of cycles in a minute, and the compression ratio is given as

(25)

where Pp is the pressure required in the cylinder and Patm is atmospheric pressure.

It is important to note that the pressure required in the cylinder is an average pressure required in a minute of operation, needed due to varying pressures during the piston’s full cycle.

In order to determine the amount of flow required by all 8 cylinders in the pneumatic circuit, the total number of cycles of all the cylinders is determined, and the average pressure of all the cylinders during one minute of operation is determined. The total flow required by all the air cylinders is then found using Equation 25.

Using this total flow required, an air compressor that can meet this outflow can then be specified. If an air compressor cannot meet this flow rate at the required pressure, there are a few possible solutions. One solution is in the form of multiple air compressors linked in parallel, which will output air at the required pressure and, due to multiple compressors being utilized, also at the necessary flow rate. Another solution utilizes a SCBA tank as the power source, instead of an air compressor, which, working at higher pressures, will be able to output air at both the required pressure and flow, utilizing a pressure relief valve.

### **Compressor**

Compressors draw in air from the outside, and pressurize it by compressing it using either a small engine or an electric motor. The compressor feeds the pressurized air into an accumulator to store the pressurized air until it is needed and also to eliminate the pressure fluctuations produced before they are put into the system. Figure 12 shows an image of a commercial compressor. Compressors suffer from a number of inefficiencies resulting in energy loss. Equation 26 is used to find the efficiency of the compressor.

 (26)

In Equation 26 ɳC is the compressors efficiency, Pin and Pout are the input and output pressures of the air, and Tin and Tout are the input and output temperatures of the air. All compressors and air supply tanks come equipped with a relief valve, a small valve kept normally closed by a spring that opens to release some of the built up pressure if it becomes too great.



Figure 12: Speedaire Air Compressor, 0.9 HP, 120V, 115 psi – Reprinted From [7]

**The air compressor can be specified based on the pressure and volumetric flow rate needs of all components of the pneumatic system. The largest portion of flow is consumed by the air cylinders in the pneumatic circuit, however flow will also be lost due to the pressure relief valve, when the system pressure limit is reached. There are also flow losses due to friction in the tubing of the system and losses possible in the control valve itself due to valve openings. An appropriate compressor is one that can provide the necessary flow and pressure of the system, although size may also be a point of consideration in the case of the robot design when taking into account the portability of the robot itself.**

### **Valves**

The main function of the solenoid valve is to either turn on or shut off the total flow in the pneumatic circuit. Solenoid valves can be controlled a number of ways, such as by air pressure and electrically [8]. Utilizing electrical current, a coil is activated, allowing flow, and thus without the electrical current, the coil is not activated and there will be no flow. In solenoids controlled by air pressure, the solenoid will only allow flow when a certain pressure, determined by the specific design, is experienced by the solenoid. Figure 13 - Figure 16 show example valves and their functional diagrams.



Figure 13: 12v DC 4mm 1/4" NPT Brass NBR 2-Way Solenoid Valve – Reprinted From [9]

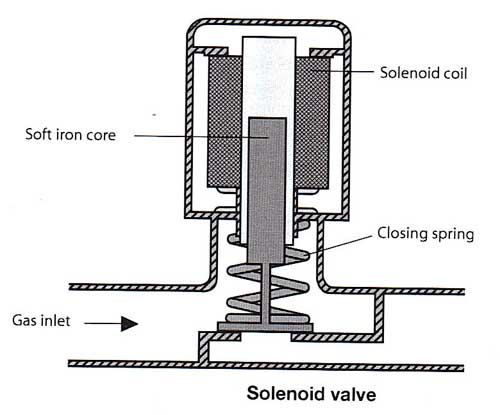


Figure 14: Electric Solenoid Valve – Cutaway – Reprinted From [10]

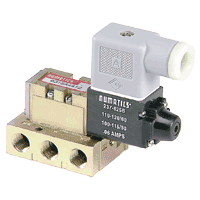
****

Figure 15: Numatics Mark 3, SPA 3, and PA 3 Series Valve – Reprinted From [11]

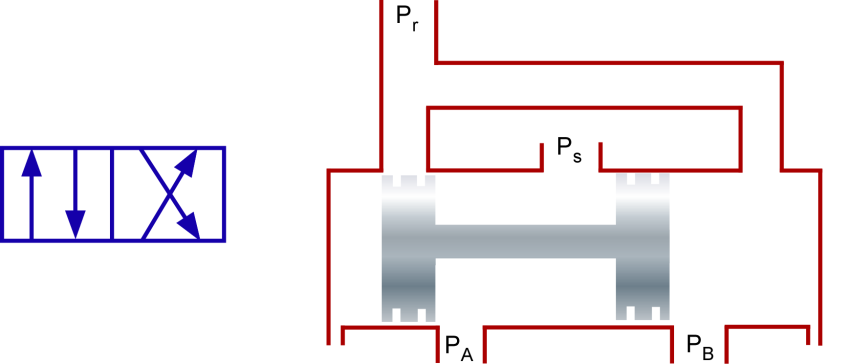


Figure 16: 4/2 Directional Control Valve – Reprinted From [12]

Directional control valves (DCV) allow free flow in one direction but restrict flow in the opposite directions, when air is flowing. A 4/3 DCV is necessary to allow flow in two directions allowing the cylinder to extend and contract. A 4/3 DCV means that there are 4 ports and 3 switch positions, as can be seen in Figure 16. Depending on the position, supply air will either go to port A or B, while the other port is connected to the exhaust line, allowing the cylinder to move in both directions. An example of a DCV is in Figure 17.



Figure 17: Belimo B208B : 2-Way 1/2" Brass .46 Cv Control Valve – Reprinted From [13]

In order to specify a suitable valve for a pneumatic system, it is important to consider the flow required by the components downstream from the valve. In order to ensure this flow is achievable, an appropriate Cv, or velocity coefficient, must be determined. It is helpful to convert Cv­ into volumetric flow in order compare the achievable flow through a prospective control valve and the necessary flow required by the air cylinder. It is however necessary to relate Cv to volumetric flow rates at a group of pressures because Cv represents flow capacity at all pressures and volumetric flow is represented at a specific pressure. Table 3 gives the relationship between Cv and volumetric flow rates at various pressures. In order to determine a volumetric flow rate at a specific pressure the Cv of the valve is divided by the appropriate factor.

Table 3: Relationship between Cv to SCFM at pressures between 40 and 100 psi – Reprinted from [14]

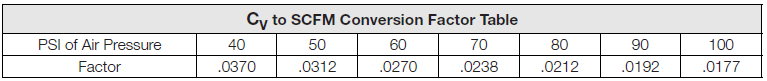


Figure 18 **shows an example pneumatic circuit for one robotic leg. The compressor, pressure relief valve, and accumulator are tethered to the robot using a high pressure line. The compressor takes air and pushes it into the accumulator tank to ensure a steady air supply during operation. The pressure relief valve opens if the system pressure is too high. The solenoid valve is electronically controlled by the robot’s processor and turns flow into the robot on and off. The electronic 4/3 valve is actuated by the microprocessor to control the position of a dual acting cylinder. Each electronic valve is setup in parallel to actuate the dual acting cylinders attached to each leg. The high pressure gas then leaves the system through an exhaust port in the robot. This circuit displays only one segment of the full circuit in which there are a total of 8 air cylinders and 8 directional control valves in parallel.**

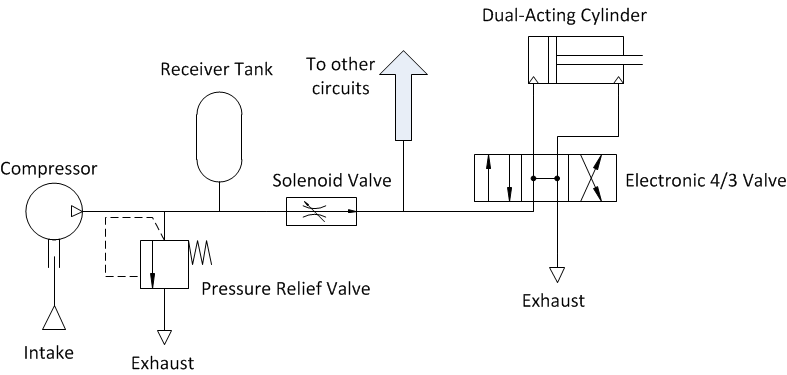


Figure 18: Sample pneumatic circuit for motion actuation

# Electrical System

The electronics of the robot are broken up into two major subsystems, the motherboard and the debug panel. The motherboard was designed to contain the auxiliary electronics and signal conditioning components needed for the robot. The debug panel contains all necessary electronics to display battery levels and other statuses of the robot.

To power the electronics two different sets of batteries are used. A cluster of 9 volt batteries is used to power the microcontroller and the first half of the signal conditioning circuits. The DCVs run on 10 volts DC. To provide the voltage needed by the DCVs a 12 volt battery is mounted onto the robot.

The debug panel subsystem contains a physical panel with light emitting diodes (LED) and connections for banana plug cables. The LEDs are used to show battery levels and the status of the robot. The banana plug connectors are used to interface to Milwaukee School of Engineering’s test equipment in the labs. Banana plugs are used because they are standard on test equipment. A USB slot is also included on the debug panel to assist in programming the microcontroller without removing it in the robot.

Two subcomponents of the debug panel are the 9 volt battery level indicator and the 12 volt battery level indicator. There were originally two options to make these indicators. The first option included using a LM 3914 chip, known as a dot/bar display driver. The LM 3914 uses 10 LEDs to create a dot graph or bar graph to display the magnitude of an input voltage. To implement the first option the battery voltage level would be connected to the LM 3914 and the 10 output LEDs used to display information to the robot operator. The second option to implement a battery level indicator uses zener diodes and LEDs. Three zener diodes with different threshold voltages are used to detect certain voltage levels of the battery. Depending on the voltage levels LEDs are turned on or off. To maintain the project timeline the simpler solution was chosen, which is using zener diodes and LEDs.

The 9 volt battery level indicator uses 3 zener diodes and LEDs. The LEDs are colored green, yellow, and red to indicate good voltage levels at green and bad voltage levels at red. To determine the voltage thresholds of the zener diodes the minimum voltage out of the battery to operate the robot was experimentally determined with an Agilent DC power supply. The microcontroller was connected to the DC power supply starting at 9 volts and slowly lowered until the microcontroller turned off. This lower voltage was measured at 4.5 volts. However, the microcontroller operates at 4.5 volts, but the 9 volt batteries have discharge curves the drop rapidly after 7 volts. To allow a long enough time for the user to change the batteries the red LED is set to turn on at 7 volts before the battery loses its electric potential. The discharge curves of an Energizer 9 volt battery is included in figure 19.

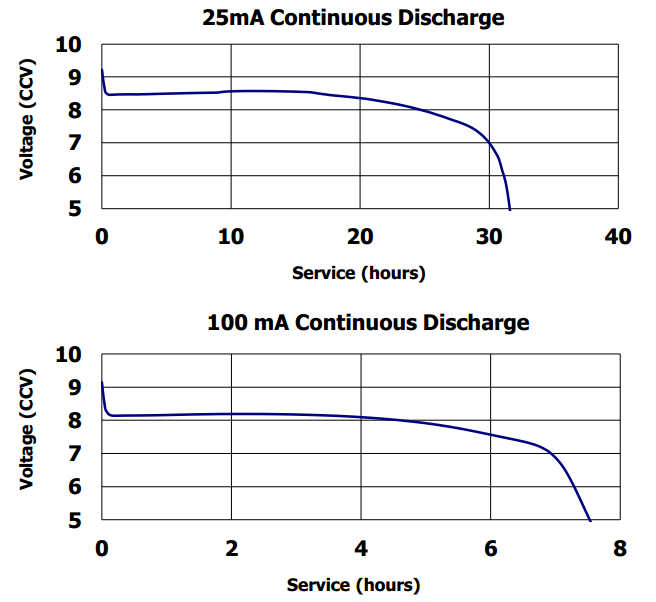


Figure 19: Energizer 9 volt battery discharge curve [15]

The Vmin is based off the 9 volt batteries and not the lower operating voltage of the microcontroller. The following equations are used to pick the required zener diode threshold voltages. Vmax is the maximum voltage of the battery. VT is the threshold voltage between each LED on voltage. The following equations are used

(27)

(28)

(29)

(30)

From the required voltages to turn on an LED the zener diode threshold voltages can be calculated.

The LEDs used are all from the same manufacturer to provide consistency in size and brightness. The LEDs are designed by Dialight and associated part numbers are 521-9210, 521-9211, and 521-9216 for green, yellow, and red respectively. The forward voltage required to turn the LEDs on is 2.1 volts. The forward current has a max rating of 30 mA for best operation. To design a path with an LED and zener diode to detect a 7 volt battery condition the following equation is used. VPath  is the voltage of the battery level being detected, VZ is the zener voltage threshold, VLED  is the LED forward bias voltage. 20mA of current is used because it is lower than the rated maximum current. The resistance of a current limiting resistor is calculated to be put in series with each path. The following three values are the zener voltage thresholds used; 5.1 volts, 4.7 volts, and 4.3 volts for green, yellow, and red LEDs respectively.

(VPath - VZ – VLED) / 20mA = R (31)

After each path was created the circuit was built in Multisim and tested for correct operation.

The motherboard contains the signal conditioning for each of the pneumatics cylinders. Each pneumatic cylinder is controlled by a signal analog direct current voltage. However, the signal driving this analog voltage is a pulse-width-modulated (PWM) output on the microcontroller. To convert a PWM into an analog signal an active low pass filter is used. After the low pass filter an opto-isolator is used to separate the microcontroller circuit from the pneumatic actuator circuit. An opto-isolator works by converting an electrical signal into an optical signal by using a diode. The optical signal is recaptures within the device and output onto another circuit as a current signal. At the output of the opto-isolator a trans-impedance amplifier is used to convert the output current signal to a voltage signal for the solenoid of the pneumatic valve. To handle the feedback signal from the pneumatic actuator another opto-isolator is used to separate the two power circuits then the signal is amplified before being read by the microcontroller’s built in analog to digital converters (ADCs).

Amplifiers are used with passive components to make an active low pass filter. The advantage of an active low pass filter is that the output impedance is near zero and the input impedance is infinity. This helps when cascading different stages of signal conditioning. The filter itself is designed to have a corner frequency of 100Hz, which is lower than the PWM frequency of 490Hz. Using 30 KΩ resistors on a third order Sallen-Key Butterworth low pass filter design tool the following capacitance values are found. The amplifiers used in the low pass filter are LM 741 standard op amps.

|  |  |  |
| --- | --- | --- |
| Stage | C1 [F] | C2 [F] |
| 1 | 5.495E-8 | 5.127E-8 |
| 2 | 7.507E-8 | 3.753E-8 |
| 3 | 2.051E-7 | 1.373E-8 |

The low pass filter circuit was built into Multisim software and tested for correct operation. The Multisim model is shown in figure 20. The possible output values of the filter are between 0 and 5 volts because of the input voltage of a 5 volt PWM.

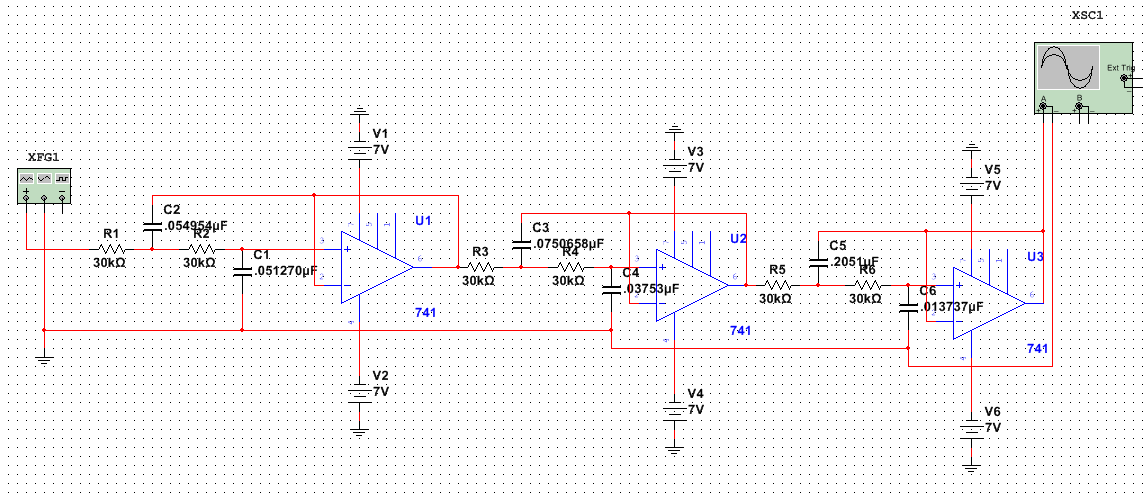


Figure 20: Low Pass Filter

The simulation is completed with the positive and negative rails of the op-amps connected to + 7 volts. This is done because 7 volts is the lower value sources by the 9 volt batteries.

The opto-isolator used in the mother board is the PS2501-4 photocoupler. This photocoupler consists of a LED and a phototransistor. The diode has a limit of 80mA forward current per channel and the transistor has a maximum collector current of 50 mA per channel. Using this device both electrical circuits will be entirely isolated from each other, but connected by an optical signal.

# Control Algorithms

The control algorithm is discrete time software implementation. The control is implemented using Simulink models cross compiled onto the target microcontroller. There are two major portions to the control algorithm, the finite state machine and the PID controllers. An overview of the architecture is given below for a single leg:

# D:\MyDocs\Documents\GitHub\AgileRoboticControls\System Modelling\Control\Control - General.png

Figure 21: General control architecture for a single leg. There are a total of four PID feedback loops in the full system, one for each leg.

This architecture was selected to ensure high system responsiveness. The state machine feedback loop involves heavy mathematical calculations to determine the position of each foot during runtime, so it runs much slower than the PID feedback loops. By creating an independent loop for each leg PID controller multiple feedback loops can be run for every system model loop, leading to high responsiveness. This master-slave architecture can be implemented through processor multithreading, and if that does not operate quickly enough additional slave microcontrollers will be purchased to run the PID loops. A detailed diagram of the real time control block diagram is given below:

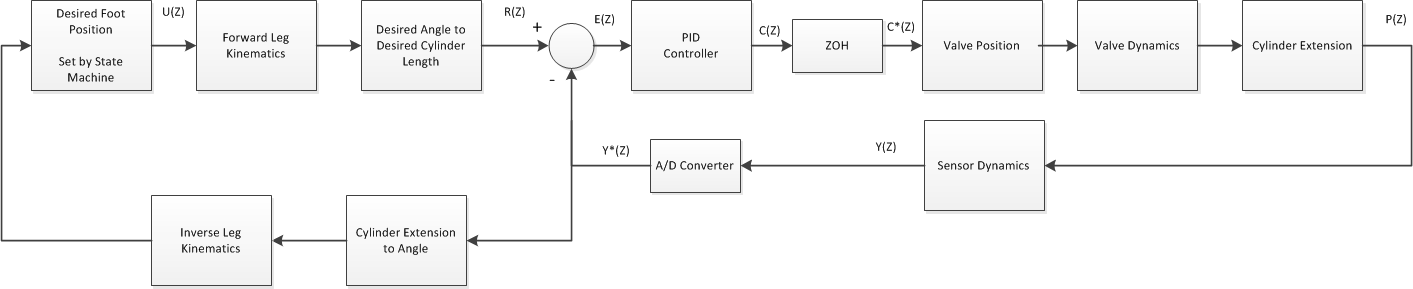


Figure 22: The master-slave architecture block diagram for a single leg. The left loop is the main system model loop and the right loop is the PID feedback controller. There are four right side loops in total, one for each leg.

The main intelligence of the robot will be implemented using a finite state machine. State machine transitions will be defined based on user input. Currently an initial state machine has been developed that has two states, stand-by and stop. Stand-by is a state in which the robot is determined to be functioning correctly and is awaiting user input. Stop is the state in which the robot completely stops ongoing motion and transitions into a stable position before powering down. Figure 21 shows a flowchart representation of the currently proposed state machine architecture:



Figure 23: Flowchart representation of the state machine architecture.

The state machine has a total of seven states. On system startup the state machine is set to *Initialize* which ensure the communication protocol is functioning and checks all subsystems for faults. When fault checking is completed the system transitions to the *Idle* state and waits for user input. Based on controller input the robot may enter the *Move Forward*, *Move Backward*, *Turn Right*, or *Turn Left* states and transition between them. The transitions between these states depends on the gait implementation of the robot. The above flowchart assumes stationary turns, but if the robot can only turn while walking forward or backward the transitions will be modified as required.

The final state is *Stop* which is transitioned to when a fault is detected or when input by the user. The stop state puts the robot into a stable default position before powering down each subsystem. The stop system will also be transitioned to if the microcontroller detects a power loss in the subsystems resulting from the emergency stop being activated.

# State Machine

It was determined that the behavior of the robot would be dictated utilizing a state machine. Using a state machine, based on the physical condition of the robot and the user input, the robot moves from different states and behaves occurring to how those states are defined within the state machine. Currently an initial state machine has been developed that has two states. The first state is a stand-by state in which the robot is determined to be functioning correctly and is awaiting user input. The second state is a stop state in which the robot, after some input which forces the robot into this state, completely stops ongoing motion in the robot and moves the robot into a stable position. Figure 20 shows a state machine flowchart in which various states are represented. States include forward and backward motion states in the robot, turning states and a stop state. The full state machine needs to be implemented in the next phase of the project for robot operation.



Figure 24: Flowchart representation of the state machine architecture.

# Conclusion

During the fall phase of the project a feasibility study and background research was conducted on robots with a similar scope. A set of criteria and specifications was developed, and four robot designs were drafted to meet the specifications. A final design was selected as a team by use of a decision matrix.

In the current phase of the project multiple simulations were developed to calculate the subsystem specifications to prevent failure during operation. Initially a dynamic simulation was created to calculate the required torques and internal forces felt at each joint during motion. These worst case scenarios were then passed through a finite element analysis to enhance the leg design. They were also passed into the motion study and pneumatic simulators to create specifications for the pneumatic circuit, such as maximum pressure and flow rate required. Finally, these specifications were used to select mechanical, pneumatic, and electrical components.

During the final phase of the project the robot will be assembled and the control architecture will be developed. When the parts arrive a prototype leg will be constructed to test run the control algorithms while the other robot subsystems are constructed. When the full robot is finished the control algorithms will be tested by moving a single leg while the other three remain stationary, allowing the robot to pull itself across the ground. Finally, if time permits, additional gaits will be programmed and optimized into the control architecture.

A project schedule, in the form of a Gantt chart, is given below:

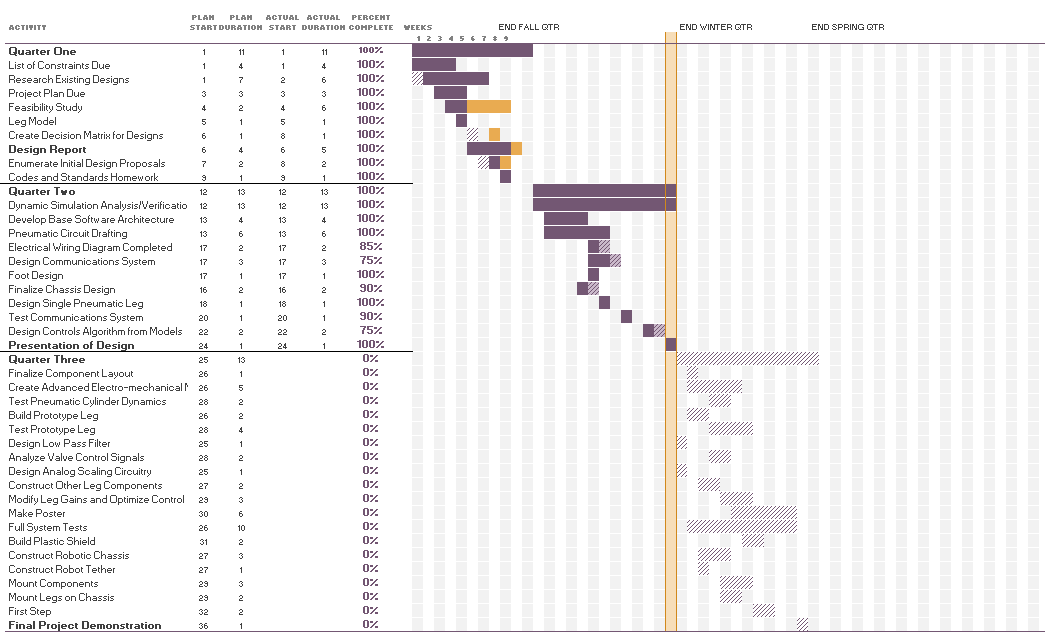


Figure 25: Gantt chart for project lifetime

# Environmental Report

## A. Materials Contained in Design

ALUMINUM EXTRUSIONS

The aluminum extrusion used for a majority of the robot hull is composed of extruded 6105-T5 aluminum. There are numerous recycling plants in Milwaukee which all buy scrap aluminum extrusions. Throughout the robot’s construction and after the robot’s life has ended all aluminum hull components will be salvaged.

TRACE METALS/ELEMENTS

Components used in the electrical design contain copper, silver, tungsten and silica. Electrical components should be recycled for reuse. These contained elements are not harmful to the environment.

LEAD

This element poses an environmental impact to water supplies and ecosystems. Organisms can be killed due to improper disposal of lead. Two different components of the system contain lead. The first component is lead acid batteries used to power the robot. These lead acid batteries must be recycled properly to reclaim the dangerous lead. The second component with lead is the solder used in the electrical connections. Components are connected together by a lead based solder. See the data sheets attached at the end of this appendix for material safety.

## B. Materials Contained in Prototype

The materials contained in the prototype are identical to the materials in the design. The prototype and the final design are the same robot. See section A for the full list of materials.

## C. Special Handling Instructions

The robot is intended for educational and demonstration purposes, primarily in classroom settings, and therefore is designed to be transported to various locations in the Milwaukee area. While the intent was to keep the robot fairly portable, given the size and weight of the robot, as well as necessary components, such as the air compressor, it is ideal to utilize a cart when transporting the robot long distances, to reduce the possibility of damage to components in case of drops. Given that many components of the robot will rely on electricity, settings where the robot may come into direct contact with water, such as in rain, are to be avoided.

Before operating the robot, all systems must be confirmed to be functioning correctly. The robot should also be placed in an open area free of unintentional obstacles, including people, to minimize the likelihood of personal injury or damage to the robot’s components. Being a user controlled robot, it is up to the users and observers to be vigilant in removing and avoiding obstacles when the robot is operated. Special care should be taken in being aware of the high pressure line running from the air compressor to the robot’s onboard system, as it may be a tripping hazard, and to make sure it is not tangled during operation.

In the event of malfunction in the robot, there will be a stop button located on the robot to stop running operations in the robot and cause it to enter a stable position and an emergency stop located on the robot stopping all operations in the robot. In cases that the microcontroller is not malfunctioning, but other systems in the robot are, the stop button located on the robot should be utilized, however if the microcontroller is not accessible due to the malfunction, the emergency stop located on the robot should be utilized to stop all power flow to the robot’s systems.

## D. Special Storage Instructions

The robot has been designed to be stored with few special considerations, as the metal parts are non-corrosive, however should be stored in a clean, dry, moderate-temperature environment when not in use. To avoid possible personal injury or damage to the robot and its components, it is advised that when in storage, the robot is stored below head level when in a shelving unit, or on level ground if possible.

## E. Disposal Instructions

All metal components should be recycled for reuse. All electrical components should be recycled as well. However, particular care of the lead acid batteries should be taken. Lead acid batteries must be recycled to reclaim the lead contained within.

# References

|  |  |
| --- | --- |
| [1] | J. R. Taylor, Classical Mechanics, Sausalito, CA: U Science, 2005. |
| [2] | K. J. Vandiver, *Introduction to Lagrange,* Cambridge, MA: MIT OpenCourseWare, 2013. |
| [3] | F. Beer, R. E. Johnston and P. Cornwell, Vector Mechanics for Engineers: Dynamics, New York: McGraw-Hill, 2013. |
| [4] | A. C. Chaing, Fundamental Methods of Mathematical Economics, McGraw-Hill, 1984. |
| [5] | Engineering Toolbox, "Friction and Coefficienst of Friction," Engineering Toolbox, [Online]. Available: http://www.engineeringtoolbox.com/friction-coefficients-d\_778.html. [Accessed 2015]. |
| [6] | Bimba Manufacturing, "Original Line® Air Cylinder," [Online]. Available: http://www.bimba.com/Products-and-Cad/Actuators/Inch/Round-Line/Non-Repairable/Original-Line-Cylinder/. |
| [7] | Grainger, "SPEEDAIRE Air Compressor,0.9 HP,120V,115 psi," [Online]. Available: http://www.grainger.com/product/SPEEDAIRE-Air-Compressor-25F537?s\_pp=false&picUrl=//static.grainger.com/rp/s/is/image/Grainger/25F537\_AS01?$smthumb$. |
| [8] | Norgen Fluid Controls, "Solenoid Valve Basics," [Online]. Available: http://www.pacontrol.com/download/Solenoid%20Valves%20Basics.pdf. |
| [9] | Amazon.com, "12v DC 4mm 1/4" NPT Normally Closed Brass NBR 2-Way Solenoid Valve," [Online]. Available: http://www.amazon.com/12v-Normally-Closed-Brass-Solenoid/dp/B005EP0WAO. |
| [10] | Upperplumbers, "Safety Devices and Controls," Upperplumbers, 12 March 2013. [Online]. Available: http://www.upperplumbers.co.uk/plumbing/plumbing\_pages.php?title=Safety%20Cut-off%20Devices&cat=1. [Accessed 21 November 2014]. |
| [11] | Emerson Industrial Automation, "Mark 3, SPA 3, and PA 3 Series Valve," [Online]. Available: http://www.numatics.com/applications/products/valves/mk3.aspx. |
| [12] | Design Aerospace LLC, "Directional Control Valve, Hydraulic - Description," Design Aerospace LLC, 2013. [Online]. Available: http://www.daerospace.com/HydraulicSystems/DirectionalValvesDesc.php. [Accessed 21 November 2014]. |
| [13] | Energy Control, "Belimo 2-Way 1/2 Inch Brass CCV Assembly," [Online]. Available: http://www.energycontrol.com/Belimo-B208B-CCV-Control-Valve-p/B208B.htm?gclid=CPPn7OeGg8ICFYZm7Aod7F4AQg. |
| [14] | Bimba, "Pneumatic Application and Reference Handbook". |
| [15] | Energizer, "www.energizer.com," [Online]. Available: www.energizer.com. [Accessed 26 2 2015]. |

# Appendix I – Dynamic Simulation MATLAB Code

%Handles configuration of the leg model and inputting values in LegModel.m

%Logan Beaver 10/23/14

clear; clc; close all;

Link1 = 'Thigh.stl';

Link2 = 'Shank.stl';

%read excel data%

CONSTANTS = ReadExcelData();

%assign the 12 read variables

totalWeight = CONSTANTS(1); % n

bodyLength = CONSTANTS(2); % m

bodyCg = CONSTANTS(3); % m from front

L1 = CONSTANTS(4); % cm1

iT = CONSTANTS(5); % m^4

thighCg = CONSTANTS(6); % m

tMass = CONSTANTS(7); % kg

L2 = CONSTANTS(8); % cm

iS = CONSTANTS(9); % m^4

shankCg = CONSTANTS(10); % m

sMass = CONSTANTS(11); % kg

frictionFactor = CONSTANTS(12); % unitless

%Cylinder velocities/accelerations, not relevant

L12 = L1; %cm

L21 = 0; %cm

P1x = -5; %cm

P1y = 0; %cm

P11 = L1/2; %cm

P21 = L1/2; %cm

P22 = L2/2; %cm

sampleDistance = 10; %cm - interpolation value for under-defined gaits

bodyVel = input('Insert Body Velocity In Meters per Second: '); % meters per second

stepDist = input('Insert Step Distance In Meters: '); % seconds

time = stepDist/bodyVel; %time to complete this step at the required speed

fprintf('Time Alloted for Step: %g seconds\n', time);

choice = input('Is this a foot drag (y/N): ', 's'); % seconds

if choice == 'y'

dragging = true;

fprintf('Running foot drag simulation...\n');

func = DragStep;

else

dragging = false;

fprintf('Running step simulation...\n');

func = SemiEllipseStep;

end

%read values from excel sheet

% ---- CONFIGURE STEP HERE BASED ON LEG LENGTHS AND STEP DISTANCE ------- %

Thetas = LegModel(Link1,Link2,L1,L2,L12,L21,P1x,P1y,P11,P21,P22,func,sampleDistance,time);

t = [0; cumsum(dt)];

theta1 = Thetas(:,1); %grabbing theta 1

theta2 = Thetas(:,2); %grabbing theta 2

dTheta1 = diff(theta1)./dt; %deltaTheta / deltaTime

dTheta2 = diff(theta2)./dt; %deltaTheta / deltaTime

ddTheta1 = diff(dTheta1)./dt(1:length(dt)-1);

ddTheta2 = diff(dTheta2)./dt(1:length(dt)-1);

MatrixDynamics();

%Put forces into moment equations

syms FH1x FH2x FH3x FH4x FH1y FH2y FH3y FH4y;

syms FK1x FK2x FK3x FK4x FK1y FK2y FK3y FK4y;

%Important values ---------------------------------- TOTAL WEIGHT

%subs forces into Torque equations

T = [Ts.TH1; Ts.TH2; Ts.TH3; Ts.TH4; Ts.TK1; Ts.TK2; Ts.TK3; Ts.TK4];

T = subs(T, FK1x, FORCES.FK1x);T = subs(T, FK2x, FORCES.FK2x);

T = subs(T, FK3x, FORCES.FK3x);T = subs(T, FK4x, FORCES.FK4x);

T = subs(T, FK1y, FORCES.FK1y);T = subs(T, FK2y, FORCES.FK2y);

T = subs(T, FK3y, FORCES.FK3y);T = subs(T, FK4y, FORCES.FK4y);

T = subs(T, FH1x, FORCES.FH1x);T = subs(T, FH2x, FORCES.FH2x);

T = subs(T, FH3x, FORCES.FH3x);T = subs(T, FH4x, FORCES.FH4x);

T = subs(T, FH1y, FORCES.FH1y);T = subs(T, FH2y, FORCES.FH2y);

T = subs(T, FH3y, FORCES.FH3y);T = subs(T, FH4y, FORCES.FH4y);

%create and subs forces

F = [FORCES.FK1x; FORCES.FH1x; FORCES.FK2x; FORCES.FH2x; ...

FORCES.FK3x; FORCES.FH3x; FORCES.FK4x; FORCES.FH4x; ...

FORCES.FK1y; FORCES.FH1y; FORCES.FK2y; FORCES.FH2y; ...

FORCES.FK3y; FORCES.FH3y; FORCES.FK4y; FORCES.FH4y];

%values to be set to constant values -------------------------SET ANGLES

syms x y tb th2 th3 th4 tk2 tk3 tk4;

syms xdot ydot tbdot th2dot th3dot th4dot tk2dot tk3dot tk4dot;

syms xddot yddot tbddot th2ddot th3ddot th4ddot tk2ddot tk3ddot tk4ddot;

%body vals---------------------------------------------------BODY ANGLES

T = subs(T, x, 0); T = subs(T, y, 0); T = subs(T, xdot, bodyVel); T = subs(T, ydot, 0);

T = subs(T, xddot, 0); T = subs(T, yddot, 0);

T = subs(T, tb, 0) ;T = subs(T, tbdot, 0); T = subs(T, tbddot, 0);

F = subs(F, x, 0); F = subs(F, y, 0); F = subs(F, xdot, bodyVel); F = subs(F, ydot, 0);

%forces

F = subs(F, xddot, 0); F = subs(F, yddot, 0);

F = subs(F, tb, 0) ;F = subs(F, tbdot, 0); F = subs(F, tbddot, 0);

%limb vals-------------------------------------------------3 LIMB ANGLES

T = subs(T, th2, pi); T = subs(T, th3, pi); T = subs(T, th4, pi);

T = subs(T, tk2, 0); T = subs(T, tk3, 0); T = subs(T, tk4, 0);

T = subs(T, th2dot, 0); T = subs(T, th3dot, 0); T = subs(T, th4dot, 0);

T = subs(T, tk2dot, 0); T = subs(T, tk3dot, 0); T = subs(T, tk4dot, 0);

T = subs(T, th2ddot, 0); T = subs(T, th3ddot, 0); T = subs(T, th4ddot, 0);

T = subs(T, tk2ddot, 0); T = subs(T, tk3ddot, 0); T = subs(T, tk4ddot, 0);

%forces

F = subs(F, th2, pi); F = subs(F, th3, pi); F = subs(F, th4, pi);

F = subs(F, tk2, 0); F = subs(F, tk3, 0); F = subs(F, tk4, 0);

F = subs(F, th2dot, 0); F = subs(F, th3dot, 0); F = subs(F, th4dot, 0);

F = subs(F, tk2dot, 0); F = subs(F, tk3dot, 0); F = subs(F, tk4dot, 0);

F = subs(F, th2ddot, 0); F = subs(F, th3ddot, 0); F = subs(F, th4ddot, 0);

F = subs(F, tk2ddot, 0); F = subs(F, tk3ddot, 0); F = subs(F, tk4ddot, 0);

%force values-----------------------------------------------FOOT FORCES

syms FF1x FF1y FF2x FF2y FF3x FF3y FF4x FF4y;

if dragging

T = subs(T, FF1x, 3\*totalWeight/4\*frictionFactor); T = subs(T, FF2x, totalWeight/4\*frictionFactor); T = subs(T, FF3x, totalWeight/4\*frictionFactor); T = subs(T, FF4x, totalWeight/4\*frictionFactor);

T = subs(T, FF1y, totalWeight/4); T = subs(T, FF2y, totalWeight/4); T = subs(T, FF3y, totalWeight/4); T = subs(T, FF4y, totalWeight/4);

%force

F = subs(F, FF1x, 3\*totalWeight/4\*frictionFactor); F = subs(F, FF2x, totalWeight/4\*frictionFactor); F = subs(F, FF3x, totalWeight/4\*frictionFactor); F = subs(F, FF4x, totalWeight/4\*frictionFactor);

F = subs(F, FF1y, totalWeight/4); F = subs(F, FF2y, totalWeight/4); F = subs(F, FF3y, totalWeight/4); F = subs(F, FF4y, totalWeight/4);

else

T = subs(T, FF1x, 0); T = subs(T, FF2x, 0); T = subs(T, FF3x, 0); T = subs(T, FF4x, 0);

T = subs(T, FF1y, 0); T = subs(T, FF2y, totalWeight/3); T = subs(T, FF3y, totalWeight/3); T = subs(T, FF4y, totalWeight/3);

%force

F = subs(F, FF1x, 0); F = subs(F, FF2x, 0); F = subs(F, FF3x, 0); F = subs(F, FF4x, 0);

F = subs(F, FF1y, 0); F = subs(F, FF2y, totalWeight/3); F = subs(F, FF3y, totalWeight/3); F = subs(F, FF4y, totalWeight/3);

end

%masses and weights ---------------------------------------MASSES

syms mS1 mS2 mS3 mS4 mT1 mT2 mT3 mT4 g;

T = subs(T, mS1, sMass);T = subs(T, mS2, sMass);T = subs(T, mS3, sMass);T = subs(T, mS4, sMass);

T = subs(T, mT1, tMass);T = subs(T, mT2, tMass);T = subs(T, mT3, tMass);T = subs(T, mT4, tMass);

T = subs(T, g, 9.81);

%forces

F = subs(F, mS1, sMass);F = subs(F, mS2, sMass);F = subs(F, mS3, sMass);F = subs(F, mS4, sMass);

F = subs(F, mT1, tMass);F = subs(F, mT2, tMass);F = subs(F, mT3, tMass);F = subs(F, mT4, tMass);

F = subs(F, g, 9.81);

%Lengths--------------------------------------------------LIMB CGs

syms LH1 LH2 LH3 LH4 LK1 LK2 LK3 LK4 LF1 LF2 LF3 LF4 LT1 LT2 LT3 LT4 LS1 LS2 LS3 LS4;

%L1 L2 L3 L4 are converted to m from cm by dividing by 100

T = subs(T, LK1, L1/100);T = subs(T, LK2, bodyLength-L1/100);T = subs(T, LK3, L1/100);T = subs(T, LK4, bodyLength-L1/100);

T = subs(T, LF1, L2/100);T = subs(T, LF2, L2/100);T = subs(T, LF3, L2/100);T = subs(T, LF4, L2/100);

T = subs(T, LH1, bodyCg);T = subs(T, LH2, bodyCg);T = subs(T, LH3, bodyCg);T = subs(T, LH4, bodyCg);

T = subs(T, LT1, thighCg);T = subs(T, LT2, thighCg);T = subs(T, LT3, thighCg);T = subs(T, LT4, thighCg);

T = subs(T, LS1, shankCg);T = subs(T, LS2, shankCg);T = subs(T, LS3, shankCg);T = subs(T, LS4, shankCg);

%forces

F = subs(F, LK1, L1/100);F = subs(F, LK2, bodyLength-L1/100);F = subs(F, LK3, L1/100);F = subs(F, LK4, bodyLength-L1/100);

F = subs(F, LF1, L2/100);F = subs(F, LF2, L2/100);F = subs(F, LF3, L2/100);F = subs(F, LF4, L2/100);

F = subs(F, LH1, bodyCg);F = subs(F, LH2, bodyCg);F = subs(F, LH3, bodyCg);F = subs(F, LH4, bodyCg);

F = subs(F, LT1, thighCg);F = subs(F, LT2, thighCg);F = subs(F, LT3, thighCg);F = subs(F, LT4, thighCg);

F = subs(F, LS1, shankCg);F = subs(F, LS2, shankCg);TF= subs(F, LS3, shankCg);F = subs(F, LS4, shankCg);

%Moments of Inertia-------------------------------------INERTIA

syms IS1z IT1z IS2z IS3z IS4z IT2z IT3z IT4z;

T = subs(T, IS1z, iS);T = subs(T, IT1z, iT);

F = subs(F, IS1z, iS);F = subs(F, IT1z, iT);

%T = subs(T, IS2z, iS);T = subs(T, IT2z, iT);

%T = subs(T, IS3z, iS);T = subs(T, IT3z, iT);

%T = subs(T, IS4z, iS);T = subs(T, IT4z, iT);

syms th1 tk1 th1dot tk1dot th1ddot tk1ddot

Tindex = 1;

Tval = 0;

Findex = 1;

Fval = 0;

fprintf('Calculaing Average and Maximum Torque/Force...\n');

for i=1:length(ddTheta1)%Loop to get all the torques added to the sum

Ti = T;

Ti = subs(Ti, th1, theta1(i)); Ti = subs(Ti, tk1, theta2(i));

Ti = subs(Ti, th1dot, dTheta1(i)); Ti = subs(Ti, tk1dot, dTheta2(i));

Ti = subs(Ti, th1ddot, ddTheta1(i)); Ti = subs(Ti, tk1ddot, ddTheta2(i));

Fi = F;

Fi = subs(Fi, th1, theta1(i)); Fi = subs(Fi, tk1, theta2(i));

Fi = subs(Fi, th1dot, dTheta1(i)); Fi = subs(Fi, tk1dot, dTheta2(i));

Fi = subs(Fi, th1ddot, ddTheta1(i)); Fi = subs(Fi, tk1ddot, ddTheta2(i));

if i == 1

FTotal = eval(Fi);

TTotal = eval(Ti);

else

FTotal(:,i) = eval(Fi);

TTotal(:,i) = eval(Ti);

end

if mean(FTotal(:,i)) > mean(Fval) && (i > 1) %probably should find equivilant force instead of max average...

Fval = FTotal(:,i);

Findex = i;

end

if mean(TTotal(:,i)) > mean(Tval) && (i > 1)%compare the max singular torque instead?

Tval = mean(TTotal(:,i));

Tindex = i;

end

end

fprintf('Fetching robot state at critical points\n');

%Divide the torques by the number of vals - average

avgT = (trapz(t(2:length(t)-1),TTotal') / sum(dt))';

avgF = (trapz(t(2:length(t)-1),FTotal') / sum(dt))';

thetas1 = [theta1(Tindex) theta2(Tindex)];

dThetas1 = [dTheta1(Tindex) dTheta2(Tindex)];

ddThetas1 = [ddTheta1(Tindex) ddTheta2(Tindex)];

thetas2 = [theta1(Findex) theta2(Findex)];

dThetas2 = [dTheta1(Findex) dTheta2(Findex)];

ddThetas2 = [ddTheta1(Findex) ddTheta2(Findex)];

fprintf('Calculaing Forces and Torques...\n');

FI1 = F;

TI1 = T;

%Insert Values-------------------------------------------ANGLES

TI1 = subs(TI1, th1, thetas1(1)); TI1 = subs(TI1, tk1, thetas1(2));

TI1 = subs(TI1, th1dot, dThetas1(1)); TI1 = subs(TI1, tk1dot, dThetas1(2));

TI1 = subs(TI1, th1ddot, ddThetas1(1)); TI1 = subs(TI1, tk1ddot, ddThetas1(2));

%forces

FI1 = subs(FI1, th1, thetas1(1)); FI1 = subs(FI1, tk1, thetas1(2));

FI1 = subs(FI1, th1dot, dThetas1(1)); FI1 = subs(FI1, tk1dot, dThetas1(2));

FI1 = subs(FI1, th1ddot, ddThetas1(1)); FI1 = subs(FI1, tk1ddot, ddThetas1(2));

FI2 = F;

TI2 = T;

%Insert Values-------------------------------------------ANGLES

TI2 = subs(TI2, th1, thetas2(1)); TI2 = subs(TI2, tk1, thetas2(2));

TI2 = subs(TI2, th1dot, dThetas2(1)); TI2 = subs(TI2, tk1dot, dThetas2(2));

TI2 = subs(TI2, th1ddot, ddThetas2(1)); TI2 = subs(TI2, tk1ddot, ddThetas2(2));

%forces

FI2 = subs(FI2, th1, thetas2(1)); FI2 = subs(FI2, tk1, thetas2(2));

FI2 = subs(FI2, th1dot, dThetas2(1)); FI2 = subs(FI2, tk1dot, dThetas2(2));

FI2 = subs(FI2, th1ddot, ddThetas2(1)); FI2 = subs(FI2, tk1ddot, ddThetas2(2));

TI1=eval(TI1);

TI2=eval(TI2);

FI1=eval(FI1);

FI2=eval(FI2);

if ~dragging

fprintf('Calculating step impulse force\n');

vhx = bodyVel;vhy = 0; %hip velocity (x, y) from body velocity at 0 deg

%find max angular velocities

i1 = find(dTheta1==max(dTheta1)); i2 = find(dTheta2==max(dTheta2));

%calculating thigh speeds

vt1 = [thighCg\*cos(dTheta1(i1))+vhx, thighCg\*sin(dTheta1(i1))+vhy];

vt2 = [thighCg\*cos(dTheta1(i2))+vhx, thighCg\*sin(dTheta1(i2))+vhy];

%calculating knee speeds

vk1 = [L1\*cos(dTheta1(i1))+vhx, L1\*sin(dTheta1(i1))+vhy];

vk2 = [L1\*cos(dTheta1(i2))+vhx, L1\*sin(dTheta1(i2))+vhy];

%calculating shank speed

vs1 = vk1 + [L2\*cos(dTheta2(i1)), L2\*sin(dTheta2(i1))];

vs2 = vk2 + [L2\*cos(dTheta2(i2)), L2\*sin(dTheta2(i2))];

%F = mLeg \* vLeg - impulse momentum equations

Fi1 = tMass \* vt1 + sMass \* vs1;

mag1 = sqrt(Fi1(1)^2 + Fi1(2)^2);

Fi2 = tMass \* vt2 + sMass \* vs2;

mag2 = sqrt(Fi2(1)^2 + Fi2(2)^2);

fprintf('\n');

if mag1 > mag2

fprintf('Impulse force of %g N\n', mag1);

fprintf('Components: %g N x, %g N y \n', Fi1(1), Fi1(2));

else

fprintf('Impulse force of %g \n', mag2);

fprintf('Components: %g N x, %g N y \n', Fi2(1), Fi2(2));

end

end

fprintf('Simulation complete!\n');

%Function used to simulate the robotic leg

%Inputs:

%Link1, Link2 - .stl files

%L1, L2 - the length of each link

%L12 - the distance along L1 where L2 is attached

%L21 - the distance along L2 where L1 is attached

%P1x, P1y - the ground location of piston 1

%P12 - the distance of piston 1's attachment point on link 2

%p21 - the distance of piston 2's attachment point on link 1

%p22 - the distance of piston 2's attachment point on link 2

%Theta1 and Theta2 are the starting conditions

function y=LegModel(Link1, Link2, L1, L2, L12, L21, P1x, P1y, P11, P21, P22,path,sampleDistance, time)

%calculate the number of points in the path

numPts = size(path);

numPts = numPts(1);

%foot position index

index = 1;

footPosition(index,:) = path(1,:);

Theta(index,:) = InverseKinematics(L12, L2-L21, footPosition(index,1), footPosition(index,2));

drawPosition(index,:) = ForwardKinematics(L12, L2-L21, Theta(1), Theta(2));

index = index + 1;

%calculate total distance of the path

totalDistance = 0;

for i = 1:numPts

desiredPos = path(i,:);

while footPosition(index-1,1) ~= desiredPos(1) || footPosition(index-1,2) ~= desiredPos(2)

%move footPosition up to sampleDistance

d = min(sampleDistance, Distance(desiredPos(1), desiredPos(2), footPosition(index-1,1), footPosition(index-1,2)));

unitVector = [desiredPos(1) - footPosition(index-1,1),desiredPos(2) - footPosition(index-1,2)];

unitVector = unitVector ./ sqrt(unitVector(1)^2 + unitVector(2)^2);

unitVector = unitVector.\*d;

%update foot position

footPosition(index,:) = footPosition(index-1,:) + unitVector;

Theta(index,:) = InverseKinematics(L12, L2-L21, footPosition(index,1), footPosition(index,2));

drawPosition(index,:) = ForwardKinematics(L12, L2-L21, Theta(index,1), Theta(index,2));

index = index + 1;

end

if i > 1

totalDistance = totalDistance + Distance(path(i-1,1), path(i-1,2), path(i,1), path(i,2));

end

end

%calculate cylinder positions

footVelocity = totalDistance/time;

for i = 1:length(footPosition)

cylPos(i,:) = FootToCylinder(L12, L2-L21, P1x, P1y, P11, P21, P22, footPosition(i,1), footPosition(i,2));

end

for i = 1:length(footPosition)-1

d(i) = Distance(footPosition(i,1), footPosition(i,2), footPosition(i+1,1), footPosition(i+1,2));

end

dt = d / footVelocity;

assignin('base', 'dt', dt');

%calculate acceleration parameters

cylAcc(:,1) = diff(cylPos(:,1), 2);

cylAcc(:,2) = diff(cylPos(:,2), 2);

%draw the foot position

DrawArm(Link1, Link2, drawPosition(:,1), drawPosition(:,2), L12, L2-L21, cylPos, dt, cylAcc);

%

% maxTheta1 = max(Theta(:,1));

% maxTheta2 = max(Theta(:,2));

% minTheta1 = min(Theta(:,1));

% minTheta2 = min(Theta(:,2));

%

% maxPL1 = max(cylPos(:,1));

% maxPL2 = max(cylPos(:,2));

% minPL1 = min(cylPos(:,1));

% minPL2 = min(cylPos(:,2));

%

% maxP1Acc = max(abs(cylAcc(:,1)));

% maxP2Acc = max(abs(cylAcc(:,2)));

%return important values

y = Theta;%[minTheta1, maxTheta1, minTheta2, maxTheta2; ...

% minPL1, maxPL1, minPL2, maxPL2;...

% 0, maxP1Acc, 0, maxP2Acc,];

end

%Calculates the forward kinematics of a variable configuration 2R

%robotic arm

%Logan Beaver 11/28/14

%D1 = Distance along link 1 of joint 1 from the base

%D2 = Distance along link 2 of joint 1 from the foot

%T1 = Theta 1; T2 = Theta 2

function footPos = ForwardKinematics(D1,D2,T1,T2)

x = D1\*cosd(T1) + D2\*cosd(T1+T2);

y = D1\*sind(T1) + D2\*sind(T1+T2);

footPos = [x, y];

end

%The inverse kinematics to determine the robot's necessary position

%Logan Beaver ,10/4/14

function angles = InverseKinematics(L1,L2, x, y)

%"max()" is used to ensure the robot stays within its operational bounds

num = max((L1+L2)^2 - (x^2 + y^2), 0);

den = max((x^2 + y^2) - (L1-L2)^2, 0);

theta2 = -2\*atan2(sqrt(num),sqrt(den));

num = y\*(L1+L2\*cos(theta2)) - L2\*x\*sin(theta2);

den = x\*(L1+L2\*cos(theta2)) + L2\*y\*sin(theta2);

theta1 = atan2(num,den)\*180/pi;

theta2 = theta2\*180/pi;

angles = [theta1, theta2];

end

function [p,V,p2,V2] = cad2poly(filename, filename2)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Main File : cad2poly.m

% Source Files: cad2mat.m

% Description : Converts CAD geometry into multiple polygons and plots

% the resulting geometry

% Input : filename, filename2 -filenames of the geometry to convert

% Output : p, V, p2, V2 -The corresponding polygons and vertices of

% the geometry in filename and filename2, respectively.

% Author : Dr. L.A. Rodriguez

% Date : 02/04/2014

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Converts CAD data to MATLAB using the cad2ply.m file, which is a

% modified version of the cad2matdemo.m file located on the

% Mathworks central file exchange.

% F-faces, V-vertices, C-color

[F,V,C] = cad2mat(filename);

[F2,V2,C2] = cad2mat(filename2);

if strcmp(filename, 'Thigh.stl')

V(:,2) = V(:,2) - 0.445;

V(:,2) = V(:,2)\*(-1);

V(:,1) = V(:,1) - 0.05;

x = V(:,1);

V(:,1) = V(:,2);

V(:,2) = x;

V(:,1) = V(:,1);

dTheta = 33;

V = (V \* [cosd(dTheta) -sind(dTheta) 0;

sind(dTheta) cosd(dTheta) 0;

0 0 1]);

end

if strcmp(filename2, 'Shank.stl')

x2 = V2(:,1);

V2(:,1) = V2(:,2);

V2(:,2) = x2 - 0.05;

V2(:,1) = V2(:,1) \* -1 + 0.27;

end

h = figure(1);

clf;

p = patch('faces', F, 'vertices' ,V); % create the polygons

p2 = patch('faces', F2, 'vertices' ,V2); % create the polygons

set(p, 'facec', 'flat'); % Set the face color flat

set(p2, 'facec', 'flat'); % Set the face color flat

set(p, 'FaceVertexCData', C); % Set the color (from file)

set(p2, 'FaceVertexCData', C); % Set the color (from file)

set(p, 'EdgeColor','none'); % Set the edge color

set(p2, 'EdgeColor','none'); % Set the edge color

% Color options yellow,magenta,cyan,red,green,blue,white, black

set(p,'FaceColor','red') % set color of filename geometry

set(p2,'FaceColor','cyan') % set color of filename2 geometry

light % add a default light

daspect([1 1 1]) % Setting the aspect ratio

view(3) % Plot isometric view

xlabel('X'),ylabel('Y'),zlabel('Z')

%title({['Imported Solidworks Geometry from ' filename ' and ' filename2] ' Used to animate a 2-link robot'})

title(['Imported Solidworks Geometry from ' filename ' and ' filename2])

drawnow

shg

% To use homogenous transformation matrices the n by 3 vertices will be

% turned to n by 4 vertices by augmenting them with ones, [V;1]

V = [V ones(length(V),1)]';

V2 = [V2 ones(length(V2),1)]';

function [F,V,C] = cad2mat(filename)

% CAD2MATDEMO, a demonstration of importing 3D CAD data into Matlab.

% To get CAD data into Matlab, the process is:

%

% 1) Export the 3D CAD data as an ASCII STL (or Pro/E render SLP) file.

% 2) This Matlab routine reads the CAD data

% 3) Once read, the CAD data is rotated around a bit.

%

% Program has been tested with: AutoCAD, Cadkey, and Pro/Engineer.

% Should work with most any CAD programs that can export STL.

%

% Format Details: STL is supported, and the color version of STL

% that Pro/E exports, called 'render.' The render (SLP) is just

% like STL but with color added.

%

% Note: This routine has both the import function and some basic

% manipulation for testing. The actual reading mechanism is located

% at the end of this file.

if nargin == 0

filename = 'link.stl'; % a simple demo part

warning(['No file specified, using demo file: ' filename]);

end

%

% Read the CAD data file:

[F, V, C] = rndread(filename);

function [fout, vout, cout] = rndread(filename)

% Reads CAD STL ASCII files, which most CAD programs can export.

% Used to create Matlab patches of CAD 3D data.

% Returns a vertex list and face list, for Matlab patch command.

%

% filename = 'hook.stl'; % Example file.

%

fid=fopen(filename, 'r'); %Open the file, assumes STL ASCII format.

if fid == -1

error('File could not be opened, check name or path.')

end

%

% Render files take the form:

%

%solid BLOCK

% color 1.000 1.000 1.000

% facet

% normal 0.000000e+00 0.000000e+00 -1.000000e+00

% normal 0.000000e+00 0.000000e+00 -1.000000e+00

% normal 0.000000e+00 0.000000e+00 -1.000000e+00

% outer loop

% vertex 5.000000e-01 -5.000000e-01 -5.000000e-01

% vertex -5.000000e-01 -5.000000e-01 -5.000000e-01

% vertex -5.000000e-01 5.000000e-01 -5.000000e-01

% endloop

% endfacet

%

% The first line is object name, then comes multiple facet and vertex lines.

% A color specifier is next, followed by those faces of that color, until

% next color line.

%

CAD\_object\_name = sscanf(fgetl(fid), '%\*s %s'); %CAD object name, if needed.

% %Some STLs have it, some don't.

vnum=0; %Vertex number counter.

report\_num=0; %Report the status as we go.

VColor = 0;

%

while feof(fid) == 0 % test for end of file, if not then do stuff

tline = fgetl(fid); % reads a line of data from file.

fword = sscanf(tline, '%s '); % make the line a character string

% Check for color

if strncmpi(fword, 'c',1) == 1; % Checking if a "C"olor line, as "C" is 1st char.

VColor = sscanf(tline, '%\*s %f %f %f'); % & if a C, get the RGB color data of the face.

end % Keep this color, until the next color is used.

if strncmpi(fword, 'v',1) == 1; % Checking if a "V"ertex line, as "V" is 1st char.

vnum = vnum + 1; % If a V we count the # of V's

report\_num = report\_num + 1; % Report a counter, so long files show status

if report\_num > 249;

% disp(sprintf('Reading vertix num: %d.',vnum));

report\_num = 0;

end

v(:,vnum) = sscanf(tline, '%\*s %f %f %f'); % & if a V, get the XYZ data of it.

c(:,vnum) = VColor; % A color for each vertex, which will color the faces.

end % we "\*s" skip the name "color" and get the data.

end

% Build face list; The vertices are in order, so just number them.

%

fnum = vnum/3; %Number of faces, vnum is number of vertices. STL is triangles.

flist = 1:vnum; %Face list of vertices, all in order.

F = reshape(flist, 3,fnum); %Make a "3 by fnum" matrix of face list data.

%

% Return the faces and vertexs.

%

fout = F'; %Orients the array for direct use in patch.

vout = v'; % "

cout = c';

%

fclose(fid);

%calculates distance between (x1, y1) and (x2, y2)

function d = Distance(x1, y1, x2, y2)

d = sqrt((x1-x2)^2 + (y1-y2)^2);

end

function DrawArm(Link1, Link2, x, y, D1, D2, cylPos, dt, cylAcc)

% Converts CAD geometry into multiple polygons and into its vertices

% link1Pnts and link2Pnts already includes the bottom

% row of ones, that is link1Pnts = [Pnts;1]

[p,link1Pnts,p2,link2Pnts] = cad2poly(Link1, Link2);

view(2); %2D

%set plot bounds

maxVal = (max(max(max(abs(x)), max(abs(y))), 0))/100 \* 1.25;

figure(1);

hold on;

axis([-maxVal maxVal -maxVal 0.05]);

xlabel('X Position [m]');

ylabel('Y Position [m]');

cdt = cumsum(dt);

for i = 1:length(x)

Theta = InverseKinematics(D1, D2, x(i), y(i));

%update position of STL models

drawRobot(p, p2, Theta(1), Theta(2), link1Pnts, link2Pnts, (D1-2)/100);

%plot current path progress

figure(1)

movegui('northwest');

title('Robot Step Animation');

plot(x(1:i)/100, y(1:i)/100);

% pause(0.05)

%draw cylinder positions

%plot the cylinder lengths

figure(2);

movegui('north');

hold on;

subplot(2,1,1);

title('Cylinder 1 - Position vs Time [m]');

axis([0, sum(dt), min(cylPos(:,1))\*.95, max(cylPos(:,1))\*1.05]);

plot(cdt(1:min(i, length(cdt))), cylPos(1:min(i, length(dt)),1));

figure(3);

movegui('northeast');

hold on;

subplot(2,1,1);

title('Cylinder 2 - Position vs Time [m]');

axis([0, sum(dt), min(cylPos(:,2))\*.95, max(cylPos(:,2))\*1.05]);

plot(cdt(1:min(i, length(cdt))), cylPos(1:min(i, length(cdt)),2));

%plot the cylinder accelerations

figure(2);

hold on;

subplot(2,1,2);

title('Cylinder 1 - Acceleration vs Time [m/s/s]');

axis([0, sum(dt), min(cylAcc(:,1))\*.95, max(cylAcc(:,1))\*1.05]);

plot(cdt(1:min(i, length(cdt)-1)), cylAcc(1:min(i, length(cdt)-1),1));

figure(3);

hold on;

subplot(2,1,2);

title('Cylinder 2 - Acceleration vs Time [m/s/s]');

axis([0, sum(dt), min(cylAcc(:,2))\*.95, max(cylAcc(:,2))\*1.05]);

plot(cdt(1:min(i, length(cdt)-1)), cylAcc(1:min(i, length(cdt)-1),2));

end

end

function drawRobot(p,p2,theta1,theta2,link1Pnts,link2Pnts, L1)

% Rotate and translate Link vertices

T\_01 = RotZ(theta1);

link1NewPnts = T\_01\*link1Pnts; % new vertices Link1

T\_12 = Trans(L1,0,0)\*RotZ(theta2); % new vertices Link2

link2NewPnts = T\_01\*T\_12\*link2Pnts;

% Draw robot

set(p,'Vertices',link1NewPnts(1:3,:)');

set(p2,'Vertices',link2NewPnts(1:3,:)');

end

%A function that takes in the foot position and returns the length of

%cylinder 1 and cylinder 2

%Inputs

%L1 - Link 1, L2 - Link 2

%D1 - Distance along Link 1 where Link 2 is attached

%D2 - Distance along Link 2 where Link 1 is attahced

%P1x, P1y - ground position of cylinder 1

%P11 - Distance along L1 where cylidner 1 is attached

%P21 - postion of Cylinder 2 on link 1, P22 - Position of Cylinder 2 on link 2

%x, y - Foot Position

function lengths = FootToCylinder(D1, D2, P1x, P1y, P11, P21, P22, x, y)

%Calculate inverse kinematics

Theta = InverseKinematics(D1, D2, x, y);

%Length of Cylinder 1

deltaX = -P1x + P11\*cosd(90-Theta(1));

deltaY = -P1y + P11\*sind(90-Theta(1));

PL1 = Distance(deltaX, deltaY, 0, 0);

%Length of Cylinder 2

Ax = P21\*cosd(Theta(1)); %x coordinate of P21

Ay = P21\*sind(Theta(1)); %y coordinate of P21

Bx = D1\*cosd(Theta(1)) + P22\*cosd(Theta(1) + Theta(2));

By = D1\*sind(Theta(1)) + P22\*sind(Theta(1) + Theta(2));

PL2 = Distance(Ax, Ay, Bx, By);

%Store Lengths in an array

lengths = [PL1 PL2];

end

function positions = SemiEllipseStep()

halfStep = 0.25;%m

stepHeight = 0.05;%m

positions = [180:-1:0; 180:-1:0]; %initial semicircle

positions = [cos(positions(1,:)\*pi/180)\*halfStep; sin(positions(2,:)\*pi/180)\*stepHeight];

positions(2,:) = positions(2,:) - .7;

positions(1,:) = positions(1,:) + .02;

for i = 2:length(positions)-1;

positions(2,i) = (positions(2,i-1)\*2 + positions(2,i+1)\*2)/4;

end

positions = positions' \* 100;

%positions = [positions; positions(1,:)];

end

function positions = DragStep()

positions = [0.125:-0.005:-0.125; (0.125:-0.005:-0.125)\*0 - 0.55]' \* 100;

end

function data = ReadExcelData()

%IMPORTFILE Import data from a spreadsheet

% data = IMPORTFILE(FILE) reads data from the first worksheet in the

% Microsoft Excel spreadsheet file named FILE and returns the data as

% column vectors.

%

% data = IMPORTFILE(FILE,SHEET) reads from the specified worksheet.

%

% data = IMPORTFILE(FILE,SHEET,STARTROW,ENDROW) reads from the specified

% worksheet for the specified row interval(s). Specify STARTROW and

% ENDROW as a pair of scalars or vectors of matching size for

% dis-contiguous row intervals. To read to the end of the file specify an

% ENDROW of inf.%

% Example:

% data = importfile('ParameterConfig.xlsx','Sheet1',1,12);

%

% See also XLSREAD.

% Auto-generated by MATLAB on 2015/02/12 18:41:31

%% Input handling

% If no sheet is specified, read first sheet

sheet = 1;

% read 12 data points

startRow = 1;

endRow = 12;

%% Import the data

data = xlsread('ParameterConfig.xlsx', sheet, sprintf('B%d:B%d',startRow(1),endRow(1)));

for block=2:length(startRow)

tmpDataBlock = xlsread('ParameterConfig.xlsx', sheet, sprintf('B%d:B%d',startRow(block),endRow(block)));

data = [data;tmpDataBlock]; %#ok<AGROW>

end

function [ output\_args ] = MatrixDynamics( input\_args )

%DYNAMICSFUNCTION Summary of this function goes here

% Detailed explanation goes here

% \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

% / | | \

% / | | \

% / | | \

% \ \ | /

% \ \ / /

% \ \ / /

% (2) (4) (3) (1)

%

% 1 - front right, 3 - front left

% 2 - rear right, 4 - rear left

%kinematic symbols

syms x y LH1 LH2 LH3 LH4 LT1 LT2 LT3 LT4 LK1 LK2 LK3 LK4 LS1 LS2 LS3 LS4 LF1 LF2 LF3 LF4

syms tb th1 th2 th3 th4 tk1 tk2 tk3 tk4

syms xdot ydot tbdot th1dot th2dot th3dot th4dot tk1dot tk2dot tk3dot tk4dot

syms xddot yddot tbddot th1ddot th2ddot th3ddot th4ddot tk1ddot tk2ddot tk3ddot tk4ddot

%Leg 1 - FR, Leg 2 - RR, Leg 3 - FL, Leg 4 - RL

xH1 = x + LH1\*cos(2\*pi-(tb)); yH1 = y + LH1\*sin(2\*pi-(tb));

xH2 = x + LH2\*cos((tb+pi)); yH2 = y + LH2\*sin((tb+pi));

xH3 = x + LH3\*cos(2\*pi-(tb)); yH3 = y + LH3\*sin(2\*pi-(tb));

xH4 = x + LH4\*cos((tb+pi)); yH4 = y + LH4\*sin((tb+pi));

xT1 = x + LH1\*cos(2\*pi-(tb)) + LT1\*cos(2\*pi-(th1+tb)); yT1 = y + LH1\*sin(2\*pi-(tb)) + LT1\*sin(2\*pi-(th1+tb));

xT2 = x + LH2\*cos((tb+pi)) + LT2\*cos((th2+tb+pi)); yT2 = y + LH2\*sin((tb+pi)) + LT1\*sin((th2+tb+pi));

xT3 = x + LH3\*cos(2\*pi-(tb)) + LT3\*cos(2\*pi-(th3+tb)); yT3 = y + LH3\*sin(2\*pi-(tb)) + LT1\*sin(2\*pi-(th3+tb));

xT4 = x + LH4\*cos((tb+pi)) + LT4\*cos((th4+tb+pi)); yT4 = y + LH4\*sin((tb+pi)) + LT1\*sin((th4+tb+pi));

xK1 = x + LH1\*cos(2\*pi-(tb)) + LK1\*cos(2\*pi-(th1+tb)); yK1 = y + LH1\*sin(2\*pi-(tb)) + LK1\*sin(2\*pi-(th1+tb));

xK2 = x + LH2\*cos(tb+pi) + LK2\*cos(th2+tb+pi); yK2 = y + LH2\*sin(tb+pi) + LK2\*sin(th2+tb+pi);

xK3 = x + LH3\*cos(2\*pi-(tb)) + LK3\*cos(2\*pi-(th3+tb)); yK3 = y + LH3\*sin(2\*pi-(tb)) + LK3\*sin(2\*pi-(th3+tb));

xK4 = x + LH4\*cos(tb+pi) + LK4\*cos(th4+tb+pi); yK4 = y + LH4\*sin(tb+pi) + LK4\*sin(th4+tb+pi);

xS1 = x + LH1\*cos(2\*pi-(tb)) + LK1\*cos(2\*pi-(th1+tb)) + LS1\*cos(2\*pi-(tk1+th1+tb)); yS1 = y + LH1\*sin(2\*pi-(tb)) + LK1\*sin(2\*pi-(th1+tb)) + LS1\*sin(2\*pi-(tk1+th1+tb));

xS2 = x + LH2\*cos(tb+pi) + LK2\*cos(th2+tb+pi) + LS2\*cos(tk2+th2+tb+pi); yS2 = y + LH2\*sin(tb+pi) + LK2\*sin(th2+tb+pi) + LS2\*cos(tk2+th2+tb+pi);

xS3 = x + LH3\*cos(2\*pi-(tb)) + LK3\*cos(2\*pi-(th3+tb)) + LS3\*cos(2\*pi-(tk3+th3+tb)); yS3 = y + LH3\*sin(2\*pi-(tb)) + LK3\*sin(2\*pi-(th3+tb)) + LS3\*sin(2\*pi-(tk3+th3+tb));

xS4 = x + LH4\*cos(tb+pi) + LK4\*cos(th4+tb+pi) + LS4\*cos(tk4+th4+tb+pi); yS4 = y + LH4\*sin(tb+pi) + LK4\*sin(th4+tb+pi) + LS4\*cos(tk4+th4+tb+pi);

xF1 = x + LH1\*cos(2\*pi-(tb)) + LK1\*cos(2\*pi-(th1+tb)) + LF1\*cos(2\*pi-(tk1+th1+tb)); yF1 = y + LH1\*sin(2\*pi-(tb)) + LK1\*sin(2\*pi-(th1+tb)) + LF1\*sin(2\*pi-(tk1+th1+tb));

xF2 = x + LH2\*cos(tb+pi) + LK2\*cos(th2+tb+pi) + LF2\*cos(tk2+th2+tb+pi); yF2 = y + LH2\*sin(tb+pi) + LK2\*sin(th2+tb+pi) + LF2\*cos(tk2+th2+tb+pi);

xF3 = x + LH3\*cos(2\*pi-(tb)) + LK3\*cos(2\*pi-(th3+tb)) + LF3\*cos(2\*pi-(tk3+th3+tb)); yF3 = y + LH3\*sin(2\*pi-(tb)) + LK3\*sin(2\*pi-(th3+tb)) + LF3\*sin(2\*pi-(tk3+th3+tb));

xF4 = x + LH4\*cos(tb+pi) + LK4\*cos(th4+tb+pi) + LF4\*cos(tk4+th4+tb+pi); yF4 = y + LH4\*sin(tb+pi) + LK4\*sin(th4+tb+pi) + LF4\*cos(tk4+th4+tb+pi);

xH1dot = derivative(xH1, [x tb], [xdot;tbdot]);

yH1dot = derivative(yH1, [y tb], [ydot;tbdot]);

xH2dot = derivative(xH2, [x tb], [xdot;tbdot]);

yH2dot = derivative(yH2, [y tb], [ydot;tbdot]);

xH3dot = derivative(xH3, [x tb], [xdot;tbdot]);

yH3dot = derivative(yH3, [y tb], [ydot;tbdot]);

xH4dot = derivative(xH4, [x tb], [xdot;tbdot]);

yH4dot = derivative(yH4, [y tb], [ydot;tbdot]);

xT1dot = derivative(xT1, [x tb th1], [xdot;tbdot;th1dot]);

yT1dot = derivative(yT1, [y tb th1], [ydot;tbdot;th1dot]);

xT2dot = derivative(xT2, [x tb th2], [xdot;tbdot;th2dot]);

yT2dot = derivative(yT2, [y tb th2], [ydot;tbdot;th2dot]);

xT3dot = derivative(xT3, [x tb th3], [xdot;tbdot;th3dot]);

yT3dot = derivative(yT3, [y tb th3], [ydot;tbdot;th3dot]);

xT4dot = derivative(xT4, [x tb th4], [xdot;tbdot;th4dot]);

yT4dot = derivative(yT4, [y tb th4], [ydot;tbdot;th4dot]);

xK1dot = derivative(xK1, [x tb th1], [xdot;tbdot;th1dot]);

yK1dot = derivative(yK1, [y tb th1], [ydot;tbdot;th1dot]);

xK2dot = derivative(xK2, [x tb th2], [xdot;tbdot;th2dot]);

yK2dot = derivative(yK2, [y tb th2], [ydot;tbdot;th2dot]);

xK3dot = derivative(xK3, [x tb th3], [xdot;tbdot;th3dot]);

yK3dot = derivative(yK3, [y tb th3], [ydot;tbdot;th3dot]);

xK4dot = derivative(xK4, [x tb th4], [xdot;tbdot;th4dot]);

yK4dot = derivative(yK4, [y tb th4], [ydot;tbdot;th4dot]);

xS1dot = derivative(xS1, [x tb th1 tk1], [xdot;tbdot;th1dot;tk1dot]);

yS1dot = derivative(yS1, [y tb th1 tk1], [ydot;tbdot;th1dot;tk1dot]);

xS2dot = derivative(xS2, [x tb th2 tk2], [xdot;tbdot;th2dot;tk2dot]);

yS2dot = derivative(yS2, [y tb th2 tk2], [ydot;tbdot;th2dot;tk2dot]);

xS3dot = derivative(xS3, [x tb th3 tk3], [xdot;tbdot;th3dot;tk3dot]);

yS3dot = derivative(yS3, [y tb th3 tk3], [ydot;tbdot;th3dot;tk3dot]);

xS4dot = derivative(xS4, [x tb th4 tk4], [xdot;tbdot;th4dot;tk4dot]);

yS4dot = derivative(yS4, [y tb th4 tk4], [ydot;tbdot;th4dot;tk4dot]);

xF1dot = derivative(xF1, [x tb th1 tk1], [xdot;tbdot;th1dot;tk1dot]);

yF1dot = derivative(yF1, [y tb th1 tk1], [ydot;tbdot;th1dot;tk1dot]);

xF2dot = derivative(xF2, [x tb th2 tk2], [xdot;tbdot;th2dot;tk2dot]);

yF2dot = derivative(yF2, [y tb th2 tk2], [ydot;tbdot;th2dot;tk2dot]);

xF3dot = derivative(xF3, [x tb th3 tk3], [xdot;tbdot;th3dot;tk3dot]);

yF3dot = derivative(yF3, [y tb th3 tk3], [ydot;tbdot;th3dot;tk3dot]);

xF4dot = derivative(xF4, [x tb th4 tk4], [xdot;tbdot;th4dot;tk4dot]);

yF4dot = derivative(yF4, [y tb th4 tk4], [ydot;tbdot;th4dot;tk4dot]);

%calculating accelerations

%hip

xH1ddot = derivative(xH1dot,[x tb xdot tbdot], [xdot;tbdot;xddot;tbddot]); %Hip 1 X

yH1ddot = derivative(yH1dot,[y tb ydot tbdot], [ydot;tbdot;yddot;tbddot]); %Hip 1 Y

xH2ddot = derivative(xH2dot,[x tb xdot tbdot], [xdot;tbdot;xddot;tbddot]); %Hip 2 X

yH2ddot = derivative(yH2dot,[y tb ydot tbdot], [ydot;tbdot;yddot;tbddot]); %Hip 2 Y

xH3ddot = derivative(xH3dot,[x tb xdot tbdot], [xdot;tbdot;xddot;tbddot]); %Hip 3 X

yH3ddot = derivative(yH3dot,[y tb ydot tbdot], [ydot;tbdot;yddot;tbddot]); %Hip 3 Y

xH4ddot = derivative(xH4dot,[x tb xdot tbdot], [xdot;tbdot;xddot;tbddot]); %Hip 4 X

yH4ddot = derivative(yH4dot,[y tb ydot tbdot], [ydot;tbdot;yddot;tbddot]); %Hip 4 Y

%thigh

xT1ddot = derivative(xT1dot, [x tb th1 xdot tbdot th1dot], [xdot;tbdot;th1dot;xddot;tbddot;th1ddot]); %Thigh 1 X

yT1ddot = derivative(yT1dot, [y tb th1 ydot tbdot th1dot], [ydot;tbdot;th1dot;yddot;tbddot;th1ddot]); %Thigh 1 Y

xT2ddot = derivative(xT2dot, [x tb th2 xdot tbdot th2dot], [xdot;tbdot;th2dot;xddot;tbddot;th2ddot]); %Thigh 2 X

yT2ddot = derivative(yT2dot, [y tb th2 ydot tbdot th2dot], [ydot;tbdot;th2dot;yddot;tbddot;th2ddot]); %Thigh 2 Y

xT3ddot = derivative(xT3dot, [x tb th3 xdot tbdot th3dot], [xdot;tbdot;th3dot;xddot;tbddot;th3ddot]); %Thigh 3 X

yT3ddot = derivative(yT3dot, [y tb th3 ydot tbdot th3dot], [ydot;tbdot;th3dot;yddot;tbddot;th3ddot]); %Thigh 3 Y

xT4ddot = derivative(xT4dot, [x tb th4 xdot tbdot th4dot], [xdot;tbdot;th4dot;xddot;tbddot;th4ddot]); %Thigh 4 X

yT4ddot = derivative(yT4dot, [y tb th4 ydot tbdot th4dot], [ydot;tbdot;th4dot;yddot;tbddot;th4ddot]); %Thigh 4 Y

%knee

xK1ddot = derivative(xK1dot,[x tb th1 xdot tbdot th1dot], [xdot;tbdot;th1dot;xddot;tbddot;th1ddot]); %Knee 1 X

yK1ddot = derivative(yK1dot,[y tb th1 ydot tbdot th1dot], [ydot;tbdot;th1dot;yddot;tbddot;th1ddot]); %Knee 1 Y

xK2ddot = derivative(xK2dot,[x tb th2 xdot tbdot th2dot], [xdot;tbdot;th2dot;xddot;tbddot;th2ddot]); %Knee 2 X

yK2ddot = derivative(yK2dot,[y tb th2 ydot tbdot th2dot], [ydot;tbdot;th2dot;yddot;tbddot;th2ddot]); %Knee 2 Y

xK3ddot = derivative(xK3dot,[x tb th3 xdot tbdot th3dot], [xdot;tbdot;th3dot;xddot;tbddot;th3ddot]); %Knee 3 X

yK3ddot = derivative(yK3dot,[y tb th3 ydot tbdot th3dot], [ydot;tbdot;th3dot;yddot;tbddot;th3ddot]); %Knee 3 Y

xK4ddot = derivative(xK4dot,[x tb th4 xdot tbdot th4dot], [xdot;tbdot;th4dot;xddot;tbddot;th4ddot]); %Knee 4 X

yK4ddot = derivative(yK4dot,[y tb th4 ydot tbdot th4dot], [ydot;tbdot;th4dot;yddot;tbddot;th4ddot]); %Knee 4 Y

%shank

xS1ddot = derivative(xS1dot,[x tb th1 tk1 xdot tbdot th1dot tk1dot], [xdot;tbdot;th1dot;tk1dot;xddot;tbddot;th1ddot;tk1ddot]); %Shank 1 X

yS1ddot = derivative(yS1dot,[y tb th1 tk1 ydot tbdot th1dot tk1dot], [ydot;tbdot;th1dot;tk1dot;yddot;tbddot;th1ddot;tk1ddot]); %Shank 1 Y

xS2ddot = derivative(xS2dot,[x tb th2 tk2 xdot tbdot th2dot tk2dot], [xdot;tbdot;th2dot;tk2dot;xddot;tbddot;th2ddot;tk2ddot]); %Shank 2 X

yS2ddot = derivative(yS2dot,[y tb th2 tk2 ydot tbdot th2dot tk2dot], [ydot;tbdot;th2dot;tk2dot;yddot;tbddot;th2ddot;tk2ddot]); %Shank 2 Y

xS3ddot = derivative(xS3dot,[x tb th3 tk3 xdot tbdot th3dot tk3dot], [xdot;tbdot;th3dot;tk3dot;xddot;tbddot;th3ddot;tk3ddot]); %Shank 3 X

yS3ddot = derivative(yS3dot,[y tb th3 tk3 ydot tbdot th3dot tk3dot], [ydot;tbdot;th3dot;tk3dot;yddot;tbddot;th3ddot;tk3ddot]); %Shank 3 Y

xS4ddot = derivative(xS4dot,[x tb th4 tk4 xdot tbdot th4dot tk4dot], [xdot;tbdot;th4dot;tk4dot;xddot;tbddot;th4ddot;tk4ddot]); %Shank 4 X

yS4ddot = derivative(yS4dot,[y tb th4 tk4 ydot tbdot th4dot tk4dot], [ydot;tbdot;th4dot;tk4dot;yddot;tbddot;th4ddot;tk4ddot]); %Shank 4 Y

%foot

xF1ddot = derivative(xF1dot,[x tb th1 tk1 xdot tbdot th1dot tk1dot], [xdot;tbdot;th1dot;tk1dot;xddot;tbddot;th1ddot;tk1ddot]); %Foot 1 X

yF1ddot = derivative(yF1dot,[y tb th1 tk1 ydot tbdot th1dot tk1dot], [ydot;tbdot;th1dot;tk1dot;yddot;tbddot;th1ddot;tk1ddot]); %Foot 1 Y

xF2ddot = derivative(xF2dot,[x tb th2 tk2 xdot tbdot th2dot tk2dot], [xdot;tbdot;th2dot;tk2dot;xddot;tbddot;th2ddot;tk2ddot]); %Foot 2 X

yF2ddot = derivative(yF2dot,[y tb th2 tk2 ydot tbdot th2dot tk2dot], [ydot;tbdot;th2dot;tk2dot;yddot;tbddot;th2ddot;tk2ddot]); %Foot 2 Y

xF3ddot = derivative(xF3dot,[x tb th3 tk3 xdot tbdot th3dot tk3dot], [xdot;tbdot;th3dot;tk3dot;xddot;tbddot;th3ddot;tk3ddot]); %Foot 3 X

yF3ddot = derivative(yF3dot,[y tb th3 tk3 ydot tbdot th3dot tk3dot], [ydot;tbdot;th3dot;tk3dot;yddot;tbddot;th3ddot;tk3ddot]); %Foot 3 Y

xF4ddot = derivative(xF4dot,[x tb th4 tk4 xdot tbdot th4dot tk4dot], [xdot;tbdot;th4dot;tk4dot;xddot;tbddot;th4ddot;tk4ddot]); %Foot 4 X

yF4ddot = derivative(yF4dot,[y tb th4 tk4 ydot tbdot th4dot tk4dot], [ydot;tbdot;th4dot;tk4dot;yddot;tbddot;th4ddot;tk4ddot]); %Foot 4 Y

%Dynamic calculations

syms mB mT1 mT2 mT3 mT4 mS1 mS2 mS3 mS4 g; %mass and weight

%Moments of inertia

syms IS1x IS1y IS1z IT1x IT1y IT1z IBx IBy IBz IT2x IT2y IT2z IS2x IS2y IS2z; %Link moments of inertia

syms IS3x IS3y IS3z IT3x IT3y IT3z IT4x IT4y IT4z IS4x IS4y IS4z; %Link moments of inertia

%Forces

syms FH1x FH2x FH3x FH4x FK1x FK2x FK3x FK4x FF1x FF2x FF3x FF4x;

syms FH1y FH2y FH3y FH4y FK1y FK2y FK3y FK4y FF1y FF2y FF3y FF4y;

%torques

syms TH1 TH2 TH3 TH4 TK1 TK2 TK3 TK4;

%weight equations

T1w = [0 -mT1 \* g 0]; S1w = [0 -mS1 \* g 0]; %weights

T2w = [0 -mT2 \* g 0]; S2w = [0 -mS2 \* g 0]; %weights

T3w = [0 -mT3 \* g 0]; S3w = [0 -mS3 \* g 0]; %weights

T4w = [0 -mT4 \* g 0]; S4w = [0 -mS4 \* g 0]; %weights

%force vectors

FH1 = [FH1x FH1y 0]; FH2 = [FH2x FH2y 0]; FH3 = [FH3x FH3y 0]; FH4 = [FH4x FH4y 0];

FK1 = [FK1x FK1y 0]; FK2 = [FK2x FK2y 0]; FK3 = [FK3x FK3y 0]; FK4 = [FK4x FK4y 0];

FF1 = [FF1x FF1y 0]; FF2 = [FF2x FF2y 0]; FF3 = [FF3x FF3y 0]; FF4 = [FF4x FF4y 0];

%vector positions and accelerations for each point of interest

%front (1)

rH1 = [xH1 yH1 0];% rH1ddot = [xH1ddot yH1ddot 0]; %hip 1

rT1 = [xT1 yT1 0]; rT1ddot = [xT1ddot yT1ddot 0]; %thigh 1

rK1 = [xK1 yK1 0];% rK1ddot = [xK1ddot yK1ddot 0]; %knee 1

rS1 = [xS1 yS1 0]; rS1ddot = [xS1ddot yS1ddot 0]; %shank 1

rF1 = [xF1 yF1 0];% rF1ddot = [xF1ddot yF1ddot 0]; %foot 1

%front (3)

rH3 = [xH3 yH3 0];% rH3ddot = [xH3ddot yH3ddot 0]; %hip 3

rT3 = [xT3 yT3 0]; rT3ddot = [xT3ddot yT3ddot 0]; %thigh 3

rK3 = [xK3 yK3 0];% rK3ddot = [xK3ddot yK3ddot 0]; %knee 3

rS3 = [xS3 yS3 0]; rS3ddot = [xS3ddot yS3ddot 0]; %shank 3

rF3 = [xF3 yF3 0];% rF3ddot = [xF3ddot yF3ddot 0]; %foot 3

%body

rB = [x y 0]; rBddot = [xddot yddot 0]; %body

%rear (2)

rH2 = [xH2 yH2 0];% rH2ddot = [xH2ddot yH2ddot 0]; %hip 2

rT2 = [xT2 yT2 0]; rT2ddot = [xT2ddot yT2ddot 0]; %thigh 2

rK2 = [xK2 yK2 0];% rK2ddot = [xK2ddot yK2ddot 0]; %knee 2

rS2 = [xS2 yS2 0]; rS2ddot = [xS2ddot yS2ddot 0]; %shank 2

rF2 = [xF2 yF2 0];% rF2ddot = [xF2ddot yF2ddot 0]; %foot 2

%rear (4)

rH4 = [xH4 yH4 0];% rH4ddot = [xH4ddot yH4ddot 0]; %hip 4

rT4 = [xT4 yT4 0]; rT4ddot = [xT4ddot yT4ddot 0]; %thigh 4

rK4 = [xK4 yK4 0];% rK4ddot = [xK4ddot yK4ddot 0]; %knee 4

rS4 = [xS4 yS4 0]; rS4ddot = [xS4ddot yS4ddot 0]; %shank 4

rF4 = [xF4 yF4 0];% rF4ddot = [xF4ddot yF4ddot 0]; %foot 4

%force calculations

EffecMomentS1 = cross(rS1,mS1\*rS1ddot)+ [IS1x\*0 IS1y\*0 IS1z\*tk1ddot]; %shank 1

EffecMomentT1 = cross(rT1,mT1\*rT1ddot)+ [IT1x\*0 IT1y\*0 IT1z\*th1ddot]; %thigh 1

EffecMomentS3 = cross(rS3,mS3\*rS3ddot)+ [IS3x\*0 IS3y\*0 IS3z\*tk3ddot]; %shank 3

EffecMomentT3 = cross(rT3,mT3\*rT3ddot)+ [IT3x\*0 IT3y\*0 IT3z\*th3ddot]; %thigh 3

%EffecMomentB = cross(rB,mB\*rBddot) + [IBx\*0 IBy\*0 IBz\*tbddot]; %body

EffecMomentT2 = cross(rT2,mT2\*rT2ddot)+ [IT2x\*0 IT2y\*0 IT2z\*th2ddot]; %thigh 2

EffecMomentS2 = cross(rS2,mS2\*rS2ddot)+ [IS2x\*0 IS2y\*0 IS2z\*tk2ddot]; %shank 2

EffecMomentT4 = cross(rT4,mT4\*rT4ddot)+ [IT4x\*0 IT4y\*0 IT4z\*th4ddot]; %thigh 2

EffecMomentS4 = cross(rS4,mS4\*rS4ddot)+ [IS4x\*0 IS4y\*0 IS4z\*tk4ddot]; %shank 2

%creating the 1D Force Matrix {F}

F = [FK1y; FH1y; FK2y; FH2y; FK3y; FH3y; FK4y; FH4y; ...

FK1x; FH1x; FK2x; FH2x; FK3x; FH3x; FK4x; FH4x];

%The "other crap" on the right half {B}

Kin = [mS1\*yS1ddot+S1w(2)+FF1y; mT1\*yT1ddot+T1w(2); mS2\*yS2ddot+S2w(2)+FF2y; mT2\*yT2ddot+T2w(2); ...

mS3\*yS3ddot+S3w(2)+FF3y; mT3\*yT3ddot+T3w(2); mS4\*yS4ddot+S4w(2)+FF4y; mT4\*yT4ddot+T4w(2); ...

mS1\*xS1ddot+FF1x; mT1\*xT1ddot; mS2\*xS2ddot+FF2x; mT2\*xT2ddot; ...

mS3\*xS3ddot+FF3x; mT3\*xT3ddot; mS4\*xS4ddot+FF4x; mT4\*xT4ddot];

%The matrix relating internal forces to accelerations {A}

Mat =[-1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;

1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0;

0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0;

0 0 1 -1 0 0 0 0 0 0 0 0 0 0 0 0;

0 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0;

0 0 0 0 1 -1 0 0 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 1 -1 0 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 1 -1 0 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 1 -1 0 0 0 0;

0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0;

0 0 0 0 0 0 0 0 0 0 0 0 1 -1 0 0;

0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0;

0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 -1];

%solving {A}{F}={B} for {F}

FORCES = solve(F == inv(Mat)\*Kin, FK1x, FK1y, FK2x, FK2y, FK3x, FK3y, FK4x, FK4y, ...

FH1x, FH1y, FH2x, FH2y, FH3x, FH3y, FH4x, FH4y);

%Torque array {T}

%These are negative because on the diagram the moments are assumed negative

T = [-TK1; -TH1; -TK2; -TH2; -TK3; -TH3; -TK4; -TH4];

%Matric {C} relating torques to movement

TMat = [1 0 0 0 0 0 0 0;

-1 1 0 0 0 0 0 0;

0 0 1 0 0 0 0 0;

0 0 -1 1 0 0 0 0;

0 0 0 0 1 0 0 0;

0 0 0 0 -1 1 0 0;

0 0 0 0 0 0 1 0;

0 0 0 0 0 0 -1 1];

%The "other crap" from the sum of the torques, matrix {D}

TorqueT = [EffecMomentS1 - cross(rF1, FF1) - cross(rK1, -FK1) - cross(rS1, S1w);

EffecMomentT1 - cross(rH1, -FH1) - cross(rK1, FK1) - cross(rT1, T1w);

EffecMomentS2 - cross(rF2, FF2) - cross(rK2, -FK2) - cross(rS2, S2w);

EffecMomentT2 - cross(rH2, -FH2) - cross(rK2, FK2) - cross(rT2, T2w);

EffecMomentS3 - cross(rF3, FF3) - cross(rK3, -FK3) - cross(rS3, S3w);

EffecMomentT3 - cross(rH3, -FH3) - cross(rK3, FK3) - cross(rT3, T3w);

EffecMomentS4 - cross(rF4, FF4) - cross(rK4, -FK4) - cross(rS4, S4w);

EffecMomentT4 - cross(rH4, -FH4) - cross(rK4, FK4) - cross(rT4, T4w)];

%Grabbing the Z direction of {D}

TorqueT = TorqueT(:,3);

%Solving {C}{T}={D} for {T}

Ts = solve(TMat\*T == TorqueT, TK1, TH1, TK2, TH2, TK3, TH3, TK4, TH4);

%Creating TH1F (Hip Torque 1) in the form shown by Dr Rodriguez by renaming and zeroing

%variables

TH1F = Ts.TH1;

TH1F = subs(TH1F, ydot, 0); TH1F = subs(TH1F, yddot, 0); TH1F = subs(TH1F, th1dot, 0);

TH1F = subs(TH1F, th1ddot, 0); TH1F = subs(TH1F, tk1dot, 0); TH1F = subs(TH1F, tk1ddot, 0);

TH1F = subs(TH1F, tbdot, 0); TH1F = subs(TH1F, tbddot, 0);

TH1F = subs(TH1F, xdot, 0); TH1F = subs(TH1F, xddot, 0);

TH1F = subs(TH1F, LH1, 0);

TH1F = subs(TH1F, tb, 0);

TH1F = subs(TH1F, x, 0);

TH1F = subs(TH1F, y, 0);

TH1F = subs(TH1F, LS1, LF1/2);

TH1F = subs(TH1F, LT1, LK1/2);

%Creating TK1F (Knee Torque 1) in the form shown by Dr Rodriguez by renaming and zeroing

%variables

TK1F = Ts.TK1;

TK1F = subs(TK1F, ydot, 0); TK1F = subs(TK1F, yddot, 0); TK1F = subs(TK1F, th1dot, 0);

TK1F = subs(TK1F, th1ddot, 0); TK1F = subs(TK1F, tk1dot, 0); TK1F = subs(TK1F, tk1ddot, 0);

TK1F = subs(TK1F, tbdot, 0); TK1F = subs(TK1F, tbddot, 0);

TK1F = subs(TK1F, xdot, 0); TK1F = subs(TK1F, xddot, 0);

TK1F = subs(TK1F, LH1, 0);

TK1F = subs(TK1F, tb, 0);

TK1F = subs(TK1F, x, 0);

TK1F = subs(TK1F, y, 0);

%Creating TH2F (Hip Torque 2) in the form shown by Dr Rodriguez by renaming and zeroing

%variables

TH2F = Ts.TH2;

TH2F = subs(TH2F, ydot, 0); TH2F = subs(TH2F, yddot, 0); TH2F = subs(TH2F, th2dot, 0);

TH2F = subs(TH2F, th2ddot, 0); TH2F = subs(TH2F, tk2dot, 0); TH2F = subs(TH2F, tk2ddot, 0);

TH2F = subs(TH2F, tbdot, 0); TH2F = subs(TH2F, tbddot, 0);

TH2F = subs(TH2F, xdot, 0); TH2F = subs(TH2F, xddot, 0);

TH2F = subs(TH2F, LH2, 0);

TH2F = subs(TH2F, tb, 0);

TH2F = subs(TH2F, x, 0);

TH2F = subs(TH2F, y, 0);

%Creating TK1F (Knee Torque 1) in the form shown by Dr Rodriguez by renaming and zeroing

%variables

TK2F = Ts.TK2;

TK2F = subs(TK2F, ydot, 0); TK2F = subs(TK2F, yddot, 0); TK2F = subs(TK2F, th2dot, 0);

TK2F = subs(TK2F, th2ddot, 0); TK2F = subs(TK2F, tk2dot, 0); TK2F = subs(TK2F, tk2ddot, 0);

TK2F = subs(TK2F, tbdot, 0); TK2F = subs(TK2F, tbddot, 0);

TK2F = subs(TK2F, xdot, 0); TK2F = subs(TK2F, xddot, 0);

TK2F = subs(TK2F, LH2, 0);

TK2F = subs(TK2F, tb, 0);

TK2F = subs(TK2F, x, 0);

TK2F = subs(TK2F, y, 0);

%Print form variables to console

TH1F;

TK1F;

TH2F;

TK2F;

%Assigning variables to workspace

assignin('base', 'TK1F', TK1F);

assignin('base', 'TH1F', TH1F);

%Assigning force matrices to workspace

assignin('base', 'Kin', Kin);

assignin('base', 'F', F);

assignin('base', 'Mat', Mat);

assignin('base', 'FORCES', FORCES);

%Assigning torque matrices to workspace

assignin('base', 'T', T);

assignin('base', 'TorqueT', TorqueT);

assignin('base', 'TMat', TMat);

assignin('base', 'Ts', Ts);

end

%inputs the function eqtn, row array of variables, column array of variable

%time derivatives

function dt = derivative(eqtn, variables, timeDerivs)

%calculates the row-major jacobian of the equation and multiplies it by the

%time derivative of each varial to find the equations derivative

dt = jacobian(eqtn,variables)\*timeDerivs;

end