MSOE

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MILWAUKEE SCHOOL OF MECHANICAL ENGINEERING SENIOR DESIGN

Team A.R.C. - Design Proposal

November 14, 2014

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Project Statement

Milwaukee School of Engineering (MSOE) participates in community outreach programs where science, technology, engineering, and mathematics (STEM) topics are demonstrated to encourage younger generations to enter into STEM based degrees and careers. Having an automated control system to demonstrate and interact with would increase the excitement at these outreach programs. Development of a robot with pneumatic locomotion for the Milwaukee School of Engineering's controls classes would give students a first-hand experience with complex control systems.

Aside from use in outreach programs this tool is designed for educational use in MSOE's classrooms. The product itself will be used to familiarize controls classes with the application of quadruped motion. Junior and Senior students at MSOE take a controls courses which look at simpler controls systems. There is an educational benefit to having an exposure to larger and more complex control system. Students may manipulate the control parameters to change the system behavior along with viewing the PIDs and compensators executing on the robot.

This project will be a continuation of the work done by Kevin Lee. who did what?

<fill with a summary from his paper> INCLUDE IN PAGE CITATION!!!!

The objective of this project is to design a pneumatic power driven quadruped robot with the ability to walk with at least a creep gait. The robot should have all of its control systems onboard, as well as its electrical power supply, in the form of batteries. Aside from walking forward, the robot should also have the ability to walk backwards as to easily get out of corners and other difficult obstacles. Safety being a major concern, the robot should have at least one emergency stop button on both the robot itself and the controller, which, upon engagement, immediately causes the robot to enter a stable condition, where all legs are on the ground, and all air flow is stopped. Other necessary features of the robot include fuses to protect hardware, insulated wiring to protect against possible pinching and the robot should be joystick controlled for ease of use.

Background Research

Locomotion

One of the first decisions to be made in the design of any mobile robot is the type of locomotion intended to be implemented. The choice of type of locomotion to be implemented in a robot design is dependent on desired functionality and the environment in which the design will be interacting. The

various ~~type~~ types of grounded locomotion are legged locomotion and wheeled locomotion. When choosing which type of locomotion to implement in a design, the advantages and disadvantages of each must be weighed against each other. Aside from weighing the advantages and disadvantages of each form of locomotion, other factors considerations that must be made include the application of the design, the intended use and the intended environment where~~in~~ the design will function.

not clear

motion planning

The implementation of wheels in a design requires simpler programming when compared to legged motion and less parts than in legged motion. An example of a wheeled robot can be seen in Figure 1, a robot designed by NASA for use in difficult lunar terrains. Wheels also provide the fastest mode of transportation on the ground and, because the wheel is usually in contact with the ground, wheeled motion is usually more energy efficient than in legged motion [1]. Wheels do, however, struggle with rugged terrain and thus lose stability, so in areas without flat surfaces, wheeled locomotion is difficult.

characteristics (sandy?)

traction?

Situations favoring wheeled motion involve environments where the surface is flat, energy usage is critical, and high speed is favorable [1] [2].

Figure 1: Wheeled robot (NASA).

re-word

Legged locomotion, on the other hand, has high mobility on surfaces that are sloped or rugged, and is functional means of locomotion on flat surfaces as well. This due to the ability of legged designs to step over obstacles and to move the center of gravity to adjust the distribution of weight on its supports, to compensate for different levels of flatness or ruggedness of terrain. This, however, causes the motion planning ~~programming~~ of legged motion in a design to be more challenging and more costly, due to the need of more parts. An example of a legged robot, a hydraulic powered robotic spider created by Matt Denton, can be seen in Figure 2. Legged motion also gives the design the option of changing direction without changing the orientation of the body, giving the design increased maneuverability. Situations favoring legged locomotion include environments that are rugged and generally sloped or even environments where the terrain is unknown and the ability to traverse these environments effectively is required [1] [2].

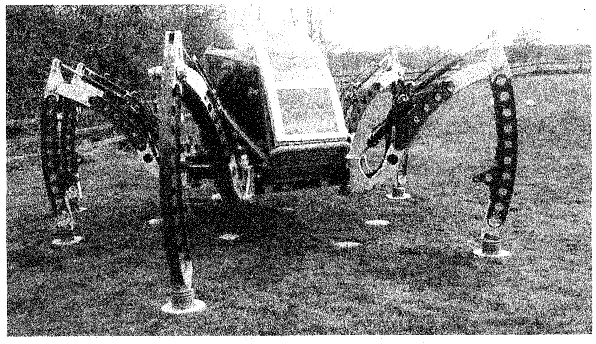


Figure 2: Legged robot (BBC).

Legged robots, among many things, are a means to replace humans and animals in tasks such as travel, exploration, military operations, equipment transportation and research, where having humans or animals could lead to exposure to hazardous conditions. Utilizing natural dynamic locomotion legged robots have the ability to strategically traverse various terrain efficiently [1]. Legged robots also provide a research platform ~~an apparatus for research~~ in fields such as biology. By being able to reproduce a fairly natural gait using a robotic tool, specific traits and characteristics of various animals can be determined without need of studying living organisms, which in turn removes the need for animal testing [3].

tie this better w/ advantages

Number of Legs For Locomotion

An important consideration when designing a legged robot is the desired amount of legs the robot has. While four legs is the minimum amount of legs necessary for the robot to be statically stable when one leg is off the ground, depending on the robot design and desired functionality, there may not be a need~~ed~~ for static stability. The amount of legs a legged robot can have ranges from one, obviously, to any number of legs necessary to meet design requirements and goals.

With one leg the robot is not statically stable and highly susceptible to tipping when exposed to some sort of disturbance. In order to prevent tipping, very complex controls must be implemented in order to keep its center of mass directly above its singular contact point. Aside from the complexity added to the design of the robot due to the reduced stability of one leg, the robot can only travel by hopping. This means the robot must be able to balance while standing still and the robot must also be able to determine how to shift its center of mass while hopping and while landing in order to go the desired direction and to avoid tipping [2].

With two legs, the robot has more stability, since it can now balance its center of gravity between two contact points while standing still and can utilize a singular contact point for balance while traveling. Compared to a one legged robot design, the level of complexity required to maintain balance decreases due to the design being more stable, however due to the addition of another leg, more controls are needed to control the extra leg [2]. The robot must still be able to shift its center of gravity while walking to maintain balance but given the extra leg, when compared to a one legged design, there are now more options when it comes to travel. A two legged robot can hop, but also has the ability to walk and can achieve various running gaits. Add another leg to the design and the complexity required to balance

~~complex~~ to manipulate the

decreases, but at the same time requires more cod~~ing to~~ control the extra leg as a trade-off.

advanced is required

A characteristic of four legged designs it the ability to remain completely stable while standing still and while in motion, if the center of gravity is balanced between the contact points created by the legs with the ground. With this ability to remain stable with one leg off the ground, less complex coding, when compared to robot designs having fewer legs, is needed to maintain balance. This also means less complex coding is necessary when coding walking gaits. Attainable gaits for four legged robots include hopping, various walking gaits and various running gaits, similar to two and three legged robots.

Legged robot designs having more than four legs are similar to robots with four legs in that as long as three legs are on the ground and the center of mass is within the support polygon created by the contact points. The disadvantage in having a design with more than four legs rather than of having four

manipulate

legs is that there is not much gained in way of stability, yet more complex ~~coding~~ is required to ~~control~~

control

it is more
stable but the complexity in the control
the once out weights the advantages

the added legs. With more legs the robot can have more legs off of the ground and remain stable, however even if those legs are off the ground, they will not contribute much to the forward motion of the robot [2].

The number of legs chosen for this robotic design is four. There is a good balance between the complexity of ~~coding~~ the control due to the amount of legs and the ability of the robot to be statically stable. The initial design for the robot will achieve a very basic gait, and the ability of the robot to remain stable with one leg off the ground will prove beneficial. If more complex gaits are desired in the future, there is also the possibility of achieving hopping and running gaits without the need of adding additional components, by instead incorporating more sophisticated coding. In order to produce walking gaits for the four legged robot, mathematical models representing the dynamics of the robot's legs must first be determined.

Why not dynamically stable legged locomotion?

Research Experience for Undergraduates, Summer 2014

During the summer of 2014, research in robotic locomotion was conducted. This research essentially provides the basis of the mathematical modeling necessary in developing physical gait patterns for the quadruped robot. Modeling the locomotion of the robot involved determining the dynamic motion for a single leg, understanding the criterion for maintaining stability and implementing the equations of a single leg into all for legs, thus created a gait pattern for the robot.

Initially, by utilizing forward and inverse kinematics, the relationship between a desired position of a link and the necessary angle of rotation in order to reach this position is determined. Similarly, in a two link leg model, the desired position of the foot, or the furthest down location on the lower link, the shank, is related to the angles of rotation of both the upper link and the lower link. For every desired position of the two link leg model throughout its walking motion, the corresponding angles of both links must be determined. With these angles known, and given lengths of the links, a walking pattern for that leg can be generated [4].

In the mathematic modeling of the two link model, the positions of the links are known at all instances in time and using homogeneous transformations, the local coordinate systems of each link are related to the global coordinate system of the leg [4]. Through these transformations, the positions of the separate links are rotated and translated to produce the desired angles of rotation necessary for the whole two link leg to reach the desired position.

Essentially, in modeling a single two link leg's motion, desired positions of the leg are known, while the angles are not known. Utilizing inverse kinematics, these angles can be determined based on the geometry of the link and the desired position of the link. Homogeneous transformations are then used to rotate and translate the individual links into the necessary orientation in order to produce the required angles to reach the desired position of the leg.

Scaling this idea up from one leg to four legs attached to some robot chassis requires the understanding of the criterion for static stability. In order for a structure to be statically stable, the structure's supports must be oriented in such a way that the center of gravity of the robot lies above the polygon generated by the robot's support's ground contact points. In quadrupeds, static stability is true when the center of gravity of the quadruped lies within the triangular support polygon generated by the three remaining legs in contact with the ground, thus preventing a tripping moment in the robot [4]. Figure 1 shows, on the left, a situation in which there is static stability, and, on the right, a situation where a tipping moment is created and consequently there is not static stability. In both situations leg 2, not depicted, is off of the ground thus generating no support point.

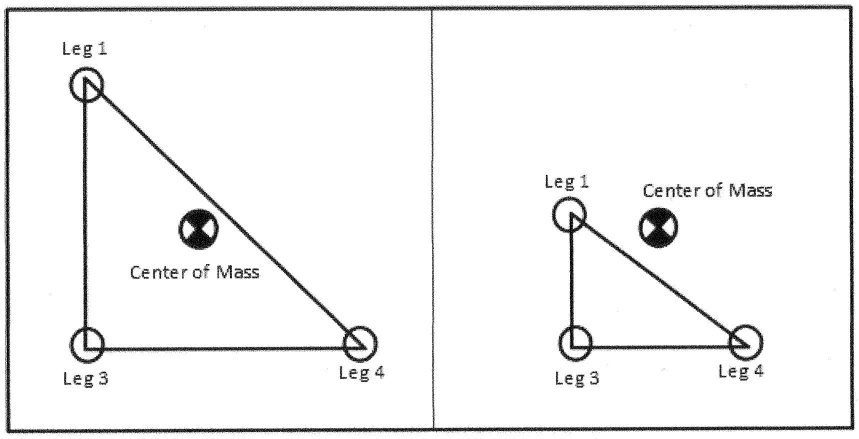


Figure 2: Leg placements resulting in statically stable and unstable conditions in legged robot.

In addition determining the relationship between the desired position of the links in the leg model and the required angles necessary to reach those positions, the forces required to lift the robot's leg and propel the robot forward when the leg pushes off of the ground are to be determined. These forces were determined utilizing concepts in dynamics, such as velocities and accelerations of the linkages, and equating the required forces to required torques at hip joints and knee joints of the robot's legs. As a starting point, the lengths, masses and mass moment of inertia of the linkages were assumed.

While Kevin Lee's preliminary research in the mathematical models representing locomotion in legged robots did provide a foundation to build upon, some assumptions made must be addressed when moving forward with this specific robot design. One such assumption is that the center of mass of the robot will be perfectly in the center of the robot. Due to the shape of the robot and the placement of components on the chassis of the robot, the center of mass will most likely not be directly in the center of the robot. The center of mass is crucial in determining which placements of legs in the robot cause the robot to be statically stable. The center of mass in the links representing the legs of the robots was also assumed to be in the center of the links, which again will most likely not be the case. Other topics not covered by Kevin Lee, which will be serious considerations include velocity analysis of the legs of the robot, the cylinders being the driving force of rotation of the legs, thus needing extensive analysis, and thus the weight of the cylinders.

Pneumatics vs. Hydraulics/Electrics

For our design, it was decided that the best course of action for transferring power throughout our robot was to use pneumatics. Other possible choices for power include hydraulics or electronics, but both of those options come with certain restrictions and downfalls that would prove difficult to compensate for with our design.

Hydraulics is the best choice when it comes to moving heavy loads immediately. With possible forces achieved being upwards of 100 tons, hydraulics is able to achieve full velocity quickly. On the downside, leaks can be a real problem in a hydraulic system. If any of the seals fail, a pressure drop in the fluid will occur, reducing the effectiveness of the system. In addition, the leaking fluid can interfere with electronic or mechanical systems near the break, creating more problems and leading to needing replacement parts for not only the hydraulics. Finally, hydraulics is heavy. The density of the hydraulic fluid is much greater than that of the electronics or air needed to power pneumatics, meaning the design will be much heavier than if either of the other two systems were implemented. This also means a hydraulic system needs a more powerful compressor to push the fluid through the lines, typically meaning an engine is required to power the system. Hydraulics is a good choice when power is needed, but for our design a light-weight, clean system is favorable over the extra power.

Electronics excel where absolute accuracy is needed or when a system is in continuous motion. Additionally, electronic control is the best when it comes to repeatability of the system. If only two or three positions are needed, fluid power can be extremely accurate and repeatable, with pneumatics remaining accurate to +/- 1 mm for systems needing more than three positions. Electronics offer the greatest number of possible accurate positions, especially when a closed loop is used and the system

Sources

apply what do you mean?

can adjust itself between iterations. The downfalls for electronics are that if linear motion is required, a transition is typically required since electronics are normally motor driven, and the power factor and ability to keep constant pressure are low for electronics compared to fluid power. Electronics are best suited for a system needing control, not power. For our robot, both qualities are needed, therefore electronics are not the best choice.

Pneumatics is compromise between hydraulics and electronics. It retains the ability to apply large amounts of constant pressure while maintaining control and accuracy within the system. Pneumatics also has the added benefit of being cleaner than hydraulics. If a leak appears, the system for the most part remains unaffected. Electrical and mechanical components are not likely to be damaged by escaping air and the power loss is negligible for small leaks. Even while maintaining its power, pneumatics remains accurate and repeatable. Also like electronics, pneumatics are easily exchangeable and are inherently modular, allowing for future expansions on an existing system with few problems. Overall, pneumatics offers the best power and accuracy of the three systems in addition to being lightweight and clean.

Summary Table
- Locomotion wheel vs legs
- # of legs
- Power method

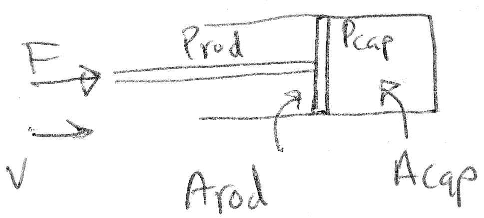
Pneumatic Components

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.

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. Contraction through some forcing mechanism such as a spring would provide contraction of the leg, however the contraction would not be controllable, as the spring would simply want to return to its un-stretched length as fast as possible, thus varying walking patterns would be challenging.

$$F = P_{cap} A_{cap} - P_{rod} A_{rod}$$



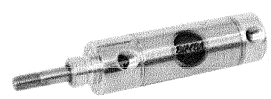


Figure 3: Bimba Original Line® Air cylinder w/ Adjustable Cushions

Efficiency of a cyl.

Energy Losses

- Seal Friction
- Viscous Friction
- Leakage
- Fluid compressibility

$$\text{Efficiency} = \eta = \frac{P_{out}}{P_{in}} = \frac{FV}{P_{in} Q_{in}}$$

Air Supply Tank /Accumulators

The air supply tank ~~carries~~ Stores the air needed to produce flow in the pneumatics circuits controlling the motion of the robot's legs. There are no special requirements for the air tank, as long as the quantity of air held in the tank is enough for the desired amount of operation time in the robot.

- Potential energy storage elements for fluid power
- Store energy steel spring or compressed gas
- High power density but modest energy density.

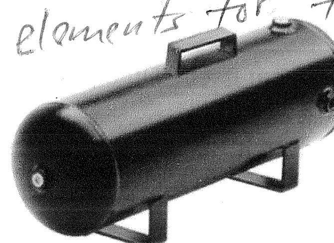
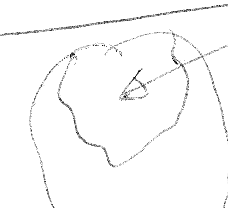


Figure 4: "Smittybilt 99210-2 2.5 Gallon Air Tank"

Common Anatomy



Used to

- Provide pressurized fluid during brief high-demand periods
- Smooth pulsations (from compressor) by absorbing pressure surges
- Should be located as close to the input of the DCV to prevent pressure drops

Energy Storage in Accumulator.

Isothermal Case

$E = PV \ln\left(\frac{V_2}{V_1}\right)$

Adiabatic Case ($\gamma = 1.4$)

$$E = \frac{PV^{\gamma}\left(V_2^{1-\gamma} - V_1^{1-\gamma}\right)}{1-\gamma}$$

Compressor

The air compressor ~~further~~ pressurizes supply air by absorbing air from the environment. The pressurized air provides the required forces to be output by the cylinders to carry loads acting on the robot during locomotion. The amount of pressurization of the air can be varied to increase the forces and speeds of the air cylinders, to vary walking gaits.

- Produces flow ripples
- Multiple sources of energy loss
- What are some typical efficiencies?

Figure 5: Speedaire Air Compressor, 0.9 HP, 120V, 115 psi

Relief Valve

Pneumatic Power Supply (Accumulator, compressor, relief valve)

Power = $P_{supply} Q_{supply}$ > Power Load

Air Reservoir Cartridge

The air reservoir cartridge holds a supply of pressurized air received from the air compressor. The air reservoir cartridge is used to equalize the flow through the pneumatic circuit of the robot, thus maintaining constant flow of pressurized air through the robot's pneumatic circuit. A constant flow rate of pressurized air through the robot's pneumatic circuit translates into constant forces through the air cylinders.

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 [5]. Utilizing electrical current, a coil is activated, allowing flow, and thus without the electrical current, the

Show a cutaway (section view) of the valve to show the components that you are describing.

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.

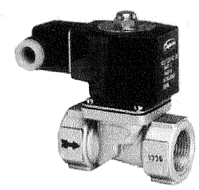


Figure 6: Bimba 1/2" 2 Way Solenoid 12V DC

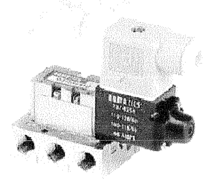


Figure 7: Numatics Mark 3, SPA 3, and PA 3 Series Valve

to allow flow in two directions to allow the cylinder to extend and contract

Directional Control valves allow free flow in one direction but restrict flow in the opposite directions, when air is flowing. A 4-way control valve is necessary, since air will be flowing in multiple directions throughout the pneumatic circuitry of the robot, such as when exhaust air and pressurized air are flowing through the pneumatic circuitry at the same time.

go over the naming convention
4-way, 3-position DCV
4/3 DVC
what is ment by this

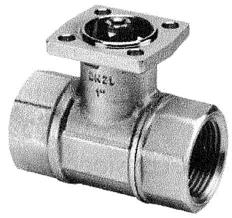


Figure 8: Belimo B208B : 2-Way 1/2" Brass .46 Cv Control Valve

An example circuit for a single leg cylinder is given in Figure 3. The reservoir tank attaches to the solenoid valve using a tether to reduce the mechanical load on the robot.

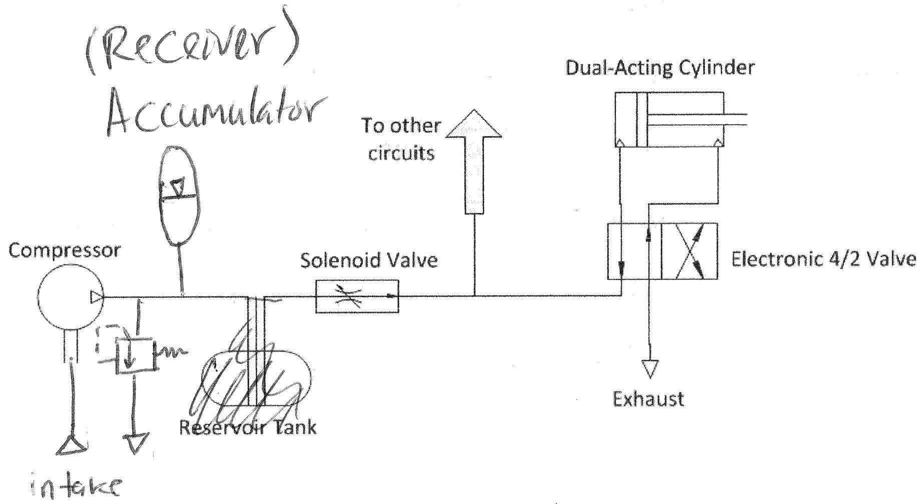


Figure 3: Sample pneumatic circuit for motion actuation

Describe the process from the compressor to the actuation of the cylinder.

Similar robots to our specifications

based on...

Specifications

For the agile quadruped robot, a list of objectives and constraints had to be created. Objectives are criteria that the robot must meet in order to be considered complete. Constraints are hard limits on certain portions of the design. Table 1 summarizes .... and Table 2 lists ....

Table 1: ~~Objectives list for the~~ Design objectives

Objective	Success Criteria
Brown Out Conditions	Robot enters stable condition on electrical failure
Emergency stop button	Robot should be able to completely shut down with one button push
Fuses	Fuses on robot to protect components
Wires organized and secured	Wires should be insulated and protected from mechanical pinching
Robot self-collision avoidance	The robot should not be able to hit itself
Onboard Batteries	All batteries must be on the robot chassis
Number of legs	4 legs
Mechanical Power System	pneumatics
Can walk on a flat surface	Robot should be able to walk on a flat surface without problems
Easy debugging of signals	Pneumatics should have an electrical panel to debug the electrical signals
Robot walks backward	The robot should be able to move backward
Controlled via ~~joystick~~ a user interface	Robot ~~is controlled via joystick~~ movements are controlled w/ a user-interface

Table 2: ~~Constraints List~~ Design constraints

Constraint	Success Criteria

Load Weight	Carry at least 1.25 its own weight safely
Walking Motions	Robot should have at least a creep gait
Maximum Walking Speed	0.5 [m/s]
Weight	15 [kg]
Size	1 [m long] 0.75 [m tall] .75 [m wide] max
Battery Life Pneumatics	3 hours at least
Cost Constraint	$10000 max
System Startup Time	Starts in less than one minute
Recover from disturbances	Robot remains stable even if disturbed up to 10N
Battery Life Microcontroller	2 months at least

Feasibility

Four Legs

The implementation of four legs in the design of the agile robot is both a sound decision both financially and technically. With more than for legs, the project budget will increase to reflect the increase in components, such as air cylinders and control valves, required for additional legs. With less than for legs, maintaining the stability of the robot, while possible, will become more complex and possible require more sensors, thus increasing the budget as well. With for legs, stability is fairly easy to maintain, as long as the center of gravity of the robot falls within the support triangle formed by the three remaining legs in contact with the ground, as the robot takes a step.

Pneumatic Power Source

When comparing pneumatics to other driving sources, such as electrical, through servos, and hydraulic, pneumatics provide a greater force and speed per unit size than servos, while also being lighter, cheaper and easier to maintain than hydraulics. More specifically, with the correctly chosen pneumatic power source the forces required to support the weight of the robot are easily obtainable.

Batteries and battery life

The robot is specified to contain all batteries needed for its power circuits. Small AA batteries can be used to power the microcontroller and other small components like analog to digital converters and filters. Two different twelve volt rechargeable batteries can be used in series to provide twenty four volts to the pneumatic components, which are specified at an operating voltage of twenty four volts. The battery lives can be calculated by taking the average consumption in amps and multiplying by the number of expected hours of operation. The robot would require batteries with high enough amp hours to meet the three hour battery life for the pneumatics and the two month battery life for the microcontroller.

Electrical Signal Components and Debugging Panel

The electrical signal for each leg can be connected to a custom debug panel for testing. The custom panel can use numerous options for connectors and wiring. Normally test equipment uses banana plugs and compatible connectors, which is the common type of connector used with Milwaukee School of Engineering's electrical labs.

Gaits and Stability

In order to achieve stability for an agile walking robot a concept known as the Zero Moment Point has been created [A]. The ZMP is the position on the ground where the moment created by the robot's feet is zero. For a stationary or slow moving robot this position coincides with the center of mass.

In order for the robot to remain stable the ZMP must remain within the convex shape created by the robot's feet in contact with the ground. This shape is known as the support polygon. If the robot's ZMP is outside of the support polygon it will create an unbalanced tipping moment and the robot will become unstable. An example of a stable support polygon is given below [B]:

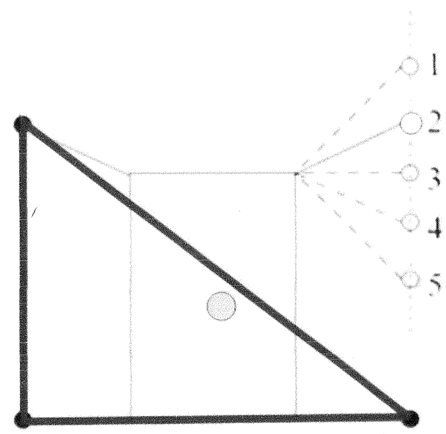


Figure 4: Statically stable leg configuration for a quadruped robot. Note the center of mass is within the support polygon created by the three feet in contact with the ground.

In order to achieve an agile walking gait the path of the ZMP path must be tightly controlled [C]. There are two families of gaits, walking and running. The A.R.C. robot will use a walking gait due to their lower control complexities and higher static stability. The three main robotic walking gaits are the crawl, trot, and pace. A summary of the leg actuation for each gait is given below [D]:

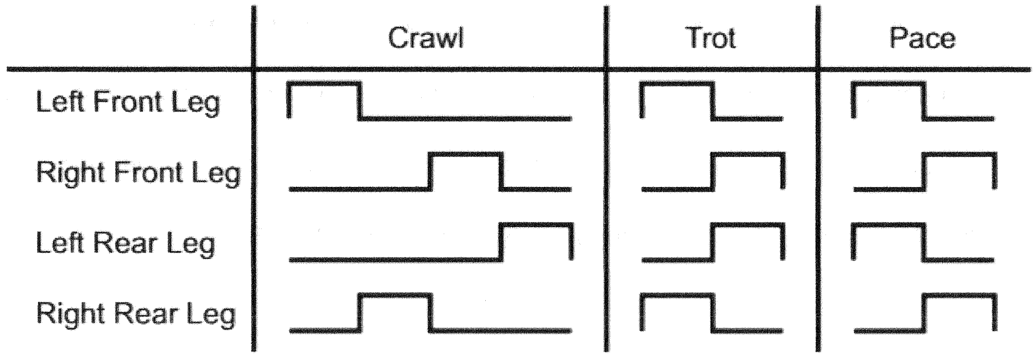


Figure 5: Actuation sequence of each leg of a quadruped robot for three common walking gaits. Due to only a single leg actuating at a time the crawl gait is the slowest and most stable of the three.

The crawl gait is the only statically stable gait due to the support polygon created by the three feet remaining on the ground. The biggest drawback of the crawl gait is the slow overall speed of the robot. Because only one leg is actuated at the time the maximum walking speed is ¼ the speed of each leg.

The trot is marginally statically stable. Two diagonal legs across from each other form a line and if this line passes through the ZMP there is no tipping moment created. However this gait is dynamically stable due to the cyclical nature of gaits. As the robot moves forward the ZMP will travel across the support line created by the feet, cancelling the tipping moments out. The trot has a much higher control complexity than the crawl gait, but it is also much faster.

Pacing involves lifting two legs simultaneously on the same side. This gait is statically unstable as the support polygon is entirely on one side of the robot. This leads to the robot swaying back and forth as it walks as each actuated tips. This gait is marginally faster than the trot while having a much higher control and dynamic complexity.

Due to the small control complexity and statically stable nature of the crawl gait it will be the primary gait developed for the project. Because only one leg is actuated at a time for the crawl gait it will be the fastest to implement in order to test the control software. Due to the static nature of the gait it can also be assumed that the robot is always in a stable configuration during initial development.

After the crawl gait is implemented additional sensors will be integrated into the system to detect and respond to system instability. This will allow the robot to not only react to external disturbances, but also allow it to remain upright while more complex gaits are actuated. Due to the statically unstable nature of faster gaits the problem of recovering from instabilities must be solved before additional gaits are implemented to avoid damage to the robot.

Size

When constraining the size of the robot, the idea of portability was in mind. The robot needed to be able to be moved relatively easy and it also needed to be able to fit in restricted spaces, such as vehicle trunks and perhaps storage closets. Robot sizes vary depending on application, and sometimes even budget. BigDog (Boston Dynamics), for example, is about 3 feet long and 2.5 feet tall, however it is also intended to be a pack-mule robot, carrying supplies thought precarious terrains. Cheetah-Cub (funded by AMARSI) on the other hand, being 0.5 feet tall and 0.69 feet long, was intended for natural locomotion research for implementation in robotics. The decided size limit kept in mind related quadruped robots, but was based heavily on the intent of the robot being educational and thus portable.

Weight (Load Capacity)

In order to keep the robot portable, as the intention is for educational purposes, including community outreach, light weight yet strong materials, such as aluminum, will be used for is chassis.

[Need strengths of materials analysis to support]

Walking Speed

A walking speed of 0.5 meters per second as a minimum should be well within the capabilities of the robot when comparing to other quadruped robots, assuming success in controlling power output of the pneumatic system. Comparable robot walking speeds, along with corresponding weights, can be seen in Table 3.

Table 3: Quadruped Robot Walking Speeds [6]

Robot (Author Year)	m_{rob} kg	h_{hip} m	l_{rob} m	v_{max} $m\,s^{-1}$	FR	BL/s s^{-1}	Gait
Quadruped (Raibert 1990)	38	0.56	0.78	2.2	0.88	2.8	trot
	38	0.56	0.78	2.9	1.53	3.7	bound
Tekken1 [2] (Fukuoka et al. 2003)	3.1	0.21	0.23	0.5	0.12	2.2	walk
Tekken1 [2] (Fukuoka et al. 2009)	3.1	0.21	0.23	1	0.49	4.3	trot
Tekken1 [2] (Fukuoka et al. 2009)	3.1	0.21	0.23	1.1	0.59	4.8	bound
Aibo RES-210A [2] (Kohl et al. 2004)	1.4	0.129	0.289	0.294	0.07	1	walk
Puppy 1 [2] (Iida et al. 2004)	1.5	0.2	0.17	0.5	0.13	2.9	bound
Scout II [2] (Poulakakis et al. 2005)	20.865	0.323	0.552	1.3	0.53	2.4	bound
Puppy II [2] (Iida et al. 2005)	0.273	0.075	0.142	0.5	0.34	3.5	bound
Tekken2 [2] (Kimura et al. 2007)	4.3	0.25	0.3	0.95	0.37	3.2	trot
BigDog [2] (Raibert et al. 2008)	109	1	1.1	3.1	0.98	2.8	bound
	109	1	1.1	1.6	0.26	1.5	trot
	109	1	1.1	2	0.41	1.8	trot
KOLT [2] (Estremera et al. 2008)	80	0.7	1.75	1.1	0.18	0.6	trot
	80	0.7	1.75	1.06	0.16	0.6	pronk
Cheetah-2008 [2] (Rutishauser et al. 2008)	0.72	0.14	0.235	0.25	0.05	1.1	walk
	0.72	0.14	0.235	0.11	0.01	0.5	pace
Rush [2] (Zhang et al. 2009)	4.3	0.2	0.3	0.9	0.41	3	bound
PAW [2] (Smith et al. 2010)	15.7	0.212	0.494	1.2	0.69	2.4	bound
HyQ [1,2] (Semini et al. 2011)	70	0.68	1	2.0	0.6	2.0	trot
Cheetah-cub	1.1	0.158	0.205	1.42	1.30	6.9	trot

Microcontroller Proposal

The microcontroller in this system is used to provide the control and user interface. There were four microcontroller that were analyzed to be used with the system. The four microcontrollers were Arduino, Raspberry Pi, Beagleboard, and Tiva controllers from Texas Instruments. Important factors in deciding the microcontroller includes the speed of the microcontroller, number of analog inputs, and others. A

to do what?

decision matrix was used and shown below in Table 4.

Decision

Table 4: Microcontroller Choice Matrix

Microcontroller Choice Matrix	Weight	0.15	0.25	0.1	0.2	0.25	0.05	1
	Field	Cost	Analog Inputs	GPIO	Speed	MATLAB compatibility	C code Programming Ease	**Evaluation**
	Arduino	3	4	5	2	4	4	3.55
	Raspberry Pi	4	0	1	4	5	2	2.85
	Tiva	5	4	5	3	3	3	3.75
	Beagleboard	1	0	5	5	5	2	3

After weighting each category by a percentage of 100 each microcontroller was analyzed and scored out of five. Each row is summed and given a final evaluation score. The highest evaluation score is the best microcontroller based on the matrix. The top microcontroller is the Tiva series controller from Texas Instruments with a score of 3.75. The second best microcontroller is the Arduino Mega 2560 with a score of 3.55.

Motherboard and Other Electronics

Signal Conditioning and Power Circuits

The motherboard of the system will include~~d~~ any filters and packaged chips like ADCs (analog digital converters) or DACs (digital to analog converters) needed for signal conditioning or analysis. Each pneumatic valve is controlled by an analog signal. Assuming two valves per leg there will be eight valves or eight analog signals. The microcontroller uses digital signals, so the digital signal will have to be converted in one of two ways. The first way would be to use a DAC package. The second solution would be to take a PWM (pulse width modulated) signal from the microcontroller and send it through a low pass filter to form an analog voltage at the output of the filter. From this point the signal might need to be sent through an amplifier to increase the amplitude of the voltage. The microcontroller will need to be isolated from the pneumatic power circuit, so relays or isolation amplifiers will need to be used to isolate the two power circuits.

Communication System

In addition to any signal conditioning there must be a wireless communications channel to allow a user to interact with the robot remotely. This communications channel will be added to the custom motherboard and interface with the microcontroller. Choosing the communications system is difficult given the multitude of options. Two capable communication systems work on the Bluetooth standard specified by the Institute of Electrical and Electronics Engineers (IEEE) 802.15.1 and the Zigbee standard specified by IEEE 802.15.4. Bluetooth has the advantages of being higher speed and has the capability to have multiple master slave relationships. The Zigbee standard is the lower power solution which is favorable in remote applications where high data rates are not needed. A disadvantage of the Zigbee standard is a limitation to only one master device, but for our application we will only need one master device. Given the listed advantages and disadvantages a Zigbee IEEE 802.15.4 standard is the leading choice for a communication system.

Dedicated Control Loop Microcontrollers

If the main controller runs to slow to handle all of the necessary controls loops for every actuator, then smaller microcontrollers can be used to run the control loops. Each microcontroller might have two or three instances of proportional-integral-derivative (PID) controllers executing on the hardware. This technique would be a simple solution to reduce the processing demand on the main microcontroller driving the robot and its movements. It is important to note that these smaller dedicated control loop microcontrollers might not be needed. However, at this stage in the project the necessity cannot be calculated or determined.

- Rough Schematic of mother-board & Location of components
- Power calculation (general using variables)

Preliminary Design

Hexbot

The “Hexbot” design is influenced by spider shaped robots, in which the chassis is square-shaped, and more specifically in the case of the Hexbot hexagonally shaped. The legs are positioned along the sides of the hexagon chassis and have three degrees of freedom, two rotation degrees of freedom, along the z-axis, achieved with use of air cylinders attached to the legs, and a rotation along the y-axis, achieved through the use of a servo attached to the bottom of the chassis. The feet of the robot are simple spheres, intended to be constructed of rubber to ensure there is enough friction in the feet of robot to avoid slippage. While this design displays an open cage-like chassis, some sort of grate is intended to be attached along the sides of the chassis to help achieve a closed off chassis to protect the internal components of the robot. One air cylinder, in the case of this design, will be attached to the servo housing and the upper link at an appropriate point, and another air cylinder will be attached to the upper link and the lower link. This orientation of the air cylinders will ensure the legs can bend at the “knees” and the “hip” and also have rotation about the “hip”.

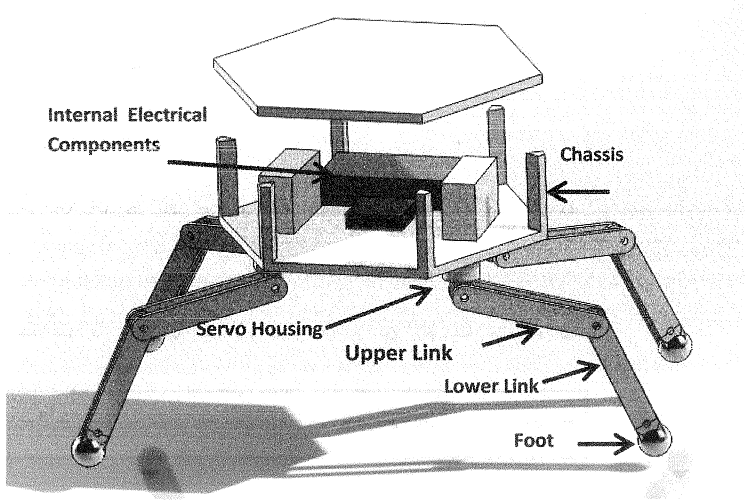


Figure 9: Hexbot – Agile Quadruped Design

other designs

The preliminary design is chosen out of the many potential designs using the following decision matrix in Figure 5. The categories are given with a weight between one and five and given a max score. Each component is then given a score that is then normalized and multiplied by the weight to get the final weighted score.

Table 5: Design Decision Matrix

	Weight [0-5]	Max Score	Score	Normal S
ɔns	5	3	0	0
	5	1	0	0
‹g plus 5kg battery	5	1	0	0
ground	5	1	0	0
ı pinching	5	1	0	0
ɜlays, and microcontroller on chassis	4	3	0	0
	4	3	0	0
	5	1	0	0
nbling the robot	3	2	0	0
	2	3	0	0
	2	3	0	0
d during operation	1	2	0	0
	4	3	0	0
;	4	2	0	0
ctronics	5	1	0	0
	3	1	0	0
ɘr of actuators	4	2	0	0
	4	3	0	0

Design parameters and weights were decided by considering important characteristics and overall functionality of the robot. Parameters were also decided with major constraints in mind, such as those related to user and robot component safety. Examples of parameters related to safety are "Design contains accessible emergency stop" and "Electronics have a cooling mechanism". Considering these parameters are crucial to key functionality and safety in the operation of the robot, the weights are appropriately high. The parameter "Servos do not have a bending moment applied during operation" has the lowest weight because, while bending moments will significantly affect the servos, any serious design will not have significant bending moments applied to the servos, and thus is not a serious consideration.

Project Management ← Bold

Some sentences describing what is to come.

Timeline

Phase I: Design Synthesis (September 12, 2014 – November 23, 2014) ← Bold

1. Research existing walking robot designs
2. Generate constraints and objectives for the robot
3. Determine feasibility of project with a feasibility study of existing robots
4. Create initial models of components to confirm project feasibility
5. Synthesize initial design solutions
6. Formulate decision matrix for final design selection
7. Compile design report detailing the constraints, criteria, feasibility study, and final design

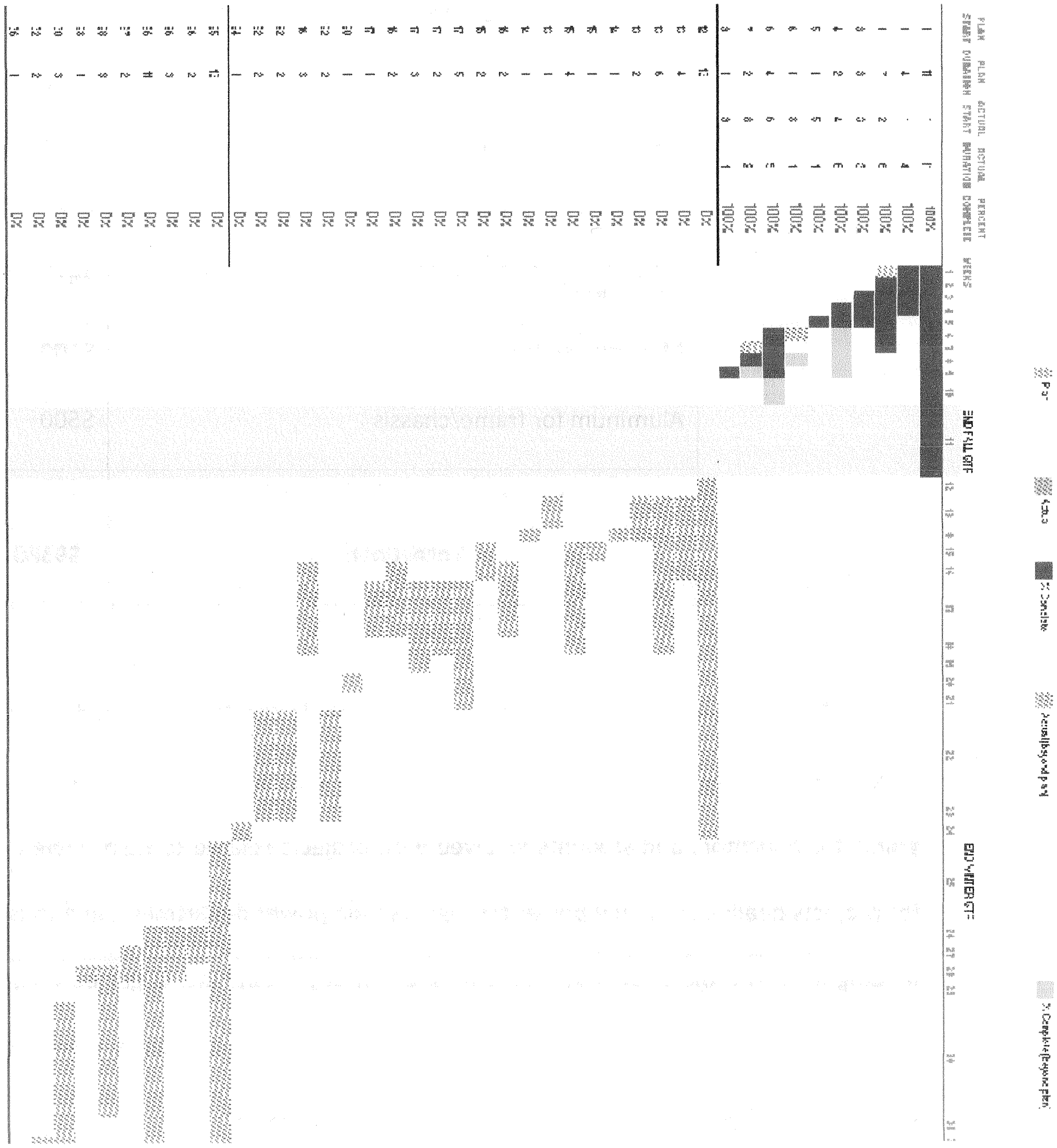
Phase II: Design Analysis (November 24, 2014 – March 1, 2014) ← Bold

1. Create advanced models of components to optimize the design
2. Perform a system response analysis on critical components
3. Develop base software architecture
4. Configure electrical wiring diagram for the robot
5. Develop communication architecture from HMI to controller
6. Determine final sizes and configuration of components
7. Use final models to develop idealized control algorithms
8. Present final design

Phase III: Development and Testing (March 2, 2014 – May 2014) Bold.

1. Construct robotic leg components
2. Modify leg gains to optimize control algorithm
3. Construct robotic chassis
4. Mount components on chassis
5. Mount legs on chassis
6. Construct robot tether
7. Test and finalize control algorithms

Table 6: Gantt Chart



Preliminary Budget

The initial budget of the project is $9380. A breakdown of the project costs is shown in the table below:

Table 7: Initial Project Budget

Item	Cost

Proportional directional control valves (8)	$4400
Double acting piston feedback cylinders (8)	$3600
Air Compressor	$150
Single solenoid valve	$100
Reservoir cartridge	$30
Rechargeable batteries	$200
Microcontroller	$100
Aluminum for frame/chassis	$500
Miscellaneous hardware/electronic components	$300
Total Cost:	**$9380**

Some possible sponsors for this project include the National Fluid Power Association (NFPA), MSOE's Fluid Power department, Johnson Controls Inc., Joy Global Inc., and Numatics. NFPA offers grants for educators and students involved with projects related to fluid power. MSOE offers funding for projects dealing with fluid power through its fluid power department, and thus are willing to provide funding for this project. Johnson Controls Inc. and Joy Global Inc. might be willing to fund this project monetarily. Numatics, a company specializing in pneumatic components, is willing to offer components, such as air cylinders and control valves, for use with the project.

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