

[TITLE]

Team A.R.C. - Design Proposal

MILWAUKEE
SCHOOL OF
ENGINEERING

MECHANICAL ENGINEERING SENIOR DESIGN

[DATE]

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Executive Summary

Project Statement

Include some pedagogical research

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For many years, pedagogical researchers have acknowledged

Milwaukee School of Engineering (MSOE) participates in community outreach programs where science, technology, engineering, and mathematics (STEM) topics are demonstrated to encourage younger generations of students 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 compact pneumatic walking robot with pneumatic locomotion for the Milwaukee School of Engineering's controls classes would give students a first-hand experience with complex control systems, expose them to the applications of fluid power, and introduce them to the kinematics of quadruped motion.

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.

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 with a user input device such as a joystick, a wheel, or any other such device for ease of use.

Background Research

Wheeled vs. Legged Locomotion

Based on the objectives of the project,....

The ~~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 wherein the design will function.

The implementation of wheels in a design requires simpler programming when compared to legged motion and less parts than in legged motion. 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. Wheels do, however, struggle with rugged terrain and thus lose stability ([traction?](#)), so in areas without flat surfaces, wheeled locomotion is difficult. Situations favoring wheeled motion involve environments where the surface is flat, energy usage is critical, and high speed is favorable.

What about legs?

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 four legs, thus creating 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.

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. 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.

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.

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 programming of legged motion in a design to be more challenging and more costly, due to the need of more parts. 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.

Commented [LAR1]: Include in wheel/leg section

Implementation

Legged robots, among many things, are a means to replace humans and animals in tasks such as travel, exploration, military operations and equipment transportation, where having humans or animals could lead to exposure to hazardous conditions or exhaustion. Utilizing natural dynamic locomotion legged robots have the ability to strategically traverse various terrain efficiently. Legged robots also provide 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.

Maybe add to
wheel/leg
section

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 (why??). 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.

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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 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.

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

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would simply want to return to its un-stretched length as fast as possible, thus varying walking patterns would be challenging.

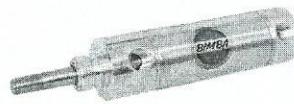


Figure #:

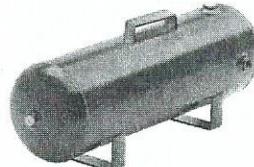
Bimba Original Line® Air cylinder w/ Adjustable Cushions

What about position feedback?

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Air Supply Tank

The air supply tank carries 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.



"Smittybilt 99210-2 2.5 Gallon Air Tank"

place in reservoir
↓ air cartridge
↓ section

An air receiver tank is an integral and important part of any compressed air system. Typically a receiver tank is sized at 6-10 times the flow rate of the system.

1. The receiver tank acts as a reservoir of compressed air for peak demands.
2. The receiver tank will help remove water from the system by allowing the air a chance to cool.
3. The receiver tank minimizes pulsation in the system caused by a reciprocating compressor or a cyclic process downstream.

Source: <http://blog.parker.com/the-importance-of-using-an-air-receiver-tank-in-a-compressed-air-system>

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Compressor

The air compressor further pressurizes air received from the air supply tank. 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.



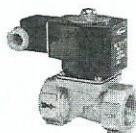
Speedaire Air Compressor, 0.9 HP, 120V, 115 psi

Air Reservoir Cartridge

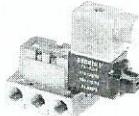
The air reservoir cartridge holds a supply of pressurized air received from the air compressor. The air reservoir cartridge is used to equalize the flow through the pneumatic circuit of the robot, thus maintaining constant flow of pressurized air through the robot's pneumatic circuit. A constant flow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

Solenoid Valve

Utilizing electric signals, the main function of the solenoid valve is to either turn on or shut off the total flow in the pneumatic circuit.



Bimba 1/2" 2 Way Solenoid 12V DC



Directional Control

Numatics Mark 3, SPA 3, and PA 3 Series Valve

Control Valves

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 possibly 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

We'll need a 4-way DCV

Allows free flow in one direction but restricts flow in the opposite direction, when air is flowing. A two way control valve is necessary, since air will be flowing two directions in the pneumatic circuitry of the robot.



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

Advantages/disadvantages of 4 legs

Similar robots to our specifications

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: Objectives List

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	Robot is controlled via joystick

Table 2: Constraints List

Constraint	Success Criteria
Load Weight	Carry at least 1.25 its own weight safely

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

Utilizing forward and inverse kinematics, gaits can be generated in MATLAB. With the use of a microcontroller, pneumatic cylinders can be forced to extend or retract, providing the necessary torques and forces to generate a gait for the robot. The robot will need to have at least a creep gait, where one leg moves forward at a time and there is no dragging of the remaining three legs. With the stability of four legs, if efficient control of the pneumatic system is achieved and all of the kinematic models are correct, the creep gait, being less complex compared to other gaits, is possible.

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 its 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.

Table 3: Quadruped Robot Walking Speeds

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] (Fukunaka et al. 2003)	3.1	0.21	0.23	0.5	0.12	2.2	walk
Tekken1 [2] (Fukunaka et al. 2009)	8.1	0.21	0.23	1	0.49	4.3	trot
Tekken1 [2] (Fukunaka et al. 2009)	3.1	0.21	0.23	1.1	0.59	4.8	bound
Albo RES-210A [4] (Kohli 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] (Pouliakakis et al. 2005)	20.865	0.323	0.552	1.8	0.33	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	0.05	0.37	3.2	trot
BigDog [2] (Raibert et al. 2008)	109	1	1.1	3.1	0.98	2.6	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	0.285	0.25	0.05	1.1	walk
	0.72	0.14	0.285	0.11	0.01	0.5	pace
Rush [2] (Zhang et al. 2008)	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] (Semanini 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

Sproewitz, Alexander et al. Towards Dynamic Trot Gait Locomotion: Design, Control, and Experiments with Cheetah-cub, a Compliant Quadruped Robot, International Journal of Robotics Research, Volume 32, Issue 8, July 2013, pp. 933-951.

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 decision matrix was used and shown below in figure four.

Figure 4: Microcontroller Choice Matrix

Figure 4
Table

Microcontroller Choice Matrix Field	0.15	0.15	0	0.2	0.25	0.05	1
	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

The motherboard of the system will include 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.

Preliminary Design

The preliminary design is chosen out of many potential designs using the following decision matrix in figure five. 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.

Figure 5: Design Decision Matrix

	Weight [0-5]	Max Score	Score
uring operation	1	5	3
ing the robot	2	5	1
simple gait	3	5	0
a simple gait	3	5	0
nding	5	5	1
rs, and microcontroller on chassis	4	5	0
safety of at least 2	4	5	0

Timeline

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

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

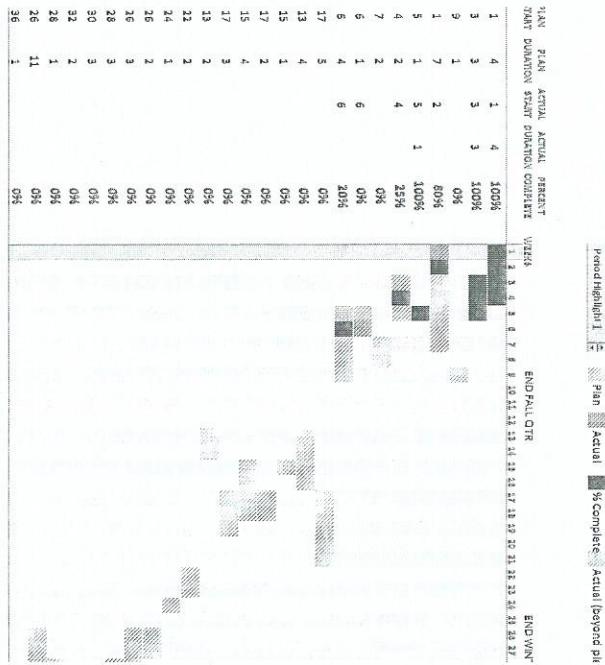
Phase II: Design Analysis (November 24, 2014 – March 1, 2014)

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)

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 4: 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 5: 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

NFPA
MSOE
Johnson Controls
Joy Global
Pneumatic
numerics