Design of a Small Pneumatic Walking Robot

by

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Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the
Degree of
Master of Science

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ABSTRACT

Many researchers have built walking robots because they promise better mobility than wheeled or tracked vehicles. The speed and payload capacity of these robots, however, has been insufficient to offer a viable alternative to traditional vehicles. The major factors that contribute to these problems are actuator force density, power to weight ratio, and limited leg workspace. Many of these problems are exacerbated for small robots. This paper presents the design of a 10 lb, six-legged, pneumatically powered walking robot named Boadicea. Boadicea walks faster, and can carry more payload, than previous small walkers. A pneumatic actuation system using solenoid valves and custom lightweight actuators produces high force and power densities. Most structural parts on Boadicea are injection molded, fiber-reinforced plastic. The legs of the robot are modeled after a cockroach, *Blaberus Discoidalis*: front, middle, and rear legs are all different, and the legs have large, overlapping workspaces. Each leg uses a pantograph mechanism to produce Cartesian foot motions. Preliminary results indicate that the mechanical capabilities of Boadicea are an improvement over previous legged robots.

Thesis Supervisor: Professor Rodney Brooks

Title: Professor of Computer Science and Engineering

"Ben, I want to say one word to you.
Just one word. Are you listening? Plastics.
There's a great future in plastics"

\- Mr. McGuire, in *The Graduate*

ACKNOWLEDGMENTS

I would like to thank all the people who helped make this project possible: Rod Brooks, Gill Pratt, Ken Salisbury, Cynthia Ferrell, Matt Williamson, and Gina Middaugh.

I would also like to thank the American Composite Technology Company for donating the carbon fiber tubing I used on Boadicea.

WHO WAS BOADICEA?

All of the legged robots built at the Mobile Robotics Laboratory have been named after marauding conquerors: Genghis, Attila, and Hannibal. In keeping with tradition, the robot I built for this thesis is named Boadicea, after a Celtic warrior-queen who led her tribe against invading Romans.

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1. Introduction

Many researchers have built walking robots because they offer the promise of better mobility than wheeled or tracked vehicles. The speed and payload capacity of these robots, however, has been insufficient to offer a viable alternative to traditional vehicles. The major factors that contribute to these problems are actuator force density, power to weight ratio, and limited leg workspace. Many of these problems are especially acute for small robots.

This paper presents the design of a 10 lb, six-legged pneumatically powered walking robot named Boadicea. Boadicea was built to address these shortcomings. Boadicea walks faster, and can carry more payload, than previous small walkers. A pneumatic actuation system and lightweight design produce high force and power densities. The legs of the robot are modeled after a cockroach, *Blaberus Discoidalis*: front, middle, and rear legs are all different, and the legs have large, overlapping workspaces. Each leg uses a pantograph mechanism to produce Cartesian foot motions. Preliminary results indicate that the mechanical capabilities of Boadicea are an improvement over previous legged robots.

1.1. Legged robot background

There are many reasons to build a legged robot. The most obvious is that legged machines can navigate over more rugged terrain than wheeled or tracked vehicles **[Waldron, et al 84] [McGhee and Iswandhi 79] [Hirose 84]**. If robots are to operate in unstructured environments, either outdoors or exploring other planets, they must be able to traverse difficult terrain. Another advantage of legs is that they can be more effective as probes for sensing the environment **[Angle 91].**

Most legged robots that have been built, however, lack the mechanical capabilities to fulfill these aspirations. They are orders of magnitude slower than wheeled vehicles, and have limited or zero payload capacity. Actuator torque and leg workspace limitations have restricted the type of terrain they can navigate. Wheeled and tracked robots with creative suspension systems, like the Russian Marskohod and the Rocky robots from the Jet Propulsion Laboratory, can traverse difficult terrain at least as well as current legged machines.

One reason for the mechanical shortcomings of legged robots is that many legged locomotion experiments have focused on control and software issues. These studies consider different methods of software control, gait generation, and stability **[Kajita, et al 92] [Zhang and Song 91] [Dwivedi and Mahlingam 91a] [Dwivedi and Mahlingam 91b] [McGhee and Iswandhi 79] [Chiel, et al 92] [Miller 94].** Although some of these experiments are performed in simulation, most involve the construction of simple legged machines. However, improved mechanics are not the goals of these experiments. As a result, their mechanical design is usually simplified as much as possible. The sensors and actuators on these robots are normally optical encoders and DC gearmotors because they are easy to use, not because they offer superior performance. These robots are not built to push the mechanical performance envelope on legged vehicle capabilities.

The legged machines with the most impressive performance, however, are the result of more thorough mechanical design, notably the Ohio State Adaptive Suspension Vehicle (ASV) and the GE Quadruped **[Vohnout, et al 83] [Song, et al 81] [Song, et al 83] [Waldron, et al 84] [Song and Waldron 89].** Both of these machines have remarkable capabilities; their speed and payload capabilities are sufficient to offer a feasible alternative to wheeled vehicles. To achieve this level of performance, both machines use hydraulic actuation systems.

Robot	**Length (m)**	**Mass (kg)**	**Speed (m/s)**	**Payload (kg)**	**Speed/ Length**	**Payload/ Mass**
Case Western *a*	.5	1	.083	unspecified	.16	---
Miller's biped *b*	1 m tall	9.5	.025	unspecified	.025	---
Chinese biped *c*	1.1 m tall	70	.05	unspecified	.045	---
Ambler *d*	3	2700	.0058	480	.0019	17 %
Dante 2 *e*	3	770	.017	unspecified	.006	---
PV-II *f*	.87	10	.02	2	.023	20 %
Attila *g*	.36	2.5	.03	unspecified	.083	---
Genghis *h*	.39	1.8	.038	.8	.097	44 %

References: *a* **[Chiel, et al 92]**, *b* **[Miller 94]**, *c* **[Jinglun and Li shiqing 90]**, *d* **[Simmons 92]**, *e* **[Nygren and Fong 94]**, *f* **[Hirose 84]**, *g* **[Angle 89]**, *h* **[Angle 91]**

Table 1.1: Performance of legged robots with electric actuators

These robots use electric actuators and maintain static stability during locomotion. The normalized speed column showsthey are quite slow; except for the Case Western robot, all take over 10 sec. to move one body length. Normalized speed (speed/length) and payload capacity (payload/weight) are useful for comparisons are because the robots are built on a wide range of scales.

The robots listed in **Table 1.1** are electrically powered and maintain static stability during locomotion. They are all slow moving, and most have a limited payload capacity. The two machines that stand out as over achievers, Genghis and the Case Western hexapod, are the simplest of the group. These two robots have two degrees of freedom per leg; all the other robots in **Tables 1.1-1.3** have more complex leg designs.

Robot	**Length (m)**	**Mass (kg)**	**Speed (m/s)**	**Payload (kg)**	**Speed/ Length**	**Payload/ Mass**
ASV *a*	5	3200	3.6	225	.72	7 %
GE Quadruped *b*	4	1300	.9	220	.23	17 %
Boadicea	.5	4.9	.11	2.3	.22	46 %

References: *a* **[Waldron, et al 84]**, *b* **[McGhee, 76]**

Table 1.2: Performance of fluid powered robots

These robots use fluid power; the ASV and GE Quadruped are hydraulic, and Boadicea is my pneumatic robot. Like the robots in Table 1.1, these machines also maintain static stability during locomotion. The normalized speed and payload capacity for these robots is superior to their electric counterparts.

Table 1.2 shows the performance of fluid powered, statically stable robots. This group is much faster than their electric counterparts, and has better payload capacity. Boadicea is the pneumatic robot I built for this thesis.

Robot	**Length (m)**	**Mass (kg)**	**Speed (m/s)**	**Payload (kg)**	**Speed/ Length**	**Payload/ Mass**
Kajita's biped *a*	.4 m tall	2.7	.3	unspecified	.75	---
Collie-2 *b*	.35	7.5	.15	unspecified	.43	---
Raibert's 2D biped *c*	.75	11.5	5.9	unspecified	7.87	---

References: *a* **[Kajita, et al 92]**, *b* **[Kimura, et al 90]**, *c* **[Hodgins, et al 86]**

Table 1.3: Performance of dynamic robots

These robots use dynamic gaits for locomotion. Kajita's biped and Kimura's Collie-2 are electrically powered. Raibert's biped uses a pneumatic air-spring for propulsion and hydraulic actuators for leg positioning. His robots are the only ones I know that combine both fluid power and dynamic stability. Although Kajita's biped falls after five steps, these robots indicate the speed advantages of dynamic locomotion.

Legged robots that locomote dynamically are listed in **Table 1.3**. Speed is the main advantage of dynamic stability. Kajita's biped and Collie-2 are electrically powered. It should be noted, however, that Kajita's biped falls down after five steps. Raibert's biped, like his other robots, combines both fluid power and dynamic balance. Its speed capability is dramatically superior to the other robots.

1.2. Project goals

The data in **Tables 1.1-1.3** show the impetus for the Boadicea project. If legged robots are to fulfill their promise of providing more capable locomotion than wheeled machines, their mechanical performance must be improved; statically stable, electric walking machines are too slow and weak. The most serious limits on robot performance is the torque density of the actuators **[Angle 89] [Angle 91] [Binnard 92]** and the power density of the robot**.** Many robots have also suffered from reliability problems, and limited leg workspace **[Ferrell 93].**

Robot weight	10 lbs
Maximum payload	4 lbs
Normal walking speed	6 in/sec
Wave gait speed	3.6 in/sec
Maximum joint torque	42 in-lb
Maximum actuator power	6 W per actuator
climb a 45° slope with the tripod gait	
climb a 45° slope with the wave gait	

Table 1.4: Design targets for Boadicea

Boadicea achieves higher power and force densities with pneumatic actuators and lightweight materials. By making frequent prototypes and design revisions, I improved the reliability of the robot. Boadicea's legs, which are modeled after the legs of a cockroach, have large workspaces, simple kinematics, and different designs for the front, middle, and back legs. Furthermore, the leg mechanism produces decoupled, linear motions to reduce computational demands.

Table 1.4 lists the performance targets which guided Boadicea's design. All of these capabilities represent substantial improvements over previous small robots. Boadicea was designed to have ten actuators moving simultaneously during walking, which means the power source supplies a maximum of 60 Watts. For comparison, our laboratory's previous walking robot, Attila, draws 15 W of electrical power for its motors. Assuming 80% efficiency, Attila's motors will produce 12 W of mechanical power. Therefore, Boadicea has up to five times the mechanical power available for locomotion.

1.3. Boadicea

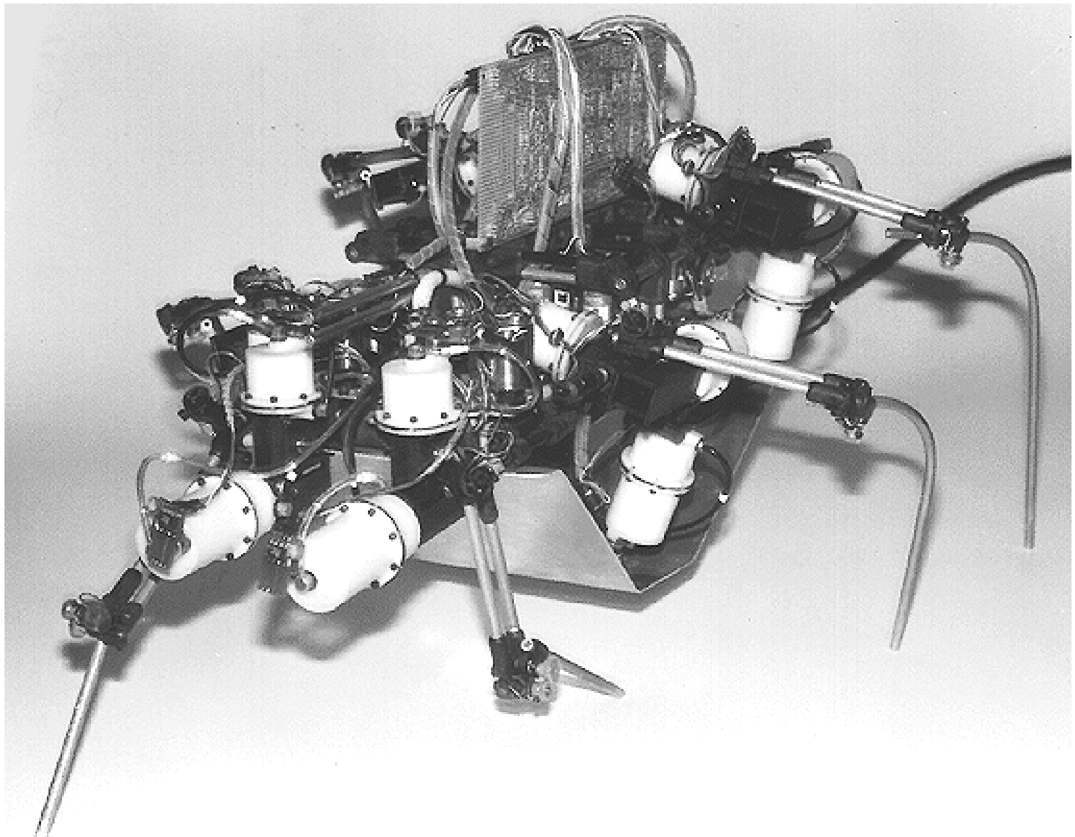
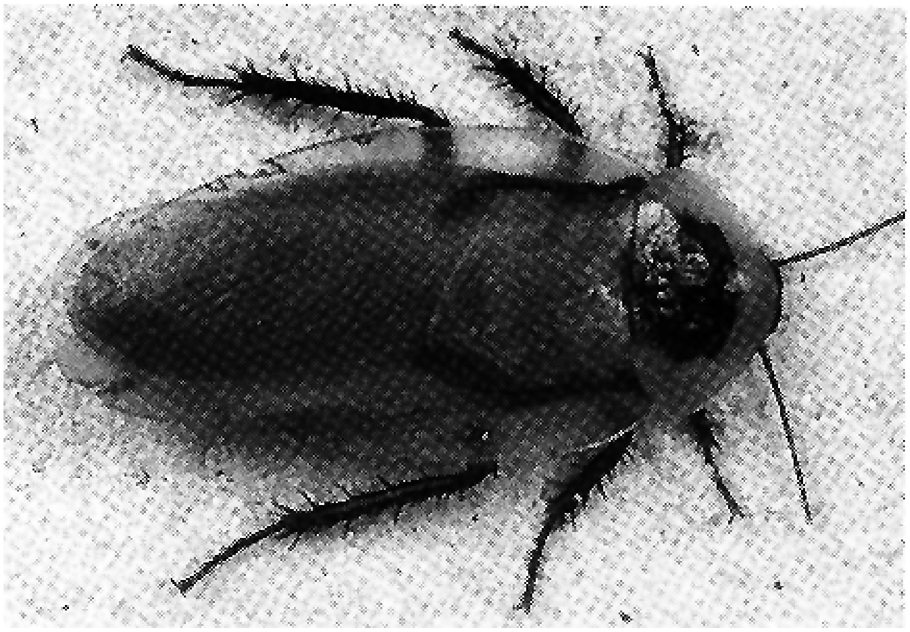


Figure 1.1: Photograph of Boadicea

Boadicea has six legs powered by compressed air at 100 psi. The rear and middle legs have three DOFs each while the front legs each have two DOFs. The robot's 16 actuators are controlled with solenoid poppet valves by a 68332 microprocessor. Pressure sensors and potentiometers (one each per DOF) measure leg position and loading.

Boadicea is a six-legged, pneumatically powered walking robot. (See **Figure 1.1**) The robot's mechanics are modeled after a cockroach, *Blaberus Discoidalis*, which is studied by Bob Full, Rodger Kram, and their colleagues at the University of California, Berkeley (see **Figure 1.2**). Boadicea's rear and middle legs have three degrees of freedom (DOFs) each, while the front legs have two DOFs. The robot has position and pressure sensors for determining leg position and loading.



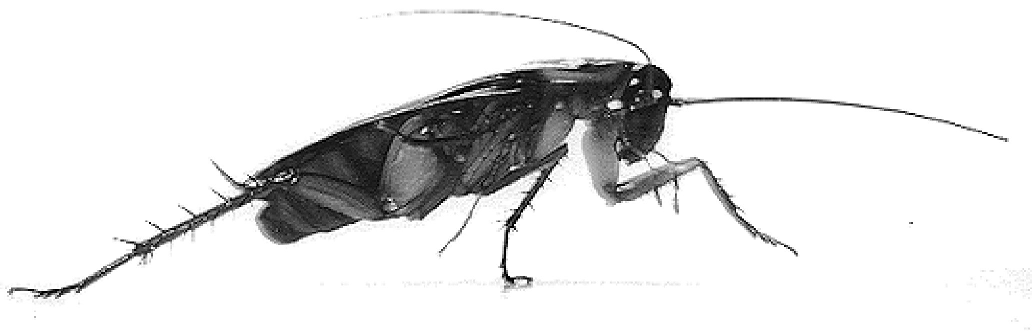


Figure 1.2: *Periplaneta Americana* and *Balberus Discoidalis*

These insects are studied by Bob Full and his colleagues at UC Berkeley. The size, orientation, and workspace of Boadicea's legs is modeled after *Blaberus Discoidalis* (top). *Periplaneta Americana* (bottom) is smaller and faster than *Blaberus* and has longer front legs.

All six legs have a two DOF pantograph mechanism (see **Figures 1.3, 1.4**) for producing Cartesian foot motions, which simplify software requirements. The front leg pantographs operate in a saggital plane; the workspace provides a 10" range of motion for the advance DOF and 4" for the lift DOF. ("saggital" refers to a plane which divides the body into left and right sides.)

Figure 1.3: Photograph of Boadicea's pantograph mechanism

This linkage provides a large Cartesian workspace with a simple and compact mechanism. The large T-shaped pieces enclose prismatic joints (sliders) that connect the pneumatic actuators to the leg links. The white cylinders are the pneumatic actuators.

The middle and rear leg pantographs are oriented in a horizontal plane; they provide a large (10" for middle legs and 14" for rear legs) advance range of motion, and a shorter (4" and 5.6" for middle and rear legs, respectively) stroke for abduction and adduction (moving the foot away from or towards the body). The pantographs for these legs can be rotated about a longitudinal axis by a third actuator. This lift motion is not Cartesian; it has an additional lateral component. Since this DOF is normally used to lift the leg off the ground or lower it until the foot touches the ground, the lateral motion is insignificant; it only occurs while the foot is in the air.

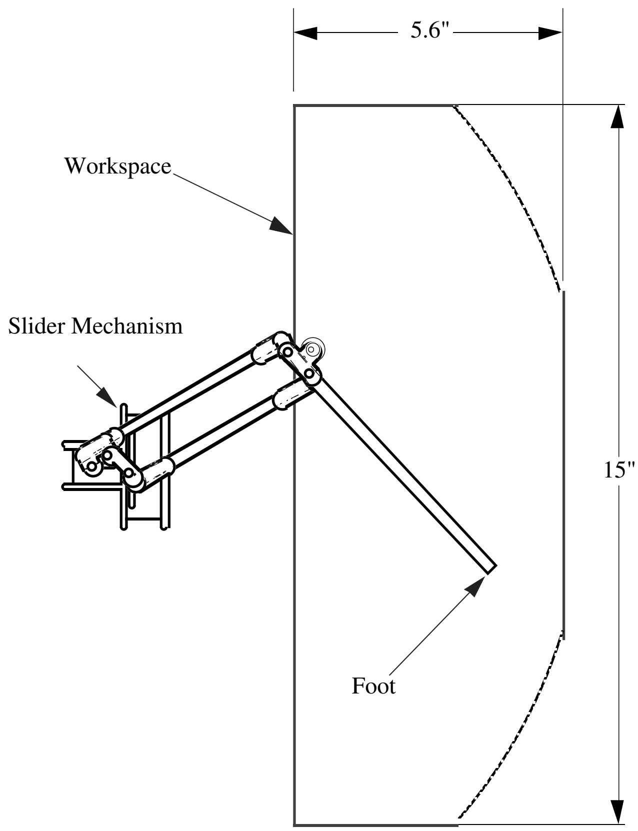


Figure 1.4: Workspace of Boadicea's pantographs

This figure shows the size and shape of the workspace for Boadicea's rear legs. Front and middle leg workspaces are slightly smaller, but are the same shape. The pantograph linkage provides a 1:10 transmission ratio; the foot moves 10 times as much as the actuator piston.

Boadicea's sixteen actuators are pneumatic cylinders. Because commercially available pneumatic actuators are unacceptably large and heavy for a robot this size, I designed and built actuators that are much lighter and smaller than off-the-shelf cylinders. The actuators weigh less than 2 oz and can produce up to 100 lb of force.

Boadicea is controlled by an on-board 68332 microprocessor. The processor is incorporated in an off-the-shelf single board computer that provides memory and communication ports. I designed and built a motherboard for the processor that contains analog to digital (A/D) converters for monitoring sensor values and H-Bridge drivers for controlling the valves.

2. Fluid Power

Boadicea, the robot I built, achieves its greatest improvement in mechanical performance by using pneumatic actuators instead of electric motors. Fluid power has several advantages over electric motors in a robotic application **[Nair, et al 83].** After deciding to use fluid power, the designer must choose between a hydraulic or a pneumatic system. Larger walking robots have generally been hydraulically powered **[Waldron, et al 84], [Liston and Mosher 68].** For a small robot, however, I believe pneumatics are the proper choice.

2.1. Advantages over electric motors

Fluid actuators, either hydraulic or pneumatic, are well suited to walking robots because they are high force, low speed actuators. Second, a pump or compressor can be powered by a denser energy source than batteries (see **Table 2.1**). Fluid systems also weigh less than their electric counterparts; are more flexible than electric systems; and have high torque to inertia ratios, easy power dissipation, and simple overload protection.

Transmission ratio

Electric motors are inherently high-speed, low-torque actuators. Robotic applications, however, involve relatively low-speed, high torque motions. This problem is exacerbated on small robots because smaller motors run faster than larger motors. One solution to this problem is to use high torque (often brushless) motors. These motors are expensive, heavy, and require large electrical currents. A more common and practical solution is to use DC gearmotors, which make force control difficult because of gearbox friction, backlash, and the amplification of motor inertia.

The critical factor in selecting an actuator for a walking robot, or a manipulator, is the torque (or force) density **[Angle 91].** The actuator weight determines the overall robot weight, which establishes the torque requirements. With small DC gearmotors, it is difficult to find a motor-gearbox combination with acceptable performance because of the high gear ratio required and the limited strength of the gear teeth.

How does size affect these liabilities? Because of different scaling properties, the limitations of large machines often do not apply to smaller versions. The graph in **Figure 2.1** shows a linear relationship between output torque and gearbox weight for a wide size range **[MicroMo 93] [Maxon 94]**. This linear relationship indicates that the torque density is constant for a wide variety of gearbox sizes. Assuming robot weight and gearbox weight scale together, there is no advantage gained by changing the robot size.

There is another factor which does penalize smaller robots, however. All of the gearboxes plotted in **Figure 2.1** have a gear ratio approximately 200:1. Because small DC motors run faster than larger motors, they require a higher gear ratio. Increasing the gear ratio adds to gearbox weight without increasing the torque capability; higher ratio gearboxes have a lower torque density. Experience with the six legged robot, Attila, indicates that the torque to weight ratio of commercial gearboxes is insufficient for a high performance legged robot **[Angle 91] [Binnard 92].**

Fluid power systems have low speed, high force actuators; the intrinsic transmission ratio is appropriate for robotics applications. Furthermore, the transmission ratio can be altered by changing the area of the actuator pistons, which does not affect actuator weight significantly.

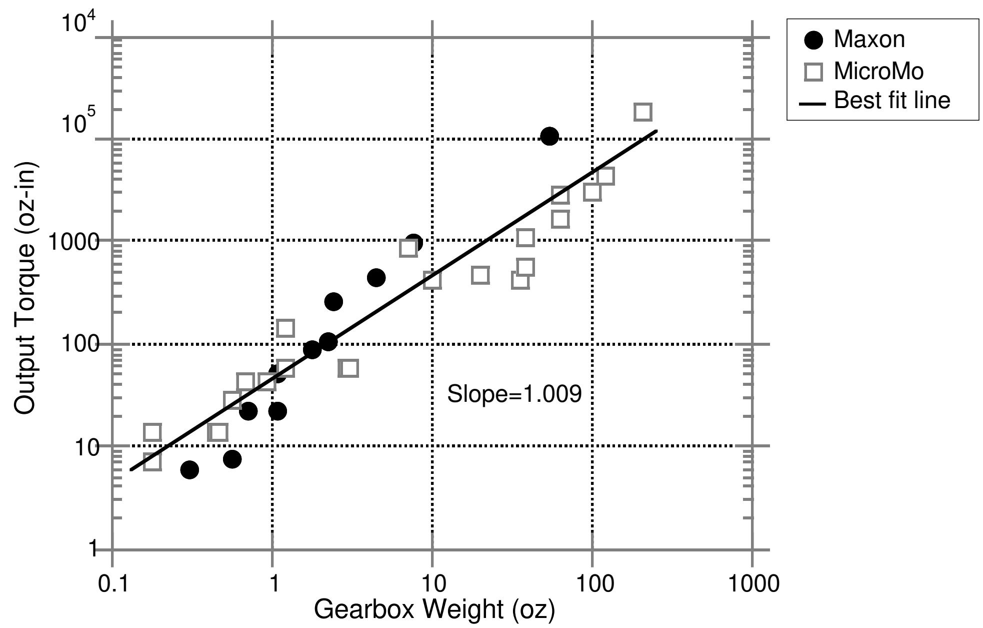


Figure 2.1: Gearbox torque comparison

This graph indicates that there is a linear relationship between output torque and gearbox weight; the torque density is constant for different gearbox sizes. All of the gearboxes shown have a gear ratio approximately 200:1.

Power density

Fluid power systems have a much higher power to weight ratio than electric systems. Typical hydraulic systems weigh 0.5 to 1 lb/HP while electric systems weigh 5 to 10 lb/HP. These figures include the weight of the prime mover, stored energy, actuators, and valves or electronics.

Energy storage

Table 2.1 lists the energy density of different storage methods. Compressed air has approximately the same density as the batteries that are normally used in electric systems. The battery technologies with the highest energy density, like Lithium, are not rechargeable.

For compressed air storage, the weight of pressure vessels depends on several factors, and can vary over orders of magnitude. Tank size, maximum pressure, shape, and materials will all affect the available energy density. Safety is another primary factor which determines tank weight; the amount of over-pressure a tank is designed for determines the strength required. Energy density is also affected by the amount of energy stored in the tank, which varies with the rate of consumption and ambient temperature. (See Section 2.2: The SCUBA Alternative)

Storage Medium	Energy Density (KJ/lb)
NiCd Batteries	40
Lithium Batteries	490
Air at 9000 psi (with tank)	65-200
Gasoline	25,000
U_{235} Fission	36,000,000

Table 2.1: Comparison of Energy Density

[Jones and Flynn 93] The energy density of compressed air is comparable to current battery technology. A fluid power system can also make use of chemical energy storage because an internal combustion engine can turn a pump directly.

Fluid power allows easy use of the better energy storage media. Compressed air can power a pneumatic system directly, and can supply hydraulic power through an accumulator. A fluid power system can also make use of chemical energy storage because an internal combustion engine can turn a pump directly.

Easy force control

Pressure sensors for fluid power systems are easily available and simple to install. They allow straightforward, high performance force control. Controlling force with electric motors is more complex; either gearbox effects makes torque control difficult, or large, high torque motors are required **[Pratt and Williamson 95].**

2.2. Hydraulics vs. pneumatics

Hydraulic and pneumatic systems have been compared many times. For a small walking robot, most of the trade-offs favor pneumatics.

Compressibility

The most significant difference between hydraulic and pneumatic systems is compressibility, which is usually deemed a disadvantage. For a robot, however, compressibility is not necessarily a liability. Several researchers have looked at the advantages of incorporating springs in legged robots **[Full, et al 89] [Cavagna, et al 77] [Alexander 90]**. A pneumatic actuation system provides these springs "for free." Furthermore, the stiffness, or impedance, of the pneumatic springs can be controlled more easily than with mechanical springs.

This controllability can be seen from the ideal gas law:

$$PV = mR_{air}T$$

If the mass of air in the actuator, m, is constant, the pressure, P, and volume, V, will be inversely related. This relationship is what causes the actuator's springiness. Changing m will adjust the apparent stiffness.

Weight

When selecting a power system for a mobile robot, weight is a primary concern. The lower viscosity of gaseous media allows comparable flow rates with smaller valves, fittings, and hoses. Another significant difference is the weight of the working fluid itself. Air weighs practically nothing, while the weight of oil or water in a hydraulic system can be substantial. In order to obtain a superior power to weight ratio, hydraulic systems must operate at a much higher pressure. For a Boadicea sized robot, the acceptable off-the-shelf components have a maximum pressure of 100 psi, which is insufficient to make a hydraulic system attractive.

Implications for control system

The high compressibility of pneumatic systems is generally eschewed because it complicates position control. However, it is not clear that position control is the best mode for robots. Unless the robot is performing brain surgery or precision assembly, high accuracy position control is not ideal. The interesting tasks that robots perform are their interactions with objects in the environment. Proper behavior for these interactions is easier to achieve with force or impedance (stiffness) control **[Pratt and Williamson 95]**

Fluid power systems make force control straightforward to implement. Additionally, the compressibility of pneumatic systems makes impedance control possible, which could be a useful capability. For example, a robot design could exploit actuator compliance to improve walking efficiency. Different gaits and environments would require different actuator stiffness. The servo system could adjust the pressure in the actuators to achieve correct passive behavior.

Leaks

Leaks are a major concern in fluid power systems, especially a prototype system like Boadicea. Virtually all fluid systems will have some leakage, particularly on a small mobile robot, where the amount of sealing hardware is limited. A major advantage of pneumatic systems for this application is that air leaks are relatively benign; they will not make a mess or short out electronics.

SCUBA alternative

Another advantage of a pneumatic system is that the mechanical energy for the robot can be stored as compressed air at a high pressure. A regulator can expand the stored air to the proper working pressure. SCUBA gear uses the same principle. This arrangement is impractical for a hydraulic system because the working fluid does not recirculate through the system; the fluid in the tank is only used once. A lifetime supply of hydraulic fluid would be difficult to carry because it is incompressible; compressibility allows a small tank to carry a large quantity of air.

The amount of useful energy stored in a compressed air tank depends on the rate at which the tank is emptied. If the air supply is exhausted quickly, the gas will expand adiabatically; the air delivered to the cylinders will be cold. If the air is consumed slowly enough, the gas leaving the regulator will warm to the ambient temperature, providing isothermal behavior. Since the isothermal case is absorbing heat energy from the environment, the air supply will last longer.

Structural Composites, Inc., located in Pomona, CA, manufactured a high pressure composite pressure vessel for the Lawrence Livermore National Laboratory **[Whitehead 95].** This vessel weighed 1.4 lb, had a rated pressure of 9000 psi, and had a volume of $45\ \text{in}^3$. Using a thermodynamic analysis, we can calculate the amount of energy stored in this tank.

The initial conditions are:

$$P_1 = 62 \cdot 10^6\ \tfrac{\text{N}}{\text{m}^2}$$

$$V = .0007\ \text{m}^3$$

$$T = 300\ \text{K}$$

$$R_{air} = 287\ \tfrac{\text{J}}{\text{Kg} \cdot \text{K}}$$

Here P_1 is the initial pressure (9000 psi), V is the tank volume, T is the ambient temperature, and R_{air} is the gas constant for air.

From the ideal gas law, we can find the mass of air, m, in the tank:

$$m = .50\ \text{kg}$$

For an isothermal expansion, the amount of mechanical work output, W, is given by

$$W = mR_{air}T \cdot \ln\left(\frac{P_1}{P_2}\right)$$

where P_2 is the final pressure, 100 psig. Solving this equation:

$$W = 280{,}000\ \text{J}$$

Boadicea is designed to produce up to 60 W of mechanical power. Assuming 60% efficiency, the air supply must provide 100 W to the actuators. With that rate of consumption, the air supply will last approximately forty-five minutes. A reversible, isothermal expansion represents the best case scenario; this calculation predicts the largest amount of available energy. The trade-off you must make to get the extra energy is to consume it slowly enough for the temperature to equilibrate.

The worst case scenario is an adiabatic expansion, which assumes the gas expands so quickly that no heat energy is absorbed from the environment. In a reversible adiabatic process,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

where

$$\gamma = \frac{C_V + R_{air}}{C_V}$$

and the subscripts 1 and 2 indicate initial and final conditions, respectively, and C_V is the specific heat of air (at constant volume).

For air,

$$C_V = 720 \tfrac{J}{Kg \cdot K}$$

$$\gamma = 1.4$$

so in our case,

$$T_2 = 50 \text{ K}$$

Although in actual operation, the air delivered to the cylinders would not be this cold, this calculation does determine a lower limit of the energy available from the pressure vessel.

The equation for work delivered from an adiabatic expansion is

$$W = mC_v \Delta T$$

yielding

$$W = 90{,}000 \text{ J}$$

which would provide 15 minutes of power at 100 W.

In actual operation, the amount of energy provided by the air tank will be between the adiabatic and isothermal predictions. Fortunately, there is some helpful positive feedback in this effect; using the air slowly allows it to absorb more heat from the environment, which extends the air supply. Boadicea will probably operate close to the isothermal case; a tank lifetime of 30 minutes is a reasonable expectation.

Of course, these calculations assume that the robot is operating full bore, consuming 100 W. Unless the robot is sprinting with a full payload, it will draw significantly less power, further extending the life of the tank. For example, if the robot was drawing 25 W, which is a realistic amount for unencumbered locomotion over level terrain, the tank should last well over one hour.

The air tank on a pneumatic robot could be recharged by an external compressor. Or, in a remote environment the robot could carry a small compressor to recharge the tank slowly. In either case, the advantage realized is that there is no prime mover or pump which must supply the 100 W required by the robot.

Conclusion: pneumatics

I decided to use a pneumatic actuation system for Boadicea. The primary concerns that motivated this decision were weight and size constraints and the effects of leakage. A pneumatic system is also less expensive and easier to work with. The possibilities for interesting dynamic properties offered by air's compressibility is another potential advantage for pneumatics.

2.3. Valve specifications

Boadicea uses solenoid poppet valves to control air flow to the actuators. These valves limit the performance of the robot in several ways: they are relatively heavy and have flow and response time limitations. However, they are the best commercial alternative, and building custom valves is beyond the scope of this project. **Table 2.2** lists the specifications for a representative sample of commercially available solenoid valves. The Power listed is the electrical power required to energize the solenoid. Cv is the Flow Coefficient which is used to compare flow rates through the valves; a large Cv valve will allow more flow for a given pressure drop across the valve.

Manufacturer Part Number	**Weight (oz)**	**Power (W)**	**Max. Press (psi)**	**C_v**	**Response Time (msec)**
Skinner 7121KBN1NF00 *a*	Not specified	10	125	.31	Not specified
Granzow D3162CB20 *b*	Not specified	14	150	.15	Not specified
ASCO 8380 *c*	Not specified	7	110	.09	Not specified
Peter Paul 153JJ2DGM *d*	4.5	10.5	100	.075	Not specified
ANGAR Scientific AL3312 *e*	1.5	2.0	100	.04	10
ANGAR Scientific 407M3.04012100N *e*	.7	2.5	100	.025	4
Lee LHDA1205025H *f*	.071	.5	50	.01	2
Redwood Microsystems Fluistor *g*	.007	.5	200	.0005	1000
IC Sensors Microvalve 4425 *h*	.011	.5	25	.0002	100

References: *a* **[Skinner 92]**, *b* **[Granzow 92]**, *c* **[ASCO 92]**, *d* **[Peter Paul 89]**, *e* **[Angar 89]**, *f* **[Lee 91]**, *g* **[Redwood 93]**, *h* **[IC Sensors 92]**

Table 2.2: Specifications for Solenoid Valves

The Power listed is the electrical power required to energize the solenoid. Cv is the Flow Coefficient which is used to compare flow rates through the valves; a large Cv valve will allow more flow. The ANGAR AL3312 valve is the most appropriate for a Boadicea-sized robot.

The Skinner, Granzow, ASCO, and Peter Paul valves are typical solenoid valves for factory equipment. This size valve is the most commonly available. Because they are not normally used in mobile servo systems, catalogs normally do not specify weight and response time. The ANGAR and Lee valves are "miniature solenoid valves" in the industry vernacular. They are the most suitable for a small mobile robot because they are relatively small and lightweight, but still have adequate flow capabilities. The Redwood and IC Sensors valves are silicon micromachined valves. Although they are extremely small, the flow rates are not nearly adequate for a Boadicea-sized robot. Also, their response time is rather poor.

For Boadicea, the two ANGAR valves are the only appropriate choices. I selected the AL3312 valve because it has a higher Cv and draws less electrical power. Another disadvantage of the 407 valve is that it requires manifold mounting, which would complicate the robot's body and negate some of the weight savings.

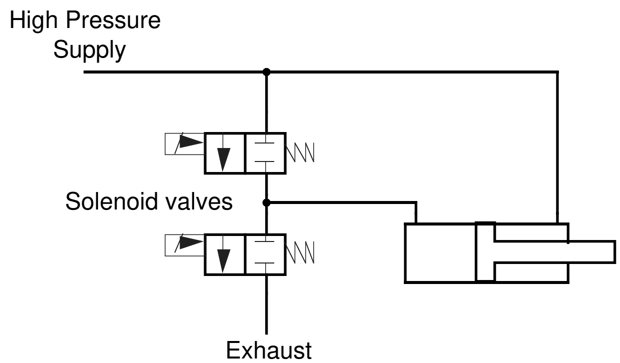


Figure 2.2: Valve configuration on Boadicea

The actuator is used in a differential jack configuration. The front end of the cylinder is maintained at system pressure while the pressure in the back end is controlled. When both valves are de-energized, the back end is sealed, and the actuator acts passively as a stiff spring.

The valves on Boadicea are connected as 2-way valves, as shown in **Figure 2.2**. Two valves are required for each DOF. The advantage of this configuration is that it provides an (electrical) energy-free stance. Only one 3-way valve would be required for each DOF if the energy-free stance were sacrificed. A possible compromise could be to use different valve configurations for different degrees of freedom.

The valves are driven by a 12 volt pulse width modulated (PWM) waveform at 70 Hz. The fluid resistance of the valve has a linear relationship to PWM duty cycle, although it has substantial dead-band and saturation effects. (See **Figure 2.3**) This relationship provides good closed-loop behavior. Another advantage of PWM is that it helps prevent debris from clogging the valve **[Lewis and Stern 62].**

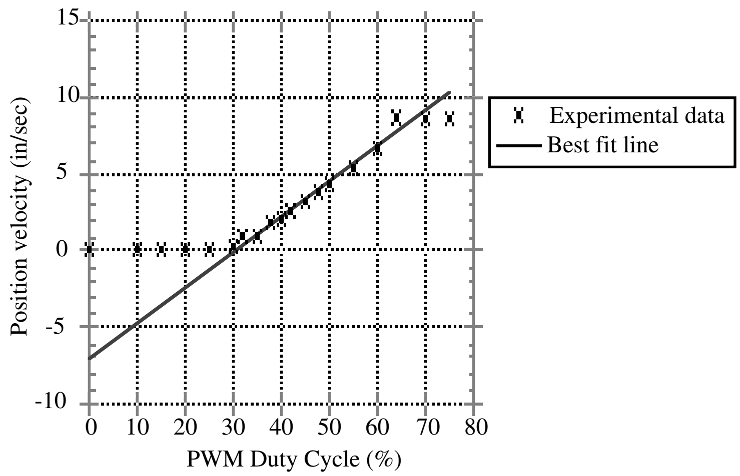


Figure 2.3: Flow rate vs. PWM duty cycle

I measured an actuator's piston velocity, which is proportional to flow rate. With no load on the piston, we can assume there is a constant pressure drop across the valve. The results indicate a linear relationship between flow and PWM duty cycle, although there are saturation and deadband effects caused by the valve's response time.

Weight

By far, the heaviest components on Boadicea are the valves. Thirty-two valves, weighing 1.5 oz each, total 3 lb, or approximately 30% of the total robot weight. Most of this weight is in the iron and coil required for the solenoid. The valves also add to the size of the robot; the body must have sufficient room for them. Smaller, lighter valves could drastically improve the performance of future robots. Silicon micro-machined valves are becoming available with flow and pressure capabilities that could be useful in smaller robots **[Redwood 93] [IC Sensors 92]**.

Flow and pressure capabilities

The maximum pressure limit for the solenoid valves is 100 psi. As mentioned before, a higher system pressure would allow smaller components. For example, the pressure limit imposed by the valves determines the cylinder bore required in the actuators. At sufficiently high pressures, a hydraulic system could be feasible.

The most serious performance limitation, however, is the orifice size in the valves. This opening determines the flow characteristics of the valve, which in turn determines actuator speed. Valves with larger internal passages could deliver more fluid power to the actuators, improving the robot's performance. The cost, however, would be bigger solenoids, or greater electrical energy requirements.

Response time

The response time of the valve solenoid is another primary constraint on control system performance. **Figure 2.4** is a graph of the solenoid current as the valve opens and closes. It shows that using a 12 volt supply, the solenoid takes approximately 5 msec to energize and 7 msec to close because of its large inductance. This performance limits the PWM frequency to about 80 Hz.

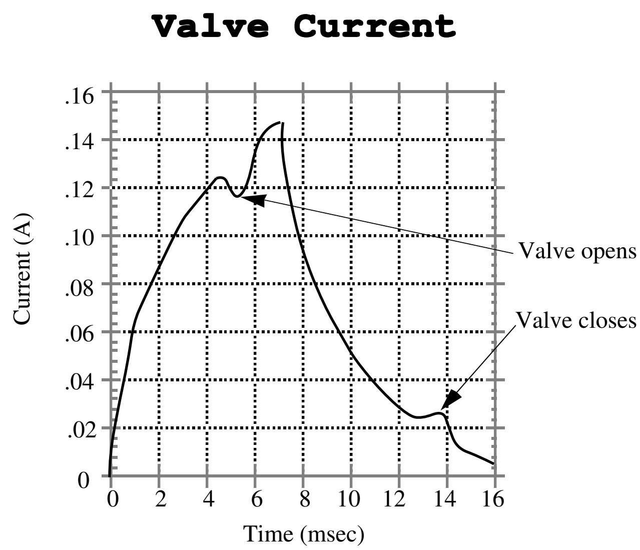


Figure 2.4: Valve current vs. time.

The input is a 12 volt square wave. The valve acts as an L-R circuit, charging and discharging exponentially. The irregularities on the graph are when the solenoid moves, opening and closing the valve. The switching time varies slightly with pressure and flow, but is typically between 5 and 7 msec.

It is not difficult to improve the valve response time. Driving the solenoid with a larger voltage will energize the coil faster. The only constraint that must be observed is thermal: a sustained higher voltage will melt the coil. The solution is to use a circuit that delivers an initial high voltage spike, then quickly drops off to a 12 volt steady state. This type of waveform will energize the solenoid quickly, without burning it out.

The drawbacks of this solution are that it requires a high voltage power supply (approximately 100 volts) and more electronics. Since one aim of this project was to keep the electrical system simple, Boadicea does not include this idea.

2.4. Custom pneumatic actuators

A small robot like Boadicea needs lightweight actuators. While there are many commercially available pneumatic actuators, they are all too heavy for this application. They are usually made from brass or stainless steel, and are much bulkier and heavier than necessary. In their typical application, factory equipment, size and weight are not critical constraints.

I designed and built my own actuators for Boadicea, using plastic to save weight. The biggest obstacle in producing an acceptable actuator was finding a low friction seal.

Comparison with commercial actuators

The actuators I designed have several advantages for robotics applications. Most importantly, they weigh less than commercial actuators, and have a much lower overall length to stroke ratio. Both of these differences make them well suited to mobile applications where size and weight constraints are paramount. Using diaphragm seals keeps stiction forces low, which makes servo control easier.

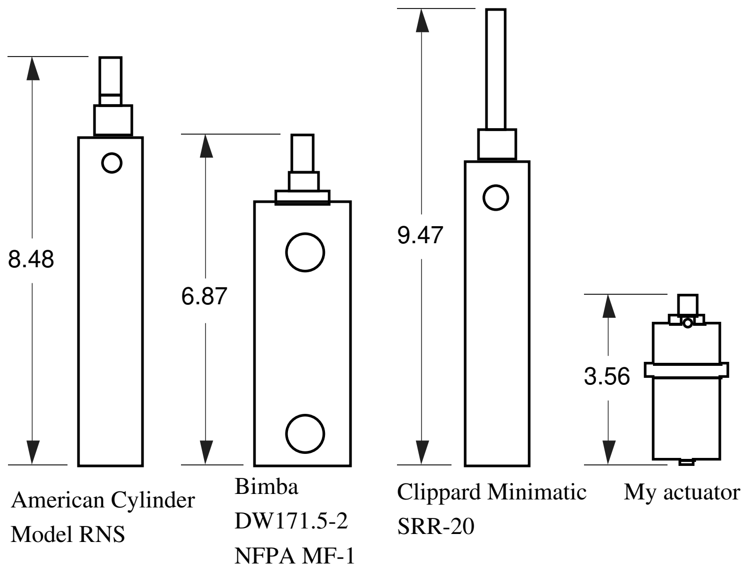
My actuators use lightweight materials, have small ports, and minimal endcaps to reduce their weight. **Table 2.3** shows the weight breakdown for my actuators. The two actuators listed are the longest and shortest stroke lengths on Boadicea. For comparison, a commercial actuator with the same stroke and bore as my 2 oz actuator weighs approximately 13 oz. It would not be feasible to build a robot like Boadicea with off-the-shelf actuators.

Part	Weight (oz)	
	1.56 stroke	.438 stroke
Housing top	.36	.30
Housing bottom	.46	.39
Top liner (Al)	.13	0
Bottom liner (Al)	.26	.14
Piston rod (brass)	.24	.16
Rod seal	.018	.018
Piston cap	.061	.061
Piston	.19	.086
Diaphragm seal	.086	.082
Screws	.164	.164
Total	**1.97**	**1.40**

Table 2.3: Weight of actuator components

The table shows the weight breakdown for the longest and shortest stroke actuators I built. A commercial actuator with the same stroke and bore as my larger actuator weighs 13 oz. It would not be feasible to build a robot like Boadicea with off-the-shelf actuators.

In addition to their low weight, my actuators are also much smaller than off-the-shelf cylinders. **Figure 2.5** shows the relative size of my actuator and the commercial alternatives. All the cylinders have similar housing and piston rod diameters. My actuator, however, has less hardware in the endcaps and a more compact design, providing a much higher stroke to length ratio. The commercial actuators also have large diameter ports which require bulkier and heavier fittings.



References: **[American Cylinder 90]**, **[Bimba 92]**, **[Clippard 92]**

Figure 2.5: Actuator size comparison.

My actuator design is shown on the right. On the left are three commercially available actuators. All of the actuators shown have a 1.25" bore and 1.5" stroke. The commercial actuators are not only bigger and heavier than my design, but they also have larger ports, which require larger and heavier fittings.

Seals

One of the major difficulties in designing a pneumatic actuator is finding an acceptable reciprocating seal. Static friction and leakage make controlling the actuator difficult. To avoid these problems, I experimented with rolling diaphragm seals that eliminate sliding contact in the actuator. I also tested more traditional piston seals: O-rings, U-cups, and other ring-type designs. Because these seals work by compressing a plastic or elastomer ring between the piston and the cylinder wall, however, they tend to have high friction. **Figure 2.6** shows the cross sections of the ring-type seals I tested.

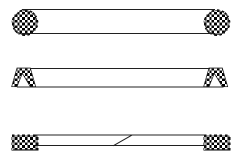


Figure 2.6: Ring-type seal cross sections

I built prototype actuators with all of these seal types. U-cups had the best performance, but in all cases either stiction or leakage were prohibitive.

Rolling diaphragms

An attractive seal technology is the rolling diaphragm seal, invented by Bellofram, Inc. (See **Figure 2.7**) A rolling diaphragm seal forms a leakage free seal between the two ends of the cylinder. The piston diameter is smaller than the cylinder bore, and the diaphragm rolls up on itself in the resulting gap. The main advantage of this design is that it eliminates sliding friction. However, there is some rolling resistance in the diaphragm, which can be considerable for small diameter seals. The diaphragm seal also relaxes the requirements for close tolerances and smooth surface finish on the cylinder parts.

I built a prototype Boadicea-sized actuator (1.25" bore, 1.4" stroke) using a Bellofram seal. The apparent friction caused by the diaphragm's rolling resistance was comparable to the sliding friction in pistons with U-cup seals, the type used in commercial actuators (see **Figure 2.8**). However, there was very little static friction, which is what limits controllability.

One limit imposed by the diaphragm seals is that pressure can only be applied to one side of the seal (the top side in **Figure 2.7**). Reversing pressure, or back driving the actuator, can kink or wrinkle the diaphragm, which jams the piston. Usually, the only way to un-kink the diaphragm is to disassemble the actuator.

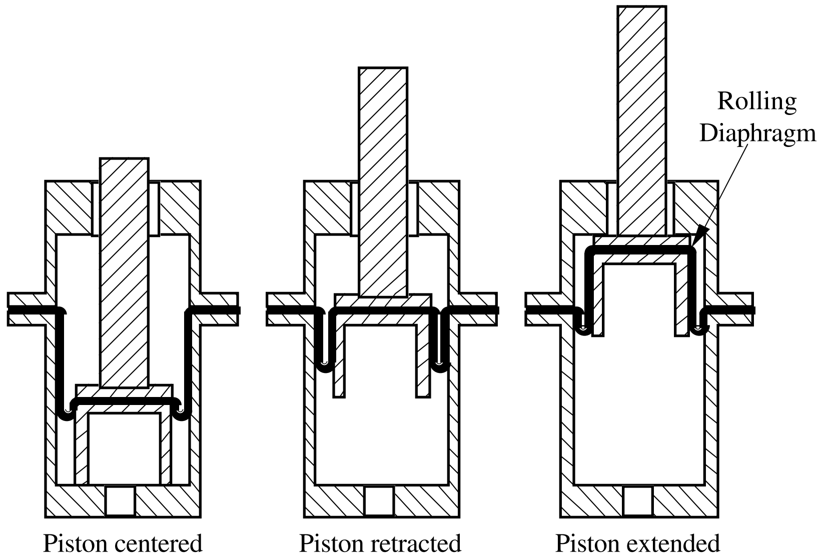


Figure 2.7: A rolling diaphragm equipped actuator

The diaphragm rolls back and forth between the cylinder bore and the piston. This type of seal reduces static friction and relaxes manufacturing surface finish and tolerance constraints.

O-rings

O-rings are a relatively poor choice for reciprocating seals. Because the pressure of the working fluid compresses the O-ring radially, there must be a large amount of pre-compression in the seal to prevent leakage. I tested O-rings of several materials: Buna-N, silicone, Teflon, and Teflon coated silicone. In every case, either friction or leakage was prohibitive.

U-cups

U-cups have the advantage that fluid pressure presses the seal against the cylinder bore (see **Figure 2.8**). Sealing force increases as pressure increases, which is precisely what you want. This feature allows the actuator to be constructed with less pre-compression in the seal, resulting in less friction than for O-rings. There is still a reasonably large amount of stiction, however, which is a controllability problem. U-cups are the most common sealing technology used on small commercial actuators.

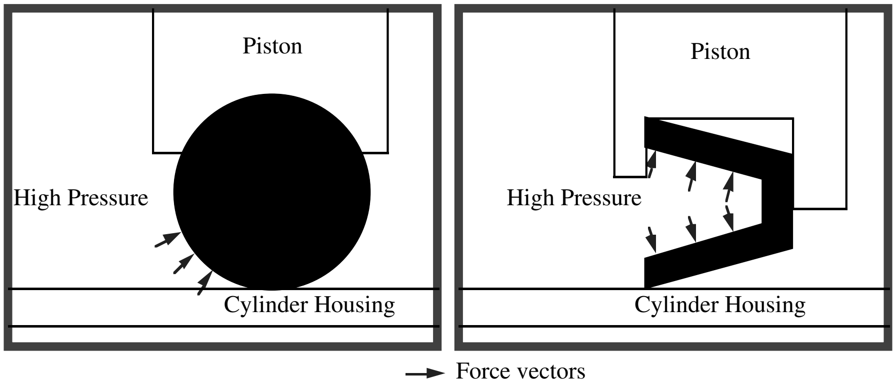


Figure 2.8: Hydrostatic forces on O-ring and U-cup piston seals

The high pressure compresses the O-ring (left), creating a leak along the inside of the cylinder housing. As pressure increases, the leak worsens. A U-cup seal (right) has the opposite behavior. Because hydrostatic forces press the seal against the housing, sealing is improved as pressure increases.

Backup rings

Backup rings are intended to provide axial support for O-ring seals, and normally are not used as seals themselves. I experimented with Teflon backup rings for piston seals. These actuators had significant leakage, but surprisingly little stiction. Like the Bellofram actuators, the resistance was very viscous.

Conclusion: diaphragm seals

Initial experiments indicated that the rolling diaphragm and U-cup seals were the best options. After many experiments comparing these two seals, I decided to use the diaphragms. The biggest consideration in this decision was stiction. The U-cup actuators were unable to produce smooth, low velocity movements. The only major problem with the rolling diaphragms is the possibility of wrinkling. Careful assembly, to maintain concentricity, and not back driving the actuator minimize this problem.

Design details

The actuator housing (see **Figure 2.9**) consists of a plastic shell with an aluminum liner on the cylinder bore. The metal liner provides strength to withstand hydrostatic pressure in the cylinder. The piston rod is a brass rod, hollowed out to save weight. Brass provides low friction and a smooth surface finish for the rod seal. The piston itself is molded plastic. Finally, a U-cup seals against the piston rod.

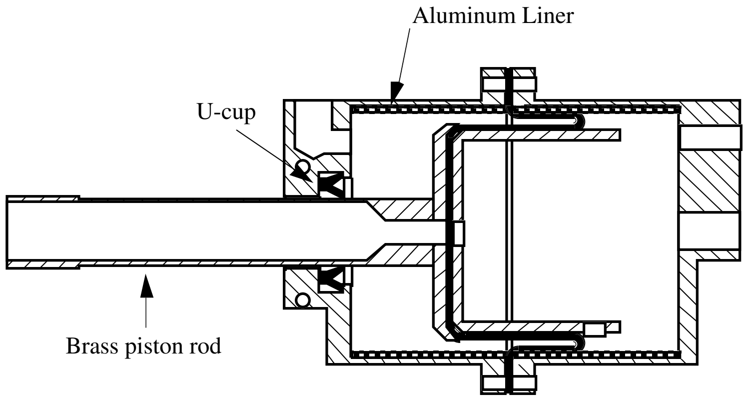


Figure 2.9: Actuator cross section

The actuator consists of a plastic housing, a molded piston, a brass piston rod, and an aluminum liner. The metal liner provides the strength to withstand the hydrostatic pressure in the actuator.

The aluminum liner must be thick enough to withstand the pressure in the cylinder. The hoop stress in the liner is:

$$\sigma = \frac{Pr}{t} \tag{1}$$

where P is the pressure, r is the cylinder radius, and t is the thickness of the aluminum liner. For Boadicea, the maximum working pressure is 100 psig and the radius is 5/8". Using 30,000 psi for the yield strength of aluminum and a factor of 10 for safety, equation (1) becomes

$$\frac{30\,\text{kpsi}}{10} = \frac{(100\,\text{psi})(.625\,")}{t}$$

solving for t, $t = .021"$

3. Materials and Construction Techniques

Chapter 2 presented the advantages of Boadicea's pneumatic actuation system. The second way I improved Boadicea's strength to weight ratio is by building the robot with lightweight materials. Previous Mobot Lab robots, including Attila and Genghis were built from aluminum. Boadicea, however, uses mostly plastic and composite materials.

For leg links and structural body parts, the critical material property is the stiffness to weight ratio which is higher for advanced composites than metals. My initial plan was to use carbon fiber tubing for the structural elements. The tubing I used, 1/4" carbon fiber arrow shaft, does not have sufficient torsional stiffness for the leg links, however. Boadicea has some carbon fiber tubes, and some aluminum tubes.

I used injection molded plastic for the robot's joints and moving parts. Molding allows more complex part geometry, rapid prototyping, and a wide selection of material properties. The part illustrated in **Figure 3.1** is an example of molding capabilities.

3.1. Injection molding

Injection molding is normally used in high volume projects because of its economic advantages. However, there are several reasons why it is appropriate for producing small robot parts, even in limited quantities. Machining small plastic parts is difficult because fixturing forces cause deformation, which limits accuracy. Also, machining fiber reinforced plastics poses serious health problems.

Complex part geometry

A primary advantage of injection molding is that it allows more complex part geometry. For example, thin walled parts are much easier to make with a molding process because the part does not need to be clamped in a vise. **Figure 3.1** shows orthographic views of a part from Boadicea's legs. This part is molded in one operation, with no post machining. Additionally, a bronze busing is insert molded in hole B, and an aluminum tube is molded in hole A.

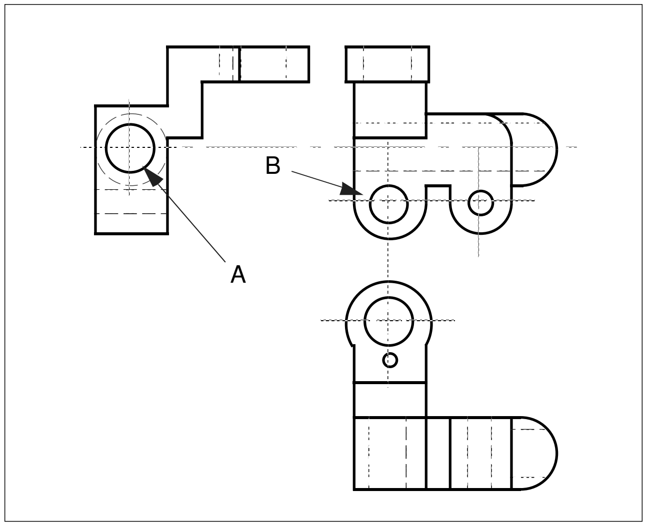


Figure 3.1: An injection molded part from Boadicea

This part is molded in one operation, with no post machining. Additionally, a bronze busing is insert molded in hole B, and an aluminum tube is molded in hole A.

Material properties

Another advantage of using plastic parts is the wide variety of plastic materials which are available. The number of polymers, fillers, and reinforcing options available is dizzying; plastic materials offer a far greater range of properties than metals **[Dexter 79].** Polymers can be selected for appropriate characteristics like wear resistance, dimensional stability, stiffness, strength, and toughness. Furthermore, fillers can be added to lubricate or reinforce the material.

Table 3.1 lists properties for some common engineering thermoplastics. Nylon is a good general purpose material, and reinforced resins have excellent stiffness to weight ratios. Its volume swells up to 10% when exposed to moisture, however **[Dexter 79].** Delrin (Du Pont's Acetal resin) is slightly stiffer than nylon, and has much better dimensional stability. Teflon has extremely low coefficients of friction, but is very soft. Polyphenylene Sulfide offers superior stiffness, but its low impact resistance makes it a poor choice for mobile robots.

Boadicea has parts made from several different plastic compounds. The structural parts are made from glass and carbon fiber reinforced Delrin and Nylon. The sliding parts in the pantograph mechanism are Teflon-filled Delrin (Delrin AF); the Teflon additive reduces the coefficient of friction.

Material	Young's modulus	Yield Strength	Specific Gravity	Static Friction	Dynamic Friction
Nylon 6/6 *b*	410	12	1.14	.1	.15-.40
Nylon 30% glass fiber *b*	1500	25	1.4	Not listed	Not listed
Delrin 500 *a*	450	14	1.4	.2	.35
Delrin AF (Teflon filled) *a*	420	10	1.54	.08	.14
Delrin 577 (glass filled) *a*	900	12	1.56	Not listed	.35
Teflon (PTFE) *b, c*	50	2-6.5	2.2	.04	.04
PPS *b*	600	20	1.34	Not listed	Not listed
PPS 40% glass *b*	2200	37	1.37	Not listed	Not listed

References: *a* **[Delrin 92]**, *b* **[Dexter 79]**, *c* **[Baumeister 67]**

Table 3.1: Properties of Engineering Polymers

Boadicea uses several of these materials: structural parts are molded from glass and carbon fiber reinforced Nylon, and sliding parts in the pantograph mechanism are Delrin 500AF. Polyphenylene Sulfide (PPS) is much stiffer than the other plastics, but is more difficult to mold, and is too brittle for this application.

Rapid prototyping

The composite and plastic construction of Boadicea allows rapid prototyping and testing of new designs. Once a set of molds for basic parts exists, leg and body components can be manufactured quickly. Even when new molds are required, manufacturing time is short; a typical mold for Boadicea requires only an hour or two of machining time.

The ability to quickly build and test design ideas is invaluable for this type of project. A prototype reveals the strengths and weaknesses of each design revision. In order to reach a robust design, the design-prototype-revision cycle must be completed many times. Injection molding shortens the time required for each iteration, especially because a multi-legged robot like Boadicea requires many copies of individual parts; it is not uncommon to need twenty-four or thirty-six pieces of a certain part.

Insert molding

I could not have built Boadicea without insert molding. This technique involves placing bushings, shafts, and structural elements in the molds, and then casting plastic around the inserts. Insert molding eliminates most post-machining operations and simplifies assembly.

A more significant benefit, however, is that this process guarantees proper alignment and positioning of critical features. Most of the parts on Boadicea, and other electromechanical machines, have relatively few critical dimensions. For example, the external dimensions of most parts have loose tolerances, but the alignment and location of bearing holes must be accurate. Once the molds have been made correctly, insert molding assures that the parts will be accurate and repeatable.

Economics

In commercial applications, the economic benefits of injection molding are typically realized at high volume (hundreds of thousands) because of high tooling costs. For Boadicea, I machined my own molds out of aluminum. Using aluminum instead of tool steel for the molds simplifies fabrication immensely. Also, since graduate student time is normally considered free, my tooling costs were minimal. Material costs were also low; plastic pellets cost a few dollars per pound. Even better, because I required small quantities, I was usually able to get free samples.

For most parts, building the mold takes approximately the same amount of time as machining one part: between one and six hours. Depending on the part size and mold complexity, molding takes between 1 and 5 minutes per part.

3.2. Composite tubing

Some of the structural members on Boadicea are pultruded carbon-fiber tubes. This tubing is commonly available off-the-shelf as arrow shafts for archery enthusiasts. Although this material is a bit unpleasant to work with, it has some superb structural properties that make it a good choice for robot construction. Unfortunately, there are also some serious drawbacks, especially low torsional strength.

Stiffness to weight ratio

On a walking robot, the primary metric for selecting structural elements is the stiffness to weight ratio, which is extraordinarily high for carbon fiber composites. The uniaxial tubing on Boadicea has nearly four times the stiffness to weight ratio of an equal size aluminum tube. High modulus graphite composites can have a specific stiffness nearly seven times that of aluminum, and about five times the tensile strength **[Kalpakjian 92].**

Internal wiring

One attractive feature of the composite tubing is that it provides a convenient way to route wires. The wires on Genghis and Attila run along the outside of the structural parts. Besides looking messier, the exposed wires are more likely to be damaged. Broken wires have been the leading hardware failure on Attila **[Ferrell 93].** Obviously, non-composite tubes would have this advantage as well.

Boadicea has internal wiring on each leg, which allows a clean and slender leg with distal (far from the body) sensors. Wires on the body do not run through tubes, however, because the additional connector complexities were beyond the scope of this project. In the future, when more time is available for cabling design, internal wiring could be used more effectively on the body.

Disadvantages of pultrusion

The biggest disadvantage of pultruded tubing is that all fibers are axially oriented. The tube's stiffness and strength under torsional and radial loading is determined solely by the matrix material; the fibers do not help at all. Since the epoxy resin is relatively weak, compressive and torsional loads cause the tubes to split. This weakness can be especially aggravating when the tubes are being insert molded in plastic parts; the injection pressure can be sufficient to crack the tubes. Boadicea's legs are subjected to large torsional loads, which makes the carbon fiber tubing a poor choice for leg links.

Working with carbon fiber composites also poses serious health risks. The dust produced by cutting or sanding is highly toxic. Inhaling small pieces of the fibers can cause lung damage similar to asbestosis. Glass reinforced composites also cause the same type of lung disease. A less serious health hazard is carbon fiber splinters. Because the fibers are very slender and stiff, they can easily pierce the skin. Because the fibers are very brittle, they nearly always break off just below the surface, making splinter removal difficult.

Fastening

Another difficult problem with carbon fiber tubing is that it is difficult to fasten parts to the tubes. Graphite-epoxy composites are brittle, especially with uniaxial fibers. Drilling holes in the tube for screws will usually cause it to split. The tubing also does not glue well, although careful surface preparation and proper glue selection would improve adhesive performance.

The most successful way to fasten parts to the tubing I have found is with insert molding. Placing the tubes in the molds eliminates the need for any post-machining or assembly. Cutting small notches in the tubing with a belt sander provides some mechanical interference that prevents the tube from pulling out or rotating. Although these notches cut the fibers, and weaken the tubing, the joints are still able to withstand loads Boadicea will experience.

The molds can be fixtured in the correct position and orientation, ensuring that the molded end parts will be properly aligned. With a traditional assembly process, it would be more difficult to get the correct alignment.

4. Biological Inspirations

One emphasis of this project was to look at insect locomotion for ideas about how to build walking robots. Bob Full, Rodger Kram, and their colleagues at the University of California, Berkeley, have been a wellspring of useful information **[Full 94] [Kram 94] [Full, et al 89] [Kram, et al 94]**. We have discussed different aspects of robot design and insect locomotion throughout the course of this research.

4.1. How much to copy biology?

A big question facing robot designers is how much to copy from real animals. The range of possibilities extends from no biological considerations to machines with dynamic behavior exactly mimicking real biology. Most of the biological inspirations for legged robots have dealt with gait generation and other software functions **[Chiel, et al 92] [Ferrell 93]**.

The mechanical design of legged machines can also be biologically inspired. **[Weidemann, et al 93]** describes development of a leg with kinematics similar to a walking stick insect, *Carausius Morosus*. Like other studies, this leg design uses DC gearmotors, and the emphasis of the experiment was on developing a controller for gait generation. In this study, an accurate kinematic reproduction of the insect was more important than improving mechanical performance. As a result, the leg they built is insect-like, but it can only support twice its own weight. This torque density is insufficient for a complete robot.

Boadicea also employs many biological ideas in its mechanical design. Because my highest priority was maximizing mechanical performance, Boadicea's legs are not as true to their biological prototype as Weidemann's. They do have superior force and speed capabilities, however. My approach has been to determine what is the best way to exploit our technological capabilities, and then look at how well that can match what insects do.

For example, I decided that a linear foot trajectory was a desirable feature, and that a planar pantograph was the best way to achieve it. That leaves the question of how to orient the leg. *Blaberus Discoidalis,* a cockroach that Full and his colleagues study, have middle and rear legs that operate primarily in a horizontal plane, and front legs that operate in a saggital plane. Those are the orientations I chose for Boadicea's legs. I also designed the range of motion for the pantograph to produce leg motions similar to the insect.

Another example is the number of DOFs in Boadicea's legs. The 68332 microprocessor has sixteen timer outputs, each of which controls one degree of freedom. My original plan was to build a robot with six 3-DOF legs, which would require eighteen outputs. Therefore, I needed to eliminate two degrees of freedom. The best candidates for elimination were the lateral DOF of the front legs. Because cockroaches locomote effectively with minimal lateral force on their front legs **[Kram, et al 94] [Kram 94],** I concluded that these degrees of freedom were not essential.

Evolutionary optimization

The attractive thing about copying biology is that evolution has been testing and optimizing locomotion designs for millions of years. To date, we have not been able to build robots that match the capabilities of insects, let alone mammals or humans. If biology has such a performance advantage over robotics technology, maybe we can learn from studying it.

Different capabilities

The biggest argument against copying biology is that the tools and materials available for machines are fundamentally different from what is used in biological systems. The technological state of the art cannot match biology's energy density, number of actuators, sensor density, or controller complexity.

For example, biological muscles are linear actuators, but with mechanical systems, rotary motion is much easier to achieve. This difference is one reason why boats use propellers and fish do not. Seals are another factor that contribute to this difference; a propeller-driven craft needs a rotary seal around the drive shaft. Evolution has not invented the variety of sealing methods technology has; animals do not have O-Rings.

Mechanical capabilities

The differences between biology and technology that have the greatest impact on legged robots are actuation and control system complexity, favorable actuator dynamics, and energy storage density. Compared to the number of muscles in insects, walking robots hardly have any actuators at all. For example, on each leg, a cockroach has twenty-seven muscles **[Full 94]**, while robots have two or three**.**

The dynamic properties of muscles have evolved to meet the requirements of legged animals: there are no gearboxes. For artificial systems, especially with electrical actuators, there is a relatively poor impedance match between the external loading and the actuator.

That is why most electrical machines require some form of gear reduction, either with a gearbox, cable drive, or an other transmission.

Finally, the energy density of animals is much higher than for machines, both in terms of energy storage and actuator power. The current state of the art in mobile robots is nowhere near the capabilities of animals.

4.2. Cockroach studies

There are many recent investigations of insect locomotion that could provide helpful suggestions to robot designers. Boadicea incorporates some of these ideas: its leg kinematics, workspace, and climbing strategies are modeled after cockroaches. Many of the more dramatic discoveries, however, were too complex for this project. These findings reveal that multi-legged insects move far more dynamically than robot designers had assumed.

Leg kinematics

Cockroaches have legs with four segments, like most other insects. (see **Figure 4.1**) **Tables 4.1** and **4.2** show the range of motion and link lengths for the legs of a running *Blaberus Discoidalis*. This data indicate that the rear and middle legs move in a similar manner. The coxa does not move much in these legs. The front legs, however, are markedly different: the coxa-body joint does flex substantially, but the coxa-femur joint does not. This motion results in the coxa/femur combination acting as a longer "upper leg" segment.

The tarsus of each leg consists of several small segments with passive, springy joints. These joints are remarkably flexible; the tip of the tarsus is nearly able to touch the ankle joint.

Joint	**Rear leg**	**Middle leg**	**Front leg**
Body-Coxa	8.1° ± 2.1°	13.2° ± 1.9°	33.9° ± 3.8°
Coxa-Femur	70.2° ± 2.4°	43.0° ± 4.7°	8.6° ± 5.5°
Femur-Tibia	68.0° ± 3.0°	26.2° ± 6.8°	23.8° ± 7.9°

Table 4.1: Range of motion for *Blaberus Discoidalis*

Angles shown are the range of motion used during locomotion, not the maximum range **[Kram, et al 94]**.

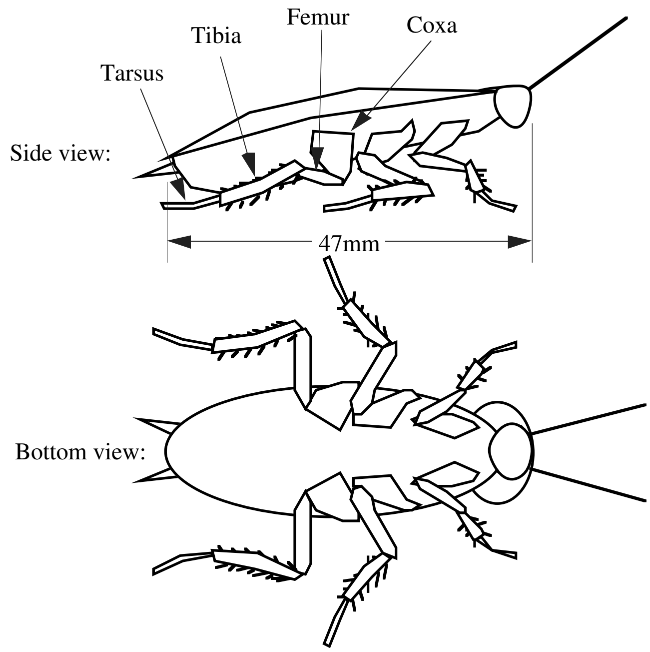


Figure 4.1: The cockroach *Blaberus Discoidalis* **[Kram, et al 94]**

Leg segment	Rear leg	Middle leg	Front leg
Coxa	6.08 ± .21	5.77 ± .11	7.2 ± .17
Femur	10.6 ± 0.2	9.86 ± .25	7.65 ± .14
Tibia	12.8 ± 0.3	7.70 ± .33	4.18 ± .16
Tarsus	8.02 ± .27	6.58 ± .19	5.39 ± .10

Table 4.2: Leg segment lengths in *Blaberus Discoidalis*

Lengths in mm, averaged for 5 insects **[Kram, et al 94]**.

Force measurements

Robot designers have traditionally assumed that a legged machine should produce vertical reaction forces at each foot (See **Figure 4.2**, left) because this minimizes the amount of force which must be generated. Full has found, however, that insects often produce opposing horizontal forces with their legs **[Full 90]**, as shown in the right of **Figure 4.2**. While this may seem inefficient, it actually reduces metabolic cost.

The amount of force leg muscles must generate is determined by the reaction torque about the leg's joints. With vertical foot forces, this torque is large because insects have a wide stance. When the forces are oriented as in the right of **Figure 4.2**, the resulting joint torque is lower because the moment arm is much shorter. Lower joint torques require less muscle force, which reduces metabolic cost for the insect. The trade-off that must be made to achieve this savings is that the knee muscles must be stronger; they have to provide the horizontal component.

Legged robots should be able to apply the same principle. Frequently, actuator torque is a design constraint for legged robots. Abandoning the assumption that foot forces should be vertical may ease the limitations imposed by these limits.

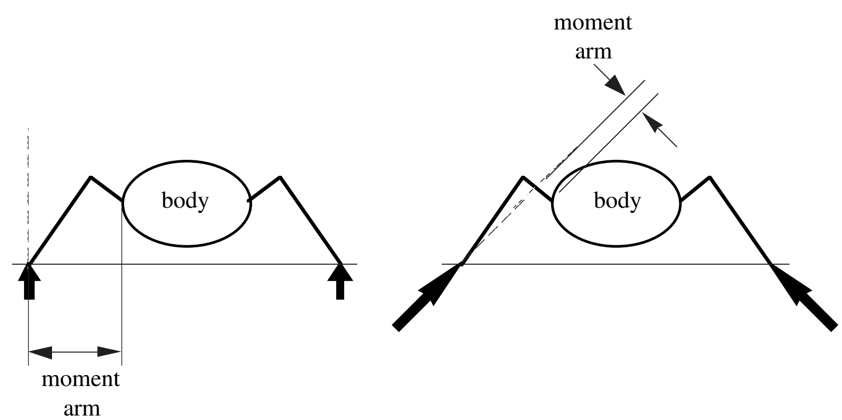


Figure 4.2: How insects minimize joint torques

[Full 90] The illustration on the left shows the situation usually assumed by robot designers; each leg produces a vertical reaction force to counteract gravity. Insects, however, produce opposing horizontal forces with their legs. Although this increases the amount of force the insect creates, it reduces the corresponding joint torque, which lowers total muscular force requirements.

Running

[Full, et al 89], **[Full and Tu 90]** and **[Full and Tu 91]** describe the dynamics of running cockroaches. The salient points of their studies are:

- Cockroaches produce ground reaction force patterns similar to two, four, and eight legged runners.
- Insects run dynamically, and even bipedally at high speed.
- The center of mass bounces, contrary to the straight line, constant velocity motion assumed by robot designers.
- Leg number and configuration do not seem to affect the energetic cost of locomotion.

Robot designers have often believed that quasi-static locomotion with no changes in center of mass height or velocity produces the most energy efficient walking machines. Full and his colleagues have shown that these assumptions are not necessarily valid.

Climbing

[Yamauchi, et al 94] investigated cockroaches climbing a step. They found the insects sometimes stop before climbing, and at other times ascend the step without stopping. Forces produced by the legs during both types of climbing exhibit these qualities:

- The front legs produce little force during the maneuver.
- A middle leg produces a large vertical force (forward of the center of mass) to pitch the body up, until the front legs clear the obstacle.
- A middle leg and its opposing rear leg produce forces to vault the body up the step.
- At times during climbing fewer than three legs were on the ground; the climbing is not a quasi-static process.

Stability

Insects are stable animals. Their wide stance and large number of legs provides static stability in most situations. Despite the assumptions made by robot designers, however, even insects depend on dynamic stability at moderate and high speeds.

Sprawled stance

Cockroaches, and many other insects, have a wide, low stance. This configuration maintains static stability even at high speeds and on inclines. For the cockroach *Blatta Orientalis*, the polygon of support is large compared to the body size, even when legs are amputated **[Hughes 57].** Boadicea has a similar wide stance, although my robot is proportionally much taller, and higher off the ground, than the insects.

Dynamic running

Full and his colleagues' results indicate that nearly all legged animals are dynamically stable. Robot designers, however, have traditionally assumed that six and eight legged animals maintain static stability. They have strived to build machines that move the body horizontally at constant velocity in order to minimize energy efficiency. The data from Full's lab, however, indicate that this may not be the best approach. It is also interesting to see that the whole-body dynamics of animal locomotion are similar, even for animals with radically different structure.

Boadicea's tripod gait definitely has substantial, although uncontrolled, dynamic components. The actuators and mechanical system on Boadicea can produce dynamic motions, but this would require a more sophisticated mode of operation to use this capability effectively. The data from **Table 1.3** show the speed advantages of dynamic locomotion; Boadicea demonstrates that a self-contained pneumatic system is a practical way to achieve dynamic locomotion.

5. Leg Design

Leg design is critical for determining a robot's mobility. Experience with Genghis and Attila has shown several shortcomings **[Ferrell 93] [Binnard 92]**. First, the legs on these robots are relatively short. The feet move in circular arcs relative to the body, producing unwanted lateral forces. Third, the force capability of the actuators is limited.

Boadicea's legs were designed to address these problems. They are longer compared to total body length than the previous robots and have larger, overlapping workspaces. The leg lengths and workspaces are modeled after a cockroach. A pantograph mechanism generates linear foot trajectories with one actuator. Finally, pneumatic actuators produce higher force and power densities than electric motors could.

5.1. Ideas from cockroach studies

The design of Boadicea's legs incorporates several ideas from studies of insect locomotion. In addition to the pneumatic actuation system and lightweight construction, these ideas also improve Boadicea's mobility.

Workspaces

Boadicea has a larger leg workspace (see **Figure 5.1**) than most other walking robots. Attila's legs, for example, have a maximum step length of 5", or 36% of the body length. Boadicea's rear legs have a 14" workspace, which is 67% of the body length. This longer workspace allows Boadicea to walk faster; although the step frequency is similar to Attila's, the stride length is greater.

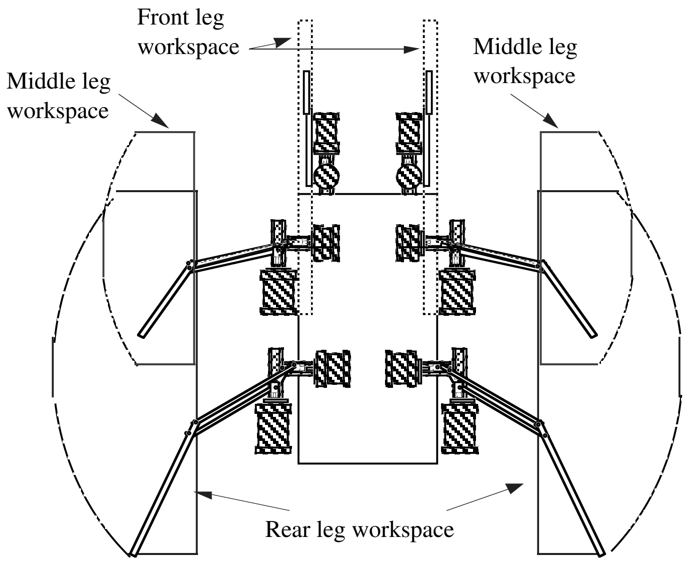


Figure 5.1: Workspace of Boadicea's legs

This picture shows the workspace of Boadicea's legs. The front legs do not have a lateral DOF; the top view of their workspace is a longitudinal line. Boadicea's leg workspace is much longer compared to total body length than most other robots. The large longitudinal overlap provides greater stability when one leg is damaged. The pneumatic actuators for the two pantograph DOFs on each leg are also shown.

The workspaces and leg lengths for Boadicea's legs are modeled after the cockroach *Blaberus Discoidalis*. **Figure 5.2** shows a comparison between the workspaces of the cockroach and Boadicea. Because the workspaces overlap, the robot can maintain a stable gait if one leg is damaged. For example, when a front leg is damaged, the middle legs reach farther forward to support the front of the robot. Cockroaches alter their gaits in this way to maintain stability after leg amputation **[Hughes 57].** Because Attila and Genghis do not have overlapping leg workspaces, they have limited stability when a leg is damaged.

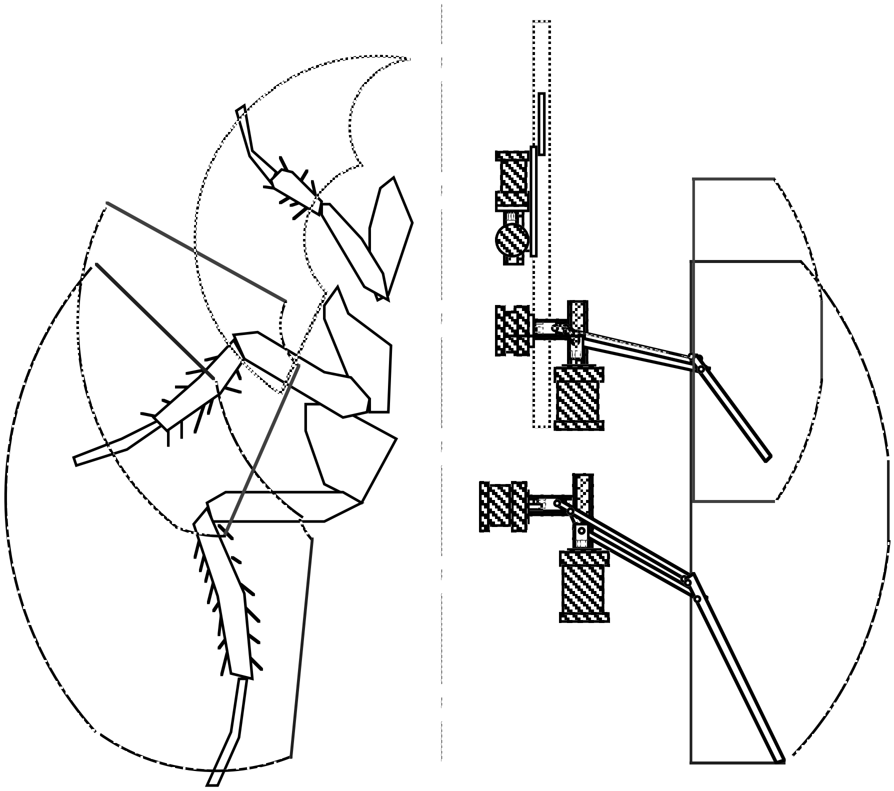


Figure 5.2: Workspace of *Blaberus Discoidalis* and Boadicea

The workspace of the cockroach legs is on the left; Boadicea's workspace is shown on the right. The rear legs of both walkers have the largest workspace, much of which overlaps the middle leg workspace. The front legs operate closer to the body, although Boadicea's lack the lateral mobility of the cockroach legs. The insect does have a relatively narrow front workspace, however, indicating that lateral motion is less important for these legs.

Leg Optimizations

Previous walking robots have had all their legs identical. Making all legs the same simplifies the design and manufacturing processes. Insects, however, have very different front, middle, and back legs. Each leg is optimized for the role it plays in locomotion. For example, most insects have powerful rear legs which provide most of the propulsion. The front legs have extra degrees of freedom to reach up or down on uneven terrain. The middle legs are frequently a compromise between the front and rear legs.

Like an insect, Boadicea has different front, middle, and rear legs. By optimizing each leg design for the role it plays in locomotion, we can achieve better walking performance.

Rear and middle legs

The rear and middle legs on Boadicea each have two segments, a femur and tibia. The length of these links is proportional to the lengths of cockroach legs listed in **Table 4.2**. I ignored the coxa segment because it does not move much in cockroaches, and a pantograph mechanism requires two links. These legs provide propulsive forces for walking and climbing. They are also responsible for supporting most of the robot's weight because the center of gravity is slightly aft of the middle legs.

Boadicea's rear legs are much longer than the front and middle legs, giving them the largest workspace. The actuators are configured so the legs are strong pushing down, back, and out. In the complementary directions, the legs cannot propel the robot.

In Full's cockroach studies, the rear legs produce the largest propulsive forces **[Full, et al 91]**; Kram estimates that the rear legs of *Blaberus Discoidalis* can produce forces five times larger than the middle legs. Manufacturing and budgetary constraints prevented me from incorporating this idea in Boadicea; all of Boadicea's actuators have the same diameter, so the force capabilities of the legs are roughly equal.

Boadicea's middle legs are identical to the rear legs, except they have shorter links. This difference allows the middle legs to operate "inside" the rear legs where the workspaces overlap, although some configurations where the middle and rear legs collide still exist. Leg collisions are likely to make future software development interesting, but have not been a problem so far.

Front legs

The front legs of *Blaberus Discoidalis* operate in a saggital plane and are much different from the middle and rear legs, which operate primarily in a horizontal plane **[Kram et al, 94].** During straight-line running, climbing, and turning, the front legs do not exert significant lateral forces **[Kram 94].**

Boadicea incorporates these differences in its front legs; which operate in a saggital plane, and do not have a lateral degree of freedom. Since the 68332 microprocessor only has sixteen timer outputs, it was desirable to have two degrees of freedom on one set of legs. Kram's examination of cockroach legs showed that insects operate successfully without much lateral action in the front legs, making those degrees of freedom the most reasonable to eliminate.

Like the other legs, Boadicea's front legs have two links, similar to the femur and tibia of the cockroaches. These links are proportionately longer on Boadicea, however, to compensate for the lack of a coxa or tarsus. Initially, I built front legs with "correctly" proportioned femur and tibia links, but the subsequent workspace was inadequate.

5.2. Pantograph mechanism

Boadicea's legs are a pantograph mechanism. Several walking robots incorporate this mechanism because it produces linear foot motions **[Waldron, et al 84] [Hirose 84] [Binnard 92].** Having a mechanism that moves the feet in straight lines simplifies the walking control software.

A second advantage of the pantograph is that it provides a large leg workspace with a relatively simple and compact mechanism. Boadicea's legs have a greater range of motion than other walking robots. Attila, Genghis, the Adaptive Suspension Vehicle, the OSU Hexapod, and other robots have all had a maximum step length about one third of the total body length **[Angle 89] [Angle 91] [Waldron, et al 84] [McGhee and Iswandhi 79].** Boadicea's rear legs have a maximum step length nearly 70% of the total body length.

The geometrical and mathematical characteristics of the pantograph mechanism have been described in **[Song and Waldron 89]**. The pantograph is a good mechanism for robot legs because it can produce decoupled, linear motion of the foot. Linear foot trajectories make walking control software easier **[Binnard 92] [Ferrell 93] [Hirose 84] [Waldron, et al 84].**

Other robots with pantograph legs

Many previous walking robots use pantograph mechanisms in their legs. Here is a quick overview of their design choices:

ASV

The Adaptive Suspension Vehicle at Ohio State University uses a two dimensional pantograph to produce linear advance and lift degrees of freedom; the pantograph operates in a saggital plane. The lateral DOF for each leg is a achieved by rotating the entire mechanism about a longitudinal axis **[Waldron, et al 84].** This design is the most similar to the pantograph on Boadicea's legs; the main differences are that Boadicea's rear and middle leg pantographs operate in a horizontal plane, and Boadicea's legs have a larger workspace.

PV II

Hirose, at the Tokyo Institute of Technology, has built quadruped robots, including the PV II, with three dimensional pantograph legs. These robots use electric motor driven lead screws to produce Cartesian foot motions **[Hirose 84].** They also have excellent energy efficiency **[Song and Waldron 89]** and a large leg workspace.

Dante

The Dante robots from Carnegie Mellon University use a two dimensional pantograph which is also driven by lead screws. Dante's legs, however, have only one independent degree of freedom **[Nygren and Fong 94].** Dante 2 has two sets of four legs which can translate and rotate relative two each other. Each leg can move up and down independently. The robot walks by lifting a set of legs, moving them forward as a group, and then placing them on the ground.

Boadicea's mechanism

The mechanism I designed for Boadicea's legs is much simpler than that used on other robots. Because Boadicea is a much smaller and lighter robot, minimizing mechanism size and complexity were severe constraints.

Trade-off between 2 and 3 dimensional pantographs

One important issue in designing a pantograph mechanism for the legs is whether to build a two or three dimensional pantograph. The three dimensional version has the advantage that it produces pure Cartesian motion at the foot; all three degrees of freedom are decoupled and linear. However, such a design requires one pivot of the mechanism to have a compound slider; it must have one joint that translates in two dimensions. Supporting loads with this type of mechanism is difficult.

Boadicea's legs are two dimensional pantographs (see **Figure 1.3**) that operate in the primary plane for each leg: horizontal for the rear and middle legs, and saggital for the front legs. The femur for the rear and middle legs lies within the horizontal plane of the pantograph. For the foot to touch the ground, the tibia is a curved tube oriented in a saggital plane. The four hind legs have a third degree of freedom that rotates the entire pantograph mechanism about a longitudinal axis. This revolute DOF and the two linear pantograph DOFs result in a cylindrical workspace for these legs. (See **Figure 5.3**)

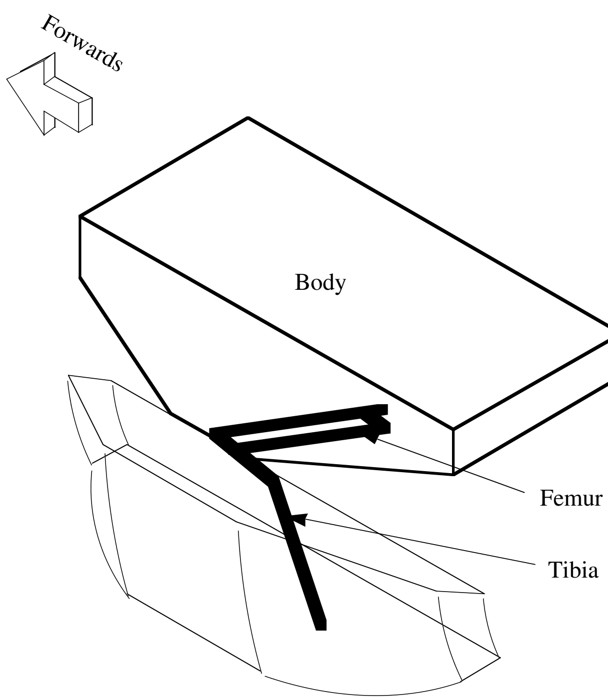


Figure 5.3:   Shape of rear and middle leg workspace

The femur lies in the horizontal plane of the pantograph mechanism, and the tibia bends to reach the ground. The leg and pantograph mechanism rotate about a longitudinal axis to lift the foot off the ground. Because this third DOF is rotational, the workspace is wedge shaped when viewed from behind.

5.3. Feet

Boadicea has no feet other than the unfinished ends of the tibia tubes. Attila and Hannibal had relatively large feet mounted on spring-loaded, passive ankles **[Angle 91].** The reasoning behind this choice was that a large foot could ignore small holes, and the ankle would allow the foot to conform to small terrain irregularities. The passive ankles proved to be a serious liability, however. If the robot stepped on a foothold that did not support the center of the foot, the foot was unable to support any weight (see **Figure 5.4**). A rigid ankle is more likely to stay where it is placed.

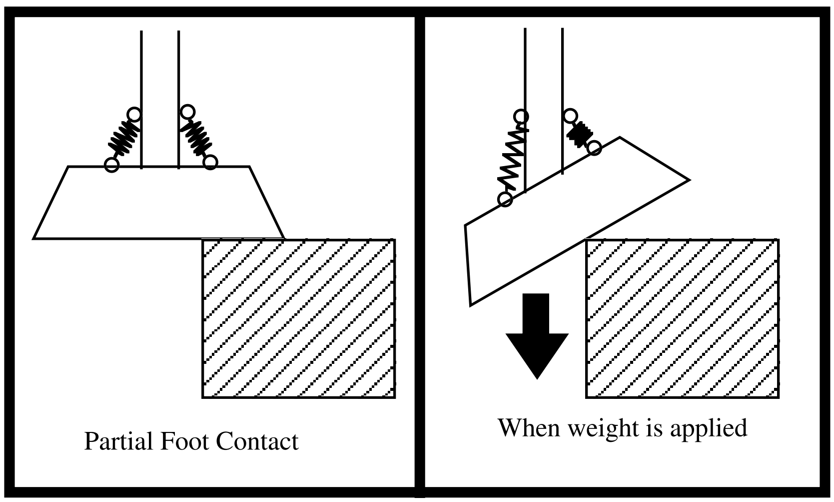


Figure 5.4: The problem with compliant ankles

If the robot stepped on a foothold that did not support the center of the foot, the foot was unable to support any weight.

5.4. Design revisions

The key to the success of Boadicea's leg design is the large number of design and prototype revisions I completed. I developed and tested five major design revisions of the pantograph mechanism, and seven versions of the pneumatic actuators. With each prototype cycle, I was able to simplify and improve the design. Building prototypes was especially helpful because I was using unfamiliar materials for the injection molded parts.

5.5. Construction details

Designing a lightweight and sturdy mechanism for the pantograph was a difficult challenge. Boadicea's pantographs use low friction materials for the prismatic joints. A 1:9 transmission ratio provides a large workspace with a compact mechanism. The third critical design issue was supporting leg loads. Because Boadicea's legs have a large workspace, supporting the mechanism was more difficult than on other pantograph robots.

Sliding parts

One of the more difficult aspects of designing a pantograph mechanism is the linear bearing which must be provided for the input pivots. The Adaptive Suspension Vehicle uses a complex system of rolling bearings to produce a well supported, low-friction prismatic joint **[Vohnout, et al 83].**

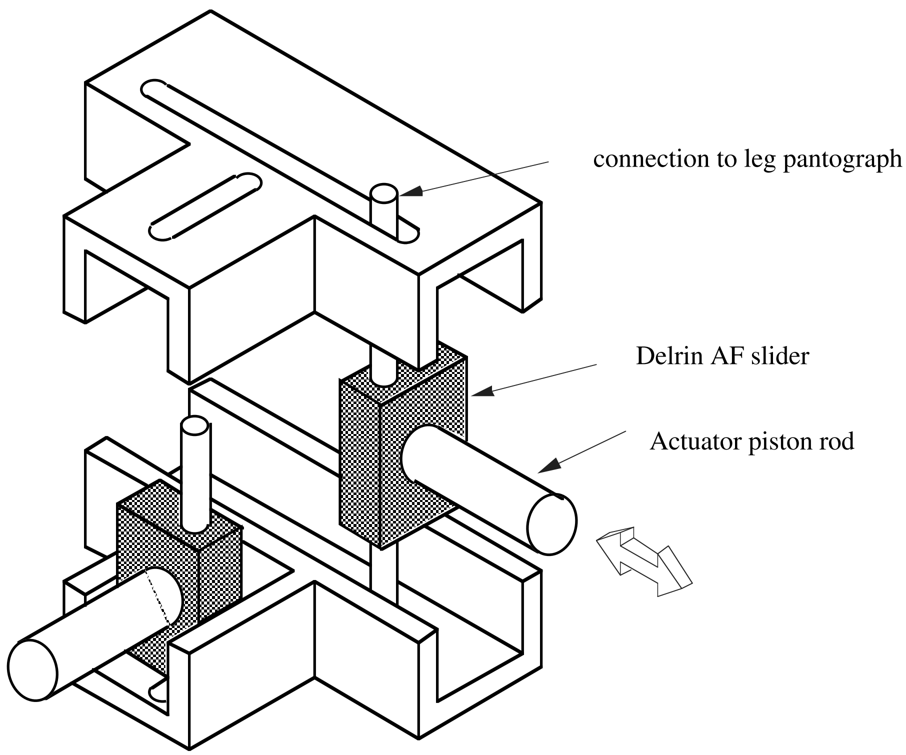


Figure 5.5: The prismatic joint in Boadicea's pantograph

The picture shows an exploded view of the sliders for both pantograph DOFs. The sliders are molded from Delrin AF because of its low coefficient of friction. The T-shaped supports are carbon fiber reinforced nylon, which has an excellent stiffness to weight ratio.

Because Boadicea experiences much smaller loads, I was able to use a simpler mechanism than the ASV. The prismatic joints I built consist of a plastic rectangular tube which acts as a guide for a close-fitting slider (See **Figure 5.5**). The slider is molded from Delrin AF, which has a low coefficient of friction because of a Teflon filler. This material has slightly higher friction as Teflon, but it has much better mechanical properties (see **Table 3.1**). I used solid Teflon sliders in early prototypes, but they were not stiff or strong enough.

The guide for the slider is molded from carbon fiber reinforced nylon because of its high stiffness. Making this part stiff enough to support the robot's weight was a primary design problem for the mechanism.

Leg links

Another difficulty in achieving a successful pantograph design was producing a large workspace with a compact mechanism. To meet these requirements, a large amplification ratio is needed. On Boadicea's legs, the feet move 9 times as much as the actuators, providing a 14" workspace with a 1.5" actuator stroke for the rear legs. Increasing the transmission ratio reduces the distance between the leg links (distance A in **Figure 5.6**).

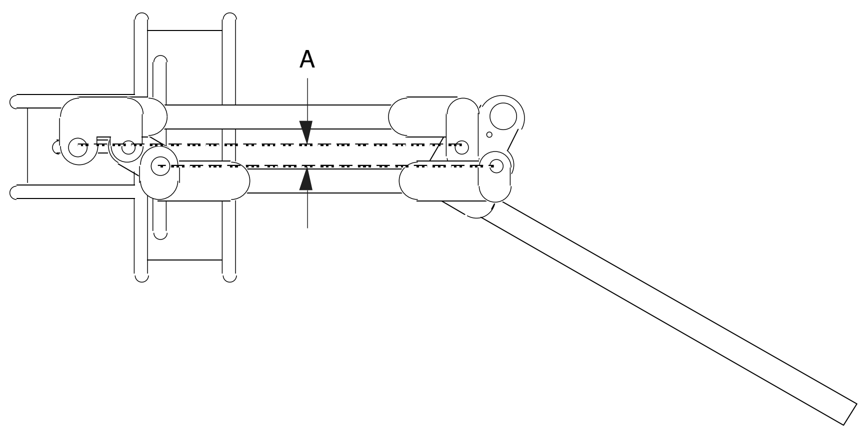


Figure 5.6: Boadicea's leg links

The dashed lines in this picture show the position of the pantograph links. To minimize the distance A, the actual leg members are C-shaped.

The behavior of the pantograph is determined by the location of the pivot joints; the actual shape of the leg links is irrelevant. To accommodate a 9:1 transmission ratio and allow a large range of motion, Boadicea's leg links are C-shaped (see **Figure 5.6**). This shape keeps the structural members from interfering at large or small knee angles. With a straight design, the two femur links would collide, limiting the workspace.

Another pantograph design difficulty is providing a support structure that can withstand leg loading. On the Adaptive Suspension Vehicle, this was accomplished by sandwiching the leg links between two support plates (see **Figure 5.7**) **[Vohnout, et al 83]**. These plates support the prismatic joints of the mechanism on both sides. The structure is stiffened and held together by connections at the corners of the plates.

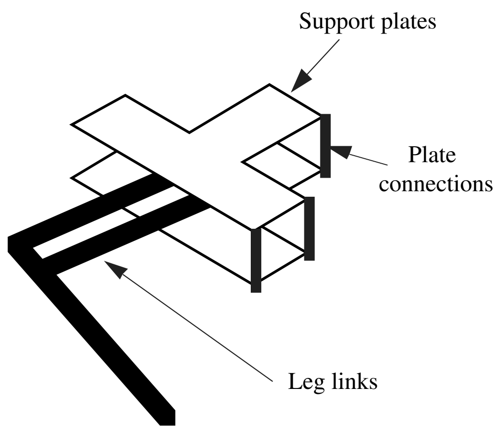


Figure 5.7: Construction of ASV pantographs

The leg links are supported between two plates. Connections join the plates at the corners, providing a stiff structure.

Boadicea's pantographs also have two plates which support the prismatic joints (see **Figure 5.5**). However, Boadicea's legs have a much larger workspace than the ASV. Therefore the leg links sweep through a larger arc at the hip (See **Figure 5.8**). This range of motion prohibits placing the links between support plates like the ASV design because the plate connections would interfere with leg motion. As a result, Boadicea's leg links are outside the two plates. This arrangement is less desirable because the loads experienced by the leg are overhung from the support structure. A small linkage on the opposite side of the support plates helps overcome this problem (see **Figure 5.9**). It keeps the shafts (see **Figure 5.5**) which connect the sliders to the leg links straight.

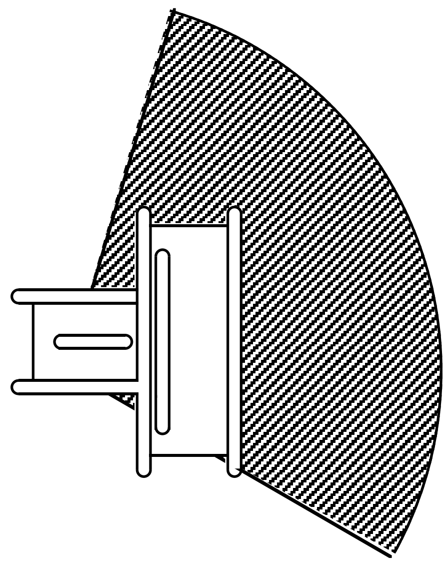


Figure 5.8: Arc swept by Boadicea's leg links

Because Boadicea's legs have a larger workspace, the links sweep through a larger arc. If the leg links were between the support plates, it would be impossible to connect them without restricting leg motion. As a result, Boadicea's leg links are outside the support plates.

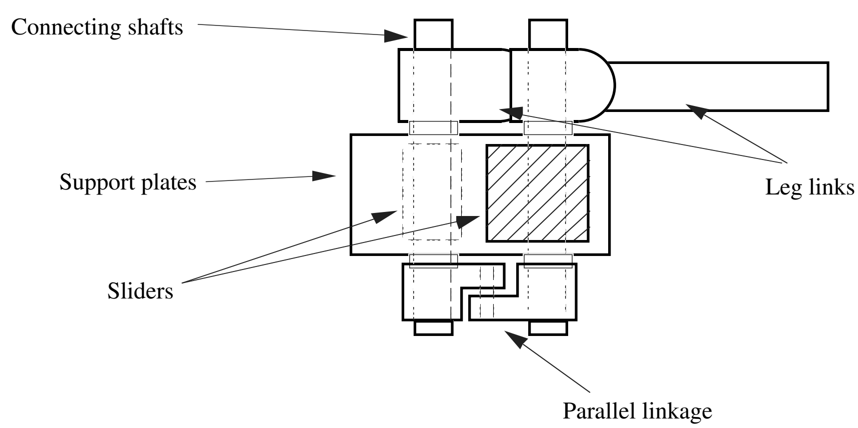


Figure 5.9: Boadicea's pantograph construction

The leg links are outside the support plates, resulting in overhung loads on the connecting shafts. The parallel linkage on the opposite side of the support plates keeps the shafts straight.

Bronze bushings

The rotary bearings on Boadicea are bronze bushings. Although they are not as nice as ball bearings, the bronze bushings are lower cost, smaller, and can be insert molded into plastic parts. Once again, this robot will not be performing microsurgery or building nuclear bombs, so the friction and play in the bushings is acceptable.

Good and bad points

The advantages of Boadicea's leg design are:

- a large workspace
- linear foot motions
- a relatively small and compact mechanism
- lightweight construction

The biggest drawback of Boadicea's legs is a relatively large amount of play in the mechanism caused by the bushings and slider mechanism. Although closer tolerances will reduce this problem, the subsequent increase in friction is unacceptable. The positioning error caused by this compliance does not hamper Boadicea's mobility. It is a source of error in the kinematic calculations, however, which does affect servo performance.

Increasing the vertical workspace for Boadicea's legs would improve the robot's mobility. This change would allow the robot to climb on more difficult terrain, and would allow it to walk over moderate-sized obstacles with less disruption to the regular gait. For example, feet would be able to step down into small holes, and supporting legs could lift the body to allow a swinging leg to clear an obstacle.

6. Electronics and Sensors

My primary interest is the mechanics of the robot. Although the electronics and sensors are a vital part of any autonomous machine, I kept them as simple as possible. Other researchers have shown advantages of sensor-rich robots **[Ferrell 93, Angle 91].** However, there are complexity and reliability problems with having many sensors. For example, more sensors means more wires that can break.

The historic philosophy of the MIT Mobile Robotics Laboratory is to explore the possibilities of simple robots. To date, most robots we have built have been computationally simple and sensor-sparse. Recent work has begun to explore the advantages of more complex hardware **[Ferrell 93] [Ferrell, et al 95]**. Boadicea, however, has the brains and sensors typical of a Mobot Lab "insect" robot: as little as possible.

6.1. 68332

Boadicea's microprocessor is a Motorola 68332. This processor combines the functionality of a 68020 with a specialized Timer Processing Unit (TPU) **[Motorola 90].** I used a single board computer from Vesta Technology, Inc. for Boadicea. This board combines a 68332 with communication ports and memory. The Vesta processor board piggy-backs on a motherboard I built. The motherboard provides interface and support circuits required for the valves and sensors.

Capabilities and architecture

The primary advantage of the 68332 microprocessor is the TPU. Boadicea uses the TPU to produce the Pulse Width Modulation (PWM) wave forms that control the valves. The servo software calculates the proper duty cycle for each DOF and passes this value to the TPU, which generates the proper waveform with no further software intervention. Previous Mobot Lab robots have used microprocessors where the PWM wave forms must be generated in software. This overhead significantly limits processor performance. On the lab's newest project, Cog, we had to build custom PWM generating circuits **[Ferrell, et al 95]**. Sixteen included PWM channels make the 68332 an attractive choice for microcontroller applications.

Boadicea's motherboard

The 68332 does not have any analog inputs or outputs, but it does provide twelve Chip Select lines which can be used to control memory mapped support chips. I built a mother board for Boadicea that contains the interface hardware I needed. The circuit board I built has an eight channel Analog to Digital (A/D) converter for the sensors on each leg. Both the hardware and software interfaces to these external chips are straightforward. My circuit board also has H-bridge drivers which amplify the 68332 signals to the 12 volts required by the solenoid valves.

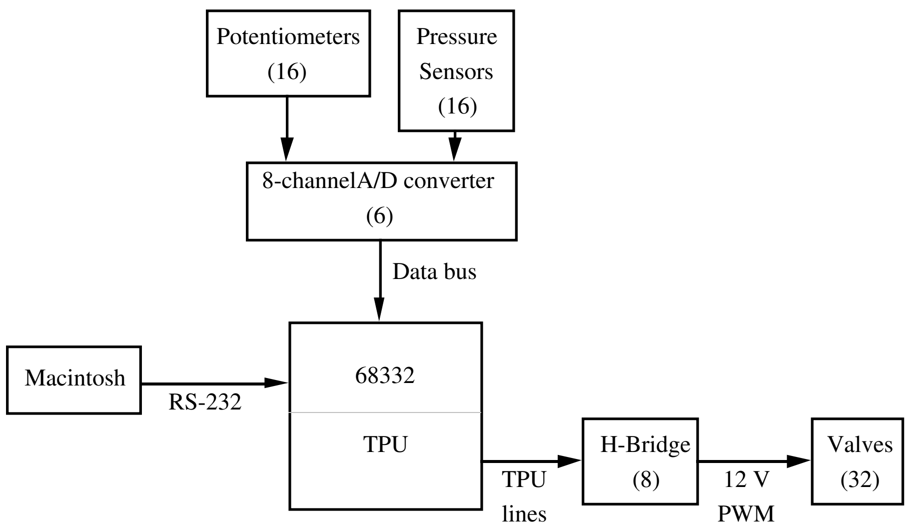


Figure 6.1: Block Diagram of Boadicea's electronics

The H-bridge drivers and A/D converters are on the motherboard I built. The Macintosh is used as a terminal; all of Boadicea's software runs on the 68332.

L programming language

Boadicea is programmed in L, a multi-tasking version of Common Lisp written by Rodney Brooks **[Brooks 94]**. This language has several features which make it appropriate for controlling Boadicea. First, it provides an interpreter which makes debugging and testing code much easier than with traditional compiler or assembler systems. The flexibility and debugging options provided by the interpreter were instrumental in allowing me to program Boadicea in the time available.

Second, L is the current lab standard programming language in the Mobile Robotics Laboratory. Using the same software tools as the rest of the group also makes development easier. It is easier to transfer innovations from one robot to another, and there are more people developing support tools. For example, other researchers in the laboratory have developed a digital oscilloscope and other debugging tools for robots programmed in L.

All of the software required to run Boadicea's software, including the interpreter, reside in EPROM on the Vesta circuit board. The servo and higher level control software are downloaded into RAM on the Vesta Board when the robot is turned on. Once this transfer is complete, Boadicea's software system is self-contained; all of the code, data, and processing power is on-board.

The 68332 communicates with a Macintosh computer over an RS-232 serial line. The Macintosh functions as a terminal and file server for L; programs and data files can be transmitted between the microprocessor and the Macintosh. Development tools, like the digital oscilloscope, also run on the Macintosh; background processes running on the 68332 send the required data to the Macintosh.

6.2. Sensors

The complexity of a robots behavior is determined in part by its sensors; it is difficult to make good decisions if there is limited information available. Although insects have several hundred mechanosensory signals from each leg **[Delcomyn, et al 94]**, technological limitations prohibit this level of complexity on robots. Insects sense leg position, velocity, acceleration, loading, and contact with the environment **[Delcomyn, et al 94]**. Robots can measure these same quantities.

Because the emphasis of this project was the robots mechanical systems, Boadicea has relatively few sensors: two per DOF. Potentiometers measure leg position, and pressure sensors determine forces acting on the legs. Unfortunately, the pressure sensors have been relatively unreliable, limiting their usefulness.

Trade-offs of many sensors

Earlier research at the Mobot Lab has shown the potential advantages of robots with many sensors **[Ferrell 93]**. The flip side of this equation, however, is that additional complexity hinders reliability. I decided a good compromise for Boadicea is pressure and position sensors which can determine the force and position of each actuator. **Figure 6.2** shows sensor location on each of Boadicea's legs. (On the front legs, the lift sensors are not present, because they only have two DOFs.)

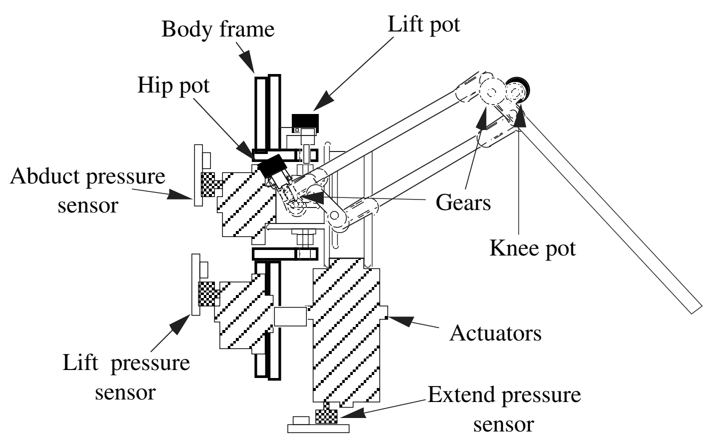


Figure 6.2: Location of Boadicea's sensors

The potentiometers (pots) measure leg position. Hip and knee potentiometers use gears to keep the mechanism compact. The gears at the knee also improve the sensor's resolution. Pressure sensors are mounted directly on the back end of each cylinder. Each pressure sensor is on a small amplifier circuit board.

Pressure sensors

Boadicea uses micromachined pressure sensors from IC Sensors. The sensors are mounted directly on the back ends of the actuators, eliminating inaccuracies caused by hose and fitting pressure drops. The sensor contains a Whetstone bridge which outputs a differential signal. A small amplifier circuit is installed on the same circuit board as the sensor.

Unfortunately, the pressure sensors are not very robust. The solder joints on the sensor leads are easily broken, and the sensors are susceptible to contamination. The silicon chip and its connecting wires are totally exposed to the air, and whatever contaminants are present, in the actuator. Rectifying these problems would improve the robot's reliability tremendously.

Currently, Boadicea cannot operate reliably in a force-servo mode because the sensors fail too often. Hopefully, future experiments with Boadicea will address this shortcoming.

Position sensors

The position sensors on Boadicea are precision potentiometers manufactured by Spectrol. These potentiometers are the smallest available with a reasonable rotational lifetime.

One potentiometer measures the angle of the lift degree of freedom for the middle and rear legs. This measurement is relatively straightforward because this DOF is rotational. For the other DOFs, two potentiometers measure the hip and knee joint angles. A simple kinematic calculation determines the actuators' displacements. These two potentiometers have one stage of gearing between the sensor and the angle being measured. The gears allow a compact joint design, which outweighs the problem of backlash. On the knee potentiometer, the gear ratio also improves resolution by 50%.

Figure 6.3 shows the notation I used for analyzing the kinematics of Boadicea's pantographs. A kinematic analysis is needed to calculate the foot position from the potentiometer values. The hip and knee potentiometers measure the angles α and β, respectively. Positions relative to the body are measured in the $\hat{i}, \hat{j}$ reference frame. The $\hat{a}, \hat{b}$ and $\hat{u}, \hat{v}$ reference frames are attached to the two leg links. L_1 and L_2 are the femur and tibia lengths.

The position of the foot is

$$\begin{bmatrix} x \\ y \end{bmatrix} = L_1\hat{a} - L_2\hat{u}$$

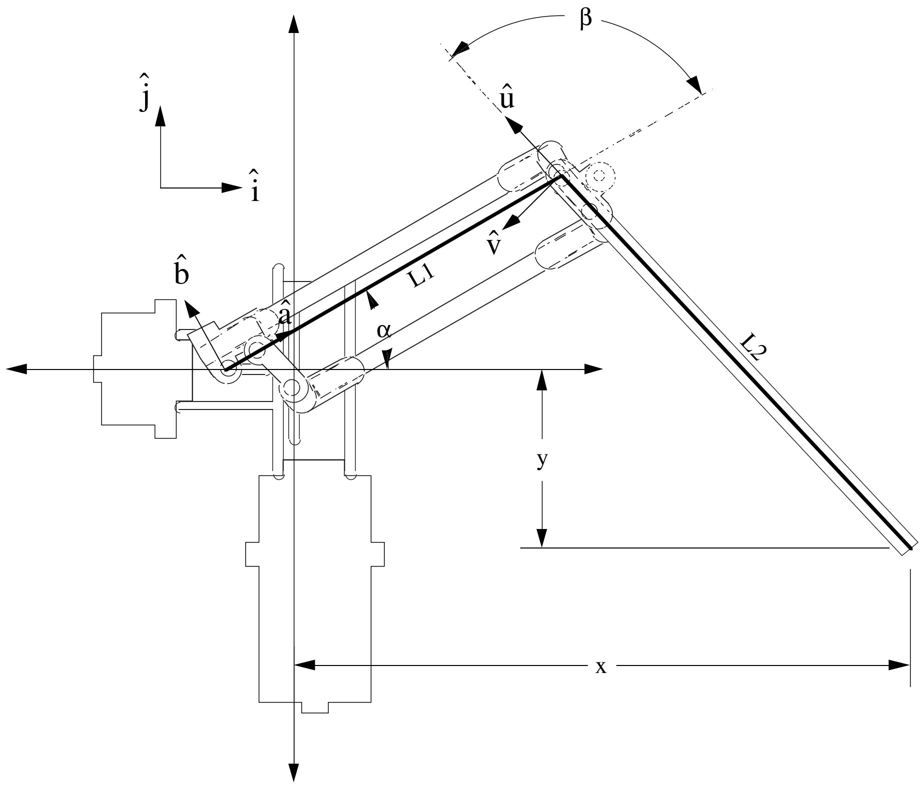


Figure 6.3: Kinematics of Boadicea's pantographs

Potentiometers at the hip and knee joints measure the angles α and β, respectively. Part of Boadicea's servo loop calculates the X, Y position of the foot based on these measurements.

To find the position in the $\hat{i}, \hat{j}$ frame, we need these two equations:

$$\begin{bmatrix} \hat{i} \\ \hat{j} \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} \hat{a} \\ \hat{b} \end{bmatrix} \text{ and } \begin{bmatrix} \hat{a} \\ \hat{b} \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} \hat{u} \\ \hat{v} \end{bmatrix}$$

Combining the above equations gives a relationship between the $\hat{i}, \hat{j}$ and $\hat{u}, \hat{v}$ frames:

$$\begin{bmatrix} \hat{i} \\ \hat{j} \end{bmatrix} = \begin{bmatrix} \cos(\alpha+\beta) & -\sin(\alpha+\beta) \\ \sin(\alpha+\beta) & \cos(\alpha+\beta) \end{bmatrix} \begin{bmatrix} \hat{u} \\ \hat{v} \end{bmatrix}$$

Using these results, we get this equation for the foot position in the $\hat{\imath}, \hat{\jmath}$ frame:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} L_1 \\ 0 \end{bmatrix} + \begin{bmatrix} \cos(\alpha+\beta) & -\sin(\alpha+\beta) \\ \sin(\alpha+\beta) & \cos(\alpha+\beta) \end{bmatrix} \begin{bmatrix} -L_2 \\ 0 \end{bmatrix}$$

which simplifies to:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} L_1\cos\alpha - L_2\cos(\alpha+\beta) \\ L_1\sin\alpha - L_2\sin(\alpha+\beta) \end{bmatrix}$$

This is the equation Boadicea uses to determine the foot position for its legs.

Linear position sensors

Ideally, Boadicea should have linear potentiometers or transducers in the prismatic joints to measure actuator position directly. Linear sensors would make kinematic calculations unnecessary, and would subsequently eliminate errors caused by inaccuracies in the computation. Linear sensors which are commercially available, however, are unacceptably large. I investigated making my own linear potentiometers with off-the-shelf wipers and resistive elements. It was still a marginal fit, however, and the probability that contamination or a collision would damage the sensor was prohibitive.

7. Control System Design

Pneumatic actuators are more difficult to control than electric motors because of nonlinear effects like compressibility. Many researchers have examined adaptive and nonlinear techniques for producing accurate position control of pneumatic actuators. These experiments use large components which are designed to minimize parasitic effects. Size and weight constraints prohibit using these components on Boadicea.

Despite the apparent difficulty in controlling a nonlinear system with poorly behaved components, Boadicea achieves reasonable force and position control with relatively simple control laws. A proportional-only feedback law produces acceptable force control. Position control is more difficult, but a simple system was good enough to demonstrate Boadicea's mechanical capabilities.

7.1. Different options

There are several strategies that can be used for controlling robots. The most common control strategy for robots is position control. Force and impedance are more appropriate outputs for controlling robot dynamics, however. These variables are more difficult to control with electric actuators. Although pneumatic systems complicate position control, they allow easier implementation of force and impedance control.

Position control

Position control is straightforward to implement in most systems because accurate position sensors are well understood. Pneumatic actuators, however, are not as amenable to position control, because of their inherent nonlinearities. A primary reason why pneumatic power has not been used in many robot applications is the difficulty in controlling position; robot designers assume that position control is the optimal mode of operation, and use that assumption as a reason to eliminate pneumatic actuation.

With Boadicea's control system, producing reasonably accurate position control has been more difficult than controlling force, as I expected. Unfortunately, the pressure sensors on Boadicea's actuators are relatively unreliable. As a result, Boadicea's legs operate under position controlled mode, even though this is not the optimal mode of operation.

Force control

The other common strategy for robotic controllers is force control **[Whitney 87]**. Especially for legged robots, force control is a good idea because it provides a more direct relationship between the control system and the robot's dynamics. Force control is more difficult to achieve with electric actuators because the sensors are more complex. Furthermore, unpleasant nonlinear effects, primarily friction, limit force servo accuracy.

Boadicea was designed to use force as the primary control variable. My idea was to use a force servo based on pressure sensors as an inner control loop. An outer control loop would modulate the goal force depending on the leg position. Unfortunately, reliability problems with Boadicea's pressure sensors prohibited this approach. I did implement a pressure control system, and verified its feasibility, but the locomotion experiments did not use this capability.

Impedance control

Another possibility for robot servo systems is to use impedance control **[Hogan 83]**. In this system, the servo system determines a goal impedance which produces a desired behavior. The system then appears to act as a passive system, but the stiffness and other characteristics can be changed. For example, in a walking robot, the legs could have compliant actuators, allowing the body and leg to act as a mass-spring system. With control, the natural frequency of this passive system could be adjusted for different walking velocities.

Pneumatic systems are well suited to impedance control because the air in the actuators acts like a spring. The stiffness of the spring can be changed by adjusting the pressure in the actuator. A pneumatic actuator with valves controlling flow to both sides of the piston has the same type of behavior as biological systems with opposing muscles. The actuators (or muscles) act as two springs with controllable stiffness. Together, the pair acts like a single spring with adjustable stiffness and equilibrium position.

I did not attempt impedance control with Boadicea because of its dynamic nature. The advantage of controlling leg stiffness is that the passive dynamics of the actuators can be set to produce a desired dynamic motion. Boadicea's sensors and software do not make the measurements necessary for determining dynamic behavior. Furthermore, modeling the whole-body dynamics of the complete robot is beyond the scope of this project.

Complexity was another reason not to use impedance control. Even with the friction, play, and nonlinearities of Boadicea's legs and actuators, I was able to achieve rough force and position control with relatively simple software. Controlling impedance would require modeling these parasitic effects and including them in the control law. Furthermore, to make impedance control worthwhile, the actuator's passive dynamics should be matched to the dynamics of the robot's locomotion. I did not undertake the calculations and modeling required to achieve this matching when I designed Boadicea's actuators.

7.2. Other pneumatic control systems

Pneumatic actuators have nonlinear dynamics because the working fluid is compressible, and effects like friction, valve deadband, and saturation are dominant. As a result, pneumatic systems have traditionally been used with "bang-bang" control, where the actuator is always at one end of its travel or the other. This strategy avoids the need for a nonlinear control system. Recently, however, progress has been made designing control systems that account for the nonlinear dynamics.

These studies, however, have several limitations. First, they use expensive components that minimize parasitic effects. Almost all of the researchers use high performance servo valves and rodless cylinders **[Pu, et al 91] [Kawashima, et al 92] [Scavarda, et al 92] [Chen, et al 92] [Keller and Isermann 93]**. Servo valves have built-in electronic feedback circuits that ensure the flow rate through the valve is proportional to the control signal. Rodless cylinders have a magnetic coupling (through the cylinder walls) between the piston and the load, eliminating leakage and friction caused by rod seals. Eliminating the piston rod also makes actuator response symmetric. These components are too large, heavy, and expensive for a robot like Boadicea.

Furthermore, the goal of these studies is to produce accurate position control. Walking robots do not require this level of position accuracy, and in many circumstances, force or impedance control may be more productive.

A summary of some of these experiments:

- **[Fok and Dransfield 91]** use a Model Reference Adaptive Control (MRAC) strategy for velocity control. Their system uses a pneumatic motor to drive a lead screw. This choice simplifies actuator dynamics because the motor has constant volume.
- **[Keller and Isermann 93]** also use an MRAC controller. Their system adapts for changes in the mass and friction properties of the load.
- **[Pu, et al 91]** use feed forward and acceleration feedback in their servo system to eliminate transients like overshoot.

- **[Chen, et al 92]** use an adaptive fuzzy-logic controller to achieve accurate position control of a pneumatic actuator.
- **[Scavarda, et al 92]** use a state-affine control strategy. This control law has position, velocity, and acceleration feedback. The controller gains are a function of the actuator position, however. This strategy compensates for the position dependence of the actuator stiffness.
- **[Kawashima, et al 92]** describes a pulse-population strategy for a positioning system with 1 micron accuracy. The sacrifice they make to achieve this accuracy is slow response time; the system takes several seconds to move the last few microns. Many researchers have used adaptive controllers for position and velocity control.

For a robot like Boadicea, size and weight of the mechanical components is far more important than the positioning accuracy of the system. The solenoid valves I used do not have linear flow characteristics, and my actuators have leakage and friction which affect their dynamics. The challenge in designing a controller for Boadicea is accommodating these parasitic effects, not producing accurate positioning.

7.3. Nonlinear dynamic model

In order to design an effective control system, it is necessary to analyze the open- and closed-loop dynamic properties of the actuator system. Boadicea's actuators have two state variables, pressure and position, with a nonlinear relationship. Depending on whether position or force is being controlled, one state is modeled as the output and the other as an unknown disturbance. Using this assumption, Boadicea's actuators approximate a first-order, linear system. Therefore, proportional-based control laws should be able to produce reasonable response.

Configuration of Boadicea's pneumatic system

Figure 7.1 illustrates the configuration of Boadicea's pneumatic system. The actuator is used in a "differential jack" configuration: the front end of the cylinder is always pressurized, and the back end pressure is controlled by valves. Obviously, if the back-end pressure is low, there will be a retracting force on the piston. If the pressures are equal, however, there is a net extending force because the two sides of the piston have different areas. The difference is the area of the piston rod's end, which is in atmospheric pressure.

Since the hydrostatic force on the piston is pressure times piston area, an extension force can be created without having a higher pressure in the back end. (see **Figure 7.2**)

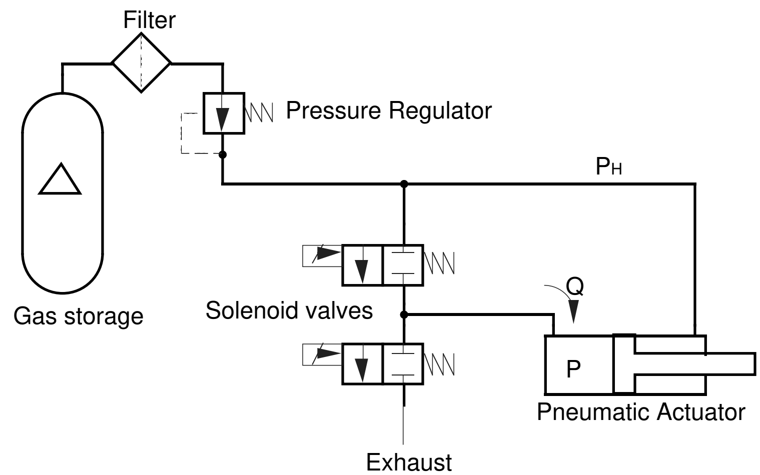


Figure 7.1: Boadicea's pneumatic system (1 actuator only)

The actuators are used in a "differential jack" configuration: the front end of the cylinder is always pressurized, and the pressure in the back end is controlled by valves.

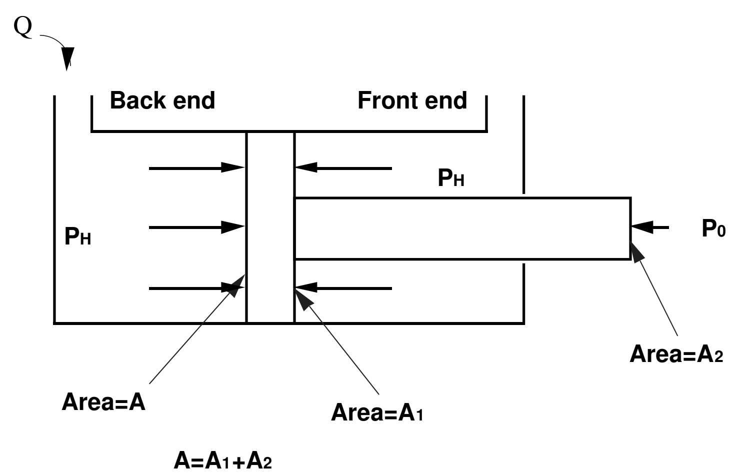


Figure 7.2: Hydrostatic forces on the piston in a differential jack

When the back end pressure is low, the actuator retracts. When the two pressures are equal, it extends because the two sides of the pistons have different areas.

The differential jack arrangement is similar to having a single-acting cylinder with a spring return. The differences are that here the restoring force is constant, the mechanical design is simpler, and flow requirements from the high pressure source are reduced. The third advantage is the most important. When the actuator is extending, the air squeezed out of the front end goes back into the high pressure supply hose, through the valve, and into the back end. Flow from the storage tank is required only to compensate for the different volumes of the two ends.

Normally, differential jacks are designed with an area ratio of 2:1. This ratio provides equal performance for extension and retraction. A walking robot, however, should not have symmetrical performance; in one direction, the actuator must propel the mass of the robot, but in the other it only moves the leg. For Boadicea, I used actuators with an 11:10 area ratio. Therefore, the maximum retracting force is 10 times the maximum extension force. The leg mechanism is designed so the larger force operates in the direction that must support the robot's body.

Actuator dynamics

In Boadicea's actuators both volume and pressure change, complicating the dynamic equations. To determine these equations, we start with the ideal gas law for the back-end of the cylinder:

$$PV = mR_{air}T$$

where P, V, and m are the pressure, volume, and mass, respectively, of the air in the back end of the cylinder. R_{air} is the gas constant for air, and T is the temperature. Throughout this analysis, I assume that temperature is constant. Experimental results indicate that this is a valid assumption.

Taking the time derivative yields

$$\dot{P}V + P\dot{V} = \dot{m}R_{air}T$$

The power flow into the cylinder is

$$\boldsymbol{P}_{in} = \frac{PQ}{\rho}$$

Here, Q is the mass flow rate into the back end, and ρ is the density of that air.

When we substitute this form of the ideal gas law:

$$\frac{P}{\rho} = R_{air}T$$

this equation becomes

$$\frac{PQ}{\rho} = QR_{air}T$$

and, since $\dot{m} = Q$, this leads to

$$\frac{PQ}{\rho} = \dot{P}V + P\dot{V}$$

This is equivalent to conservation of energy, with $\dot{P}V$ representing the power being stored in the cylinder and $P\dot{V}$ representing the power transmitted through the piston. To model this part of the actuator on a bond graph requires a nonlinear, multi-port capacitive element (see **Figure 7.3**).

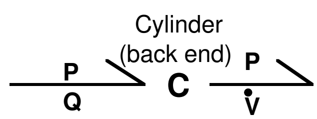


Figure 7.3: Actuator capacitance model

The left bond represents fluid power delivered to the actuator. Some of this power is stored in the compressed air in the cylinder. The remainder is transmitted through the piston as mechanical work.

Note that here the two variables on the input bond do not truly represent power, because Q is a mass flow rate. The fluid power transmitted through this bond is really PQ/ρ. The output bond is pressure, P, times volume rate of change, $\dot{V}$, which has units of power; this bond is the mechanical power transmitted through the piston.

Solving for Q, we get

$$Q = \frac{\dot{P}V\rho}{P} + \dot{V}\rho$$

Substituting $\rho = \frac{m}{V}$ to eliminate ρ,

$$Q = \dot{m} = \frac{\dot{P}m}{P} + \frac{\dot{V}m}{V}$$

which leads to this interesting equation:

$$\frac{\dot{m}}{m} = \frac{\dot{P}}{P} + \frac{\dot{V}}{V} \tag{1}$$

Equation (1) describes the distribution of energy in the actuator. Some energy is stored in the back end by compressing air, and the rest is transmitted through the piston as mechanical power.

To complete the model, we must determine the power transmitted through the piston. This is the actuator's purpose, converting fluid power into mechanical power. The retracting force on the piston is

$$F_r = P_H A_1 + P_0 A_2$$

and the extension force is simply

$$F_e = PA \tag{2}$$

leading to this expression for the net piston force:

$$F = PA - P_H A_1 - P_0 A_2$$

In these equations, P_H and P_0 are the system and atmospheric pressures, respectively. A_1 is the area of the front side of the piston, A_2 is the area of the piston rod, and A is the area of the piston's back side. So, we know that $A = A_1 + A_2$.

The volume of the back end, V, is related to piston position, x, by

$$V = Ax + V_0$$

where V_0 is the minimum volume. This equation leads to an intuitive relationship between piston velocity, $\dot{x}$, and $\dot{V}$:

$$\dot{V} = A\dot{x} \tag{3}$$

Since the power transmitted to the piston is $P\dot{V}$, and the power output of the actuator, $\boldsymbol{P}_{\text{out}}$, is given by

$$\boldsymbol{P}_{\text{out}} = F\dot{x},$$

the piston can be modeled as a transformer and an effort sink, as shown in **Figure 7.4**.

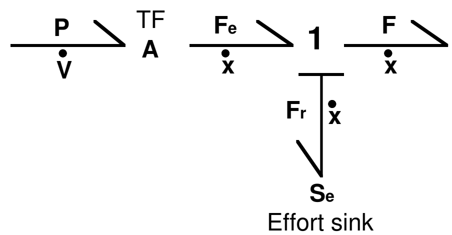


Figure 7.4: Transformer and effort sink model for piston

The effort sink represents the hydrostatic force on the piston from the front side of the piston. The power flowing through this bond is returned to the high pressure supply.

The power flow into the sink is really fluid power pushed back into the high pressure supply hose, which reduces the power required from the compressed air supply. Equations (2) and (3) characterize the transformer, converting P and $\dot{V}$ into F_e and $\dot{x}$. The actual work out of the actuator is

$$F\dot{x} = F_e\dot{x} - F_r\dot{x}$$

The $F_r\dot{x}$ term is the power flow into the effort sink.

The bond graph elements in **Figures 7.3** and **7.4** can be combined with traditional bond graph models of the valve, fittings, and hose capacitance to produce a complete bond graph for the valve-actuator system, as shown in **Figure 7.5**.

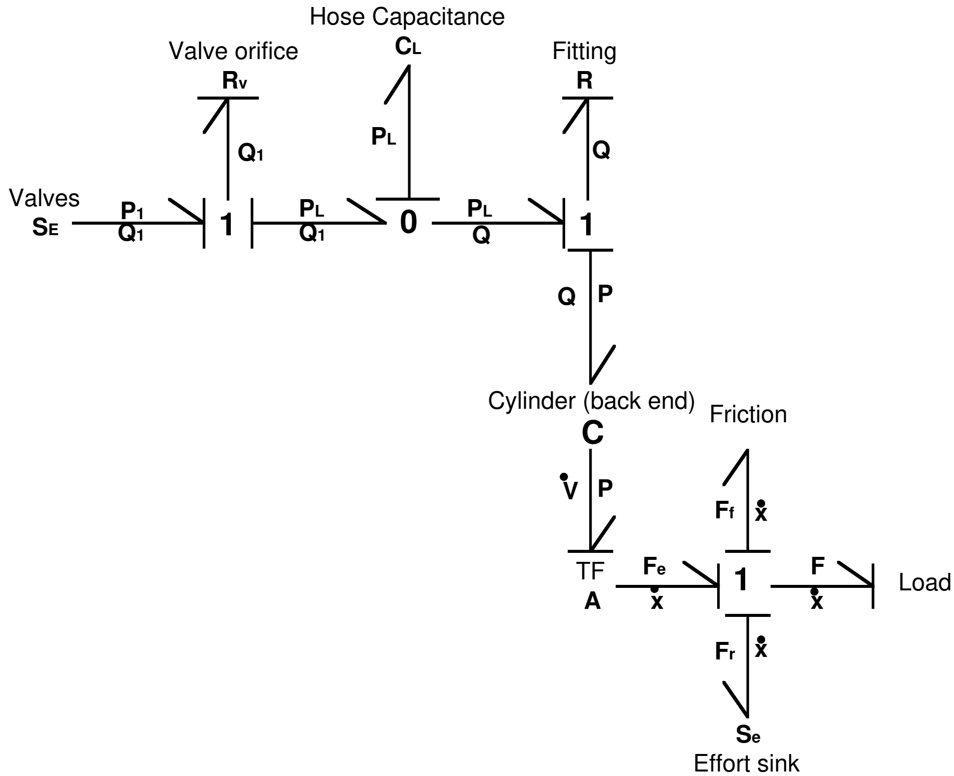


Figure 7.5: Complete bond graph for actuator dynamics

The valve is modeled as a pressure source, fittings are resistances, and the hose is a normal capacitance.

Closed loop dynamics

The closed loop dynamics can be characterized with Equation (1). The mass flow rate, $\dot{m}$, is proportional to the PWM output from the control law. Depending on which variable is being controlled, force or position, the output of the closed loop system is difficult to predict, and is best modeled as an unknown disturbance. Using these assumptions, the closed loop dynamic equation has the form

$$\dot{y} = ku + d(t)$$

where y is the output, u is the PWM signal, and d(t) is the unmodeled disturbance. The closed loop gain, k, depends on m, V, P, and the valve properties. All of these effects are relatively slow moving compared to the closed loop response time.

This equation is first order, and has approximately linear behavior. As a result, linear control system techniques should be able to produce reasonable performance. My controller designs, both for force and position, were therefore based on a proportional feedback law. For the pressure controller, a proportional term was sufficient without any additional compensation. The position controller, however, did require more terms in the control law.

7.4. Boadicea's pressure controller

Boadicea was designed to operate primarily under force control. Pressure sensors are mounted directly on the actuators, providing accurate measurements of leg loading. In contrast, Boadicea's position sensors measure joint angles, which must be converted to actuator position by a kinematic calculation. As a result, Boadicea measures position less accurately than force.

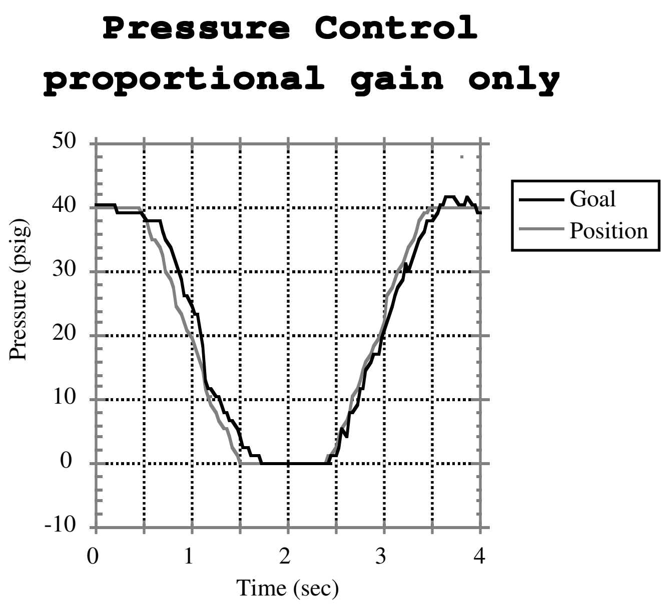


Figure 7.6: Pressure controller performance

This controller uses a simple proportional control law, but still achieves good tracking performance. The lag on the downslope occurs when the actuator moves; the valve cannot supply enough flow for perfect tracking.

Figure 7.6 shows the tracking performance of Boadicea's pressure controller. The control law for this experiment is simply proportional feedback. Because the relationship between valve flow rate and pressure is well behaved, even a simple control law performs well. The lag on the down slope is caused by the actuator's motion. When the piston is moving, the valve cannot provide enough flow to maintain the correct pressure.

7.5. Boadicea's Position controller

The second mode for Boadicea's controller is position based. This controller differs from other pneumatic servo systems because the system components are not well behaved. Most researchers use linear servo valves and low friction actuators for their experiments. Boadicea's dynamics, however, are dominated by effects like friction, valve limitations, and sensor noise. All of these factors have poorly behaved nonlinear dynamics which degrade controller performance.

Proportional control

For the first version of the position control system, I used a simple, proportional-only control law. This system did not produce satisfactory performance, as shown in **Figure 7.7**. The sensor signals received by Boadicea's microprocessor are relatively noisy; I did not attempt to shield the sensor signals from electrical interference. Also, the leg dynamics have significant nonlinear and unmodeled effects: friction, backlash, bearing play, diaphragm nonlinearities, and external loads. The results illustrated in **Figure 7.7** illustrate this difficulty; a small difference in control system input between the first and second periods creates radically different responses, either a large overshoot, or slow response.

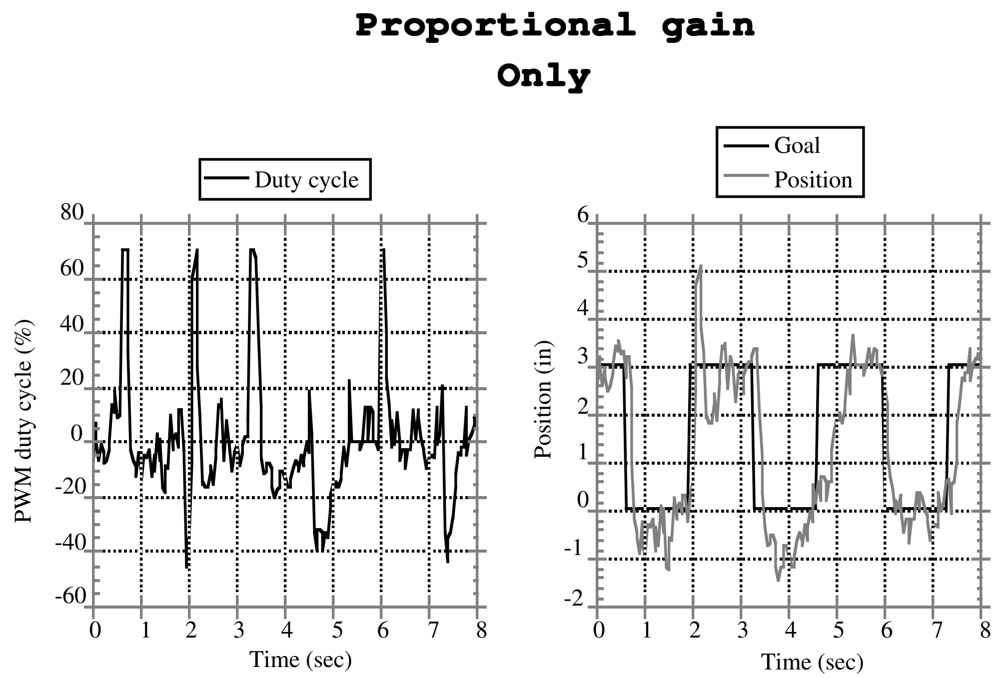


Figure 7.7: Controller performance - Proportional only

This figure shows the performance of Boadicea's position controller using a Proportional-only control law. Sensor noise and quantization errors cause a noisy control signal, which results in erratic motion. The system's nonlinearities also cause unpredictable responses: sometimes there is a large overshoot, and other times the response is too slow.

Proportional - integral control law

In order to mitigate some of these problems, I added a second order digital filter to the sensor values. The subsequent reduction in signal noise improved system performance. Adding an integral term to the control law provided further dramatic improvement (see **Figure 7.8**). The advantage of an integrator is that it provides high gain at low frequencies and attenuates higher frequency noise. The Proportional-Integral (P-I) control law produced smoother motions with greater repeatability and accuracy, although the system performance was still not ideal. A serious problem with the P-I control law was that integral windup caused improper motions when leg loading changed.

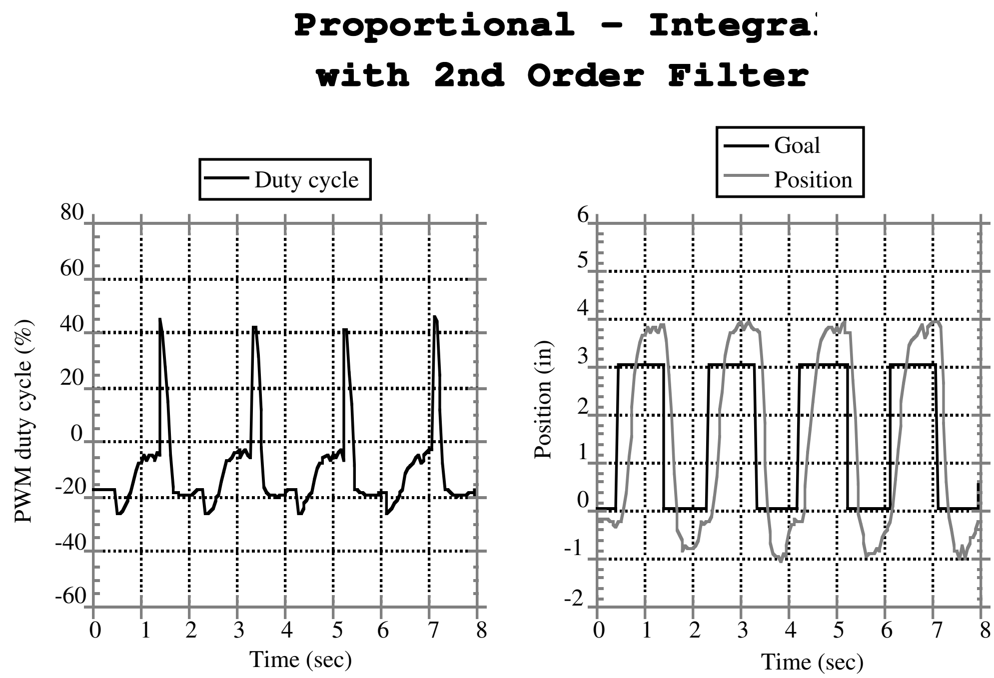


Figure 7.8: Controller performance - P-I with digital filter

These graphs show the controller performance after an Integral term and a second order digital filter are added. The filter eliminates most of the sensor noise and quantization effects. The integrator adds a term to the control law with high gain at low frequencies, and zero gain at high frequencies, which further attenuates noise.

The Root Locus plot for the closed loop P-I control system is shown in **Figure 7.9**. The control law implements this equation:

$$u = K_P \left(e + \frac{\int e \cdot dt}{\tau_I} \right)$$

In this equation, u is the PWM duty cycle, K_p is the proportional gain, e is the current position error, and τ_I is the integral time constant.

Decreasing τ_I moves the zero to the left on the root locus plot, causing two effects. First, the natural frequency of the closed loop system increases, resulting in a faster response time. Decreasing τ_I also enlarges the circle on which the closed loop poles move. As the system gets faster, the part of the circle near the origin becomes more vertical, decreasing the damping ratio. Increasing the closed loop gain, K_P, moves the closed loop poles leftward on the circle, increasing both response time and damping. Once the poles reach the real axis, the system behavior begins to appear first order. Experiments have corroborated this theory; despite the unpleasant nonlinearities of the system, the closed loop system responds to step inputs as predicted.

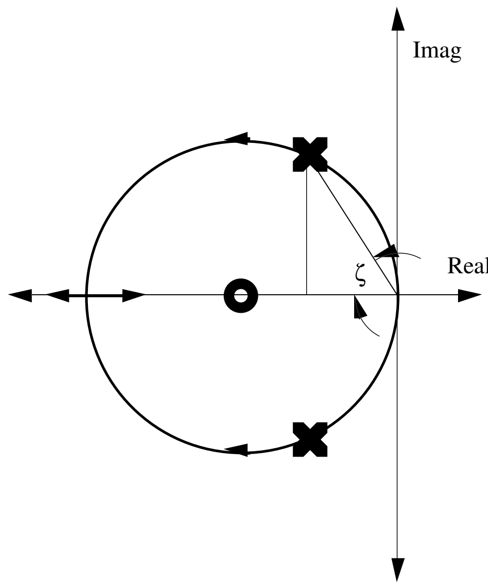


Figure 7.9: Root Locus plot for P-I controller

Increasing the Proportional gain will move the poles to the left, increasing damping and response time. Decreasing the integrator time constant moves the zero left, which increases response time and lowers the damping ratio. Once the poles reach the Real Axis, the system behavior begins to appear first order.

Feed forward control law

Although the Integral term and digital filter improved the servo controller's performance, there was still a large amount of overshoot in the response. This problem is caused by integral wind-up during the motion. When the goal position makes a step change, the real system cannot possibly track it, even with an optimal controller. While the leg is moving, there will always be an error. This error is not caused by the loading condition on the leg, however, so it should not be included in the integral term.

Also, the P-I control law will always respond slightly slower than necessary. Because the control law depends solely on the error (and its time history), the controller will not open the valve until after an error is established. To improve response time, the controller should open the valve when the goal position changes, not after a sufficiently large error has built up. This effect is significant on Boadicea because the integral term dominates the control law, and it is the slowest to respond.

To solve these shortcomings, I added a feed forward term to the control law. This term is designed to produce a step change in leg position without the feedback terms. When the goal position changes, the feed forward term generates the valve PWM signal instead of the feedback controller. The feed forward controller opens the appropriate valve full bore for a time proportional to the distance being moved. At the end of the motion, the valve is closed and the opposing valve is energized to provide a deceleration period. Then the feed forward controller shuts off and allows the feedback controller to operate normally.

The step response of the feed forward system is shown in **Figure 7.10**. The large spikes in PWM Duty cycle are produced by the feed forward controller. The lower level control activity between motions is generated by the feedback controller.

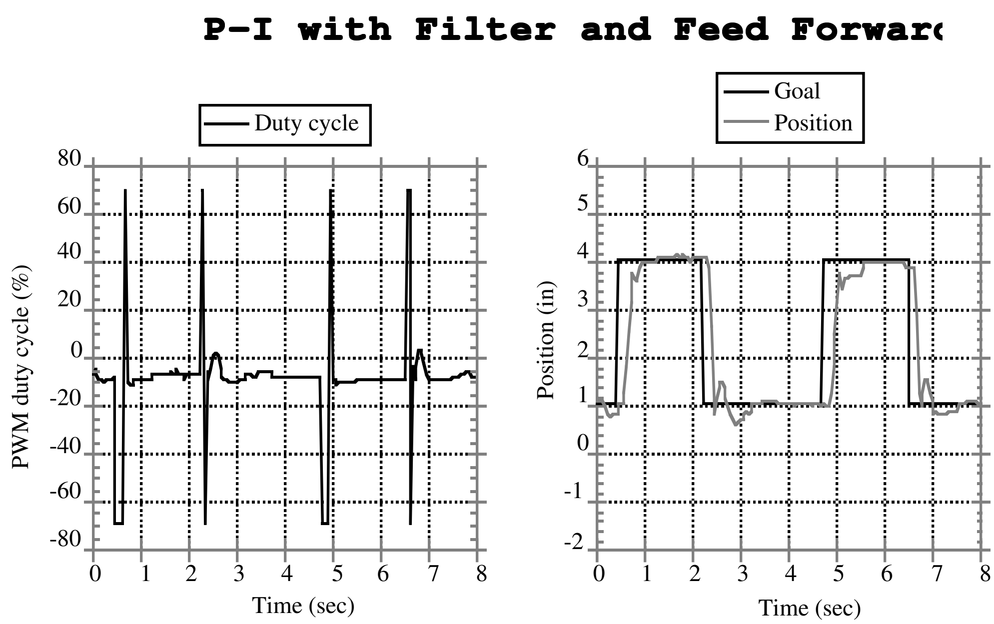


Figure 7.10: Controller performance - P-I with feed forward

The large spikes in PWM Duty cycle are produced by the feed forward controller. The lower level control activity between motions is produced by the feedback controller.

The feed forward controller has several advantages. First, because the integrator is disabled during the motion, it does not build up a large error. Second, the response time of the system is improved because the valve opens full bore without waiting for an error to accumulate. A third benefit is that the feedback controller only operates on smaller errors, so the proportional gain, K_p, can be increased without causing instability. **Figure 7.11** shows the step response of the controller with the same gains as **Figure 7.10**, but without the feed forward control law.

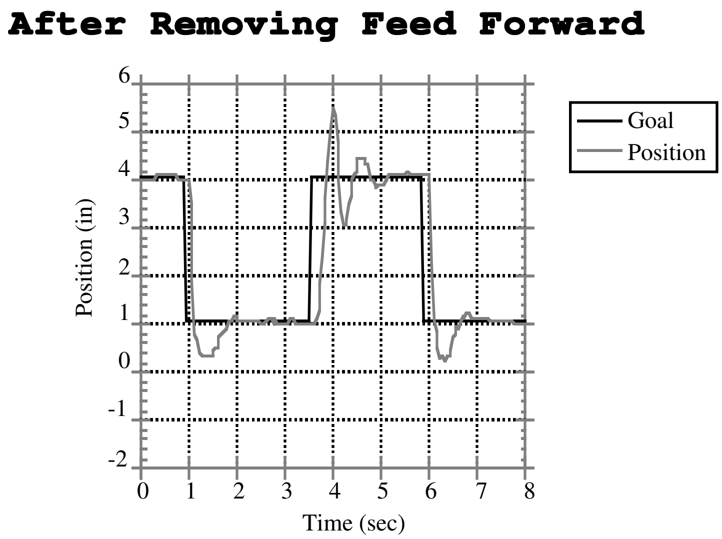


Figure 7.11:   Effect of turning off the feed forward controller

The feed forward controller allows higher proportional gain in the control law. This graph shows the performance of the feedback controller with the same gains as in Figure 7.9.

The performance of Boadicea's servo system is certainly not ideal. There are many sources of noise, inaccuracy, and nonlinearity in the system. Despite these difficulties, though, I was able to develop a controller without the computational complexity of an adaptive, fuzzy logic, or neural net controller. The legs do not always move exactly as commanded, but the control system behaves well enough for the robot to demonstrate its capabilities.

8. Results

I have performed preliminary experiments for measuring Boadicea's performance. The pneumatic actuators provide force and power densities far higher than what could be achieved with electric motors. Together with the pantograph leg mechanism, the actuation system is capable of supporting the robot and a substantial payload. The robot's walking speed is limited by the performance of the position controller, however; Boadicea does not walk as fast as the design targets.

On rough terrain, Boadicea's climbing abilities are an improvement over previous small walkers. The robot can climb over 4" steps, twice as high as Genghis and Attila **[Ferrell 93]**. Again, the robot's versatility is hampered by the limitations of the control system. A high center of gravity and limited ground clearance also constrain the robot's mobility.

8.1. Force and speed capabilities

Boadicea's actuators have adequate force and speed capabilities to meet the design targets. The leg mechanism is capable of supporting the loads encountered during locomotion on level and slightly rugged terrain, with and without a payload. Each leg is capable of producing more than 15 lb of vertical force, more than enough to support the entire robot and payload.

On the propulsion stroke, the feet move at 35 in/sec, with no load. On the recovery stroke, the feet move approximately 14 in/sec. These speeds are more than adequate for Boadicea to achieve the 6 in/sec design speed. The robot's top speed of 4 in/sec was determined by the stability of the servo system. To maintain proper behavior of the servo controller, delays are needed in the motion profile and the step length is limited. The robot's mechanical system, however, is able to propel at faster speeds.

The horizontal force capability of each leg should be sufficient to propel the unencumbered robot up a 45° slope with two legs. With a payload, more legs can be used because the robot should walk with a slower gait. Boadicea's legs produce a maximum forces of 4.5 lb when moving and 9 lb when stationary. This force is sufficient to propel the robot up a 64° slope with a tripod gait and no load, or a wave gait and full payload. Using a tripod gait and carrying a payload, the legs could propel the robot up a 37° slope.

There is an important caveat for these results, however. Because mounting the lift actuators on the robot's underside was the only feasible alternative, Boadicea is much taller than I had originally envisioned. Its high center of mass makes climbing on steep slopes impossible; the robot topples over backwards. This problem is a result of the process I used to design the robot. I developed the leg mechanism first and revised its design many times. The robot's body, however, was only built once; I did not have enough time to test and revise the body.

Actuator performance

I used one of Boadicea's actuators (1.25" bore, 1.5" stroke) to lift heavy objects. The apparatus for these experiments is shown in **Figure 8.1**. This test measured both the speed and force capabilities of Boadicea's actuation system. The maximum force is determined by the cylinder bore in the actuator, while the speed is determined by the flow capacity of the solenoid valves. The actuator was able to lift 22 lb at 3 in/sec and 50 lb at 1 in/sec. These numbers correspond to actuator power outputs of 7.5 W and 5.6 W, respectively.

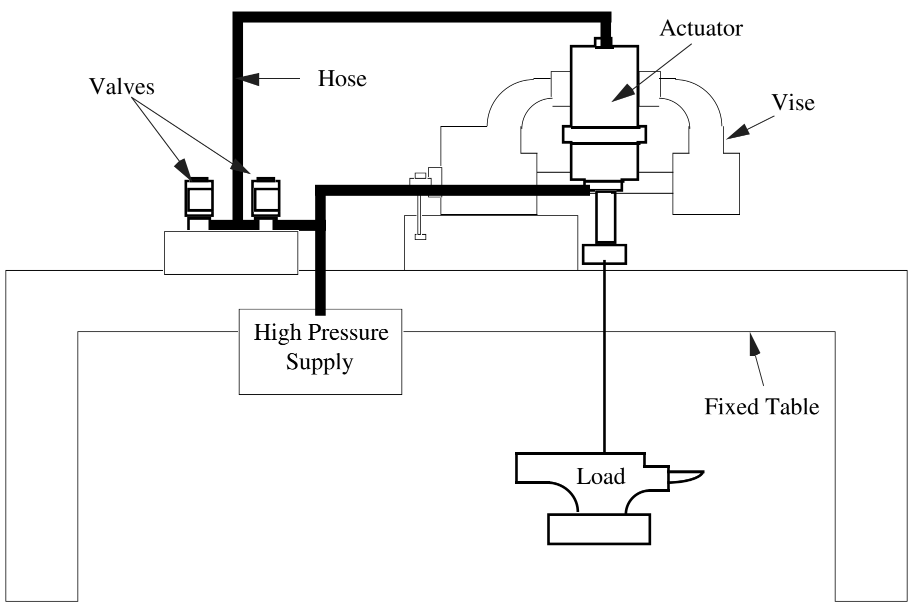


Figure 8.1: Apparatus for measuring actuator performance

Because the actuator produces large forces when it retracts, I had to hang loads from the piston while holding the actuator fixed in a vise. The actuator lifted 22 lb at a speed of 3 in/sec and 50 lb at 1 in/sec. These figures correspond to power outputs of 7.5 and 5.6 W. The performance measured is determined by the force capability of the actuator and the flow capability of the valves.

The design goal for Boadicea's actuation system was to produce a maximum of 6 W per DOF, with a combined valve and actuator weight of 3.2 oz. Boadicea's pneumatic system as built can produce more than the 6 W required, although it is somewhat overweight. Each DOF has two valves that weigh 1.5 oz each. The actuators weigh between 1.4 and 2.0 oz, so the total weight per DOF is 4.5 to 5 oz. This factor is the reason why Boadicea is slightly overweight even without an on-board power source.

Comparison with other robots

Other robot studies have compared performance based on the energetic cost of motion, or specific resistance. A more practical measure of locomotion capability, however, is the mechanical work the robot is able to perform. Although it is exciting to build a machine that can navigate treacherous environments, the value of this exercise is created by a sensor package or other payload the robot takes with it. Payload capacity and top speed are important factors for evaluating the utility of legged vehicles.

Robot	Normalized work capability
Ambler	.0323
PV-II	.46
GE Quadruped	3.91
Genghis	4.27
ASV	5.04
Boadicea	10.12

Table 8.1: Normalized work capability of legged robots

The data in this table are the product of normalized speed (speed/length) and payload capacity (payload/mass) of the robots in Tables 1.1 and 1.2. Boadicea and PV-II do not carry on-board power supplies.

Chapter 1 lists the normalized speed (speed/length) and payload capacity (payload/weight) of previous walking robots. The product of these two numbers is a measure of mechanical work the robot can perform adjusted for size differences. Unfortunately, most researchers do not report payload capacity because that is not a goal of their research. **Table 8.1** lists the normalized work capabilities for the robots where this information is available. One caveat on this comparison is that Boadicea and PV-II do not have on-board power supplies. Carrying batteries, and an air tank in Boadicea's case, would lower their normalized payload capacity. Even with an on-board power source, though, Boadicea would still have a higher work capability than the other robots.The graph in **Figure 8.2** shows the different speed and payload capacities of these robots. The dashed lines are curves of constant work capability. Using this basis for comparison, a robot can trade payload capacity for speed and maintain the same level of performance. The optimum position on this curve for each machine depends on the specific task and environment. For example, a robot exploring Mars would benefit from increased payload size, while speed is less important. For terrestrial military operations, speed may be more critical.

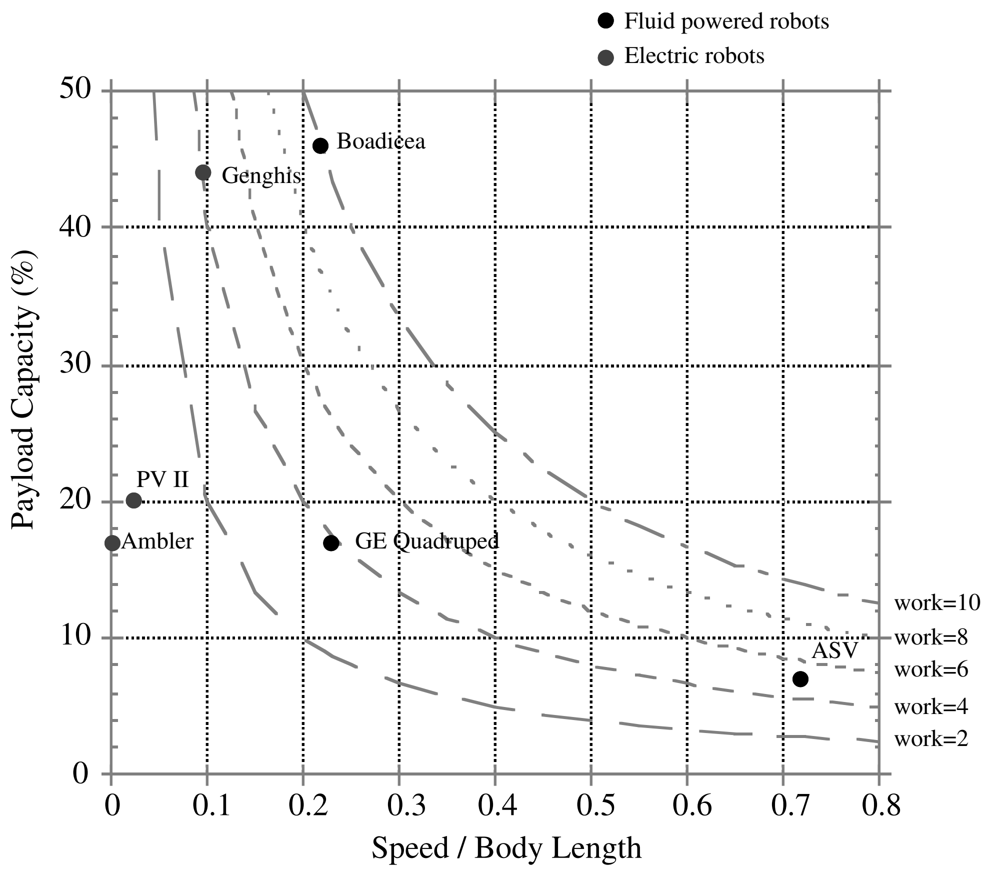


Figure 8.2: Payload and speed capabilities of legged robots

This graph shows normalized payload and speed capabilities of the robots where data was available. The product of these two numbers is a measure of the work the robot can perform. The dashed lines are lines of constant work. Boadicea has double the work capacity of the ASV.

These comparisons do not include the relative size of the robots. Although the ASV and Genghis have similar work capacities, Genghis' maximum payload is only .3% the ASV payload. The normalized work comparison indicates that a fleet of Genghis robots can do the same work as one ASV, but unless the cargo can be broken into .8 Kg packages this is not a feasible solution. In many situations, small robots can perform as well as larger ones **[Angle 91]**, but only if the payload can be subdivided or reproduced for each robot.

8.2. Walking

Boadicea's top speed is 4 in/sec, which is 67% of the design target. The limitation on the robot's speed is the performance of the servo controller. Mechanically, the robot is capable of higher speeds, but then the lack of leg coordination (caused by the servo controller) hinders locomotion. With step lengths longer than 3" or stride frequencies higher than .6 Hz, control instabilities destroy all semblance of coordination. Even within these values, Boadicea's feet often overshoot their goal positions and exhibit other erratic, transient behaviors. The robot can still walk, however, as long as the legs pause long enough after each movement to reach steady state. This process normally takes between .25 and .5 seconds.

Disabled legs

Insects are able to locomote effectively after suffering limb amputation **[Hughes 57] [Kram 94]**. Some cockroaches are even able to climb steps with shortened, or amputated, front legs **[Kram 94]**. I designed Boadicea with large, overlapping leg workspaces to provide similar capabilities. When one leg is damaged, an adjacent leg can reach far enough to take its place and support the body. This is the same strategy employed by insects **[Hughes 57]**.

I tested Boadicea walking with one and two front legs disabled. In both cases, the robot was able to maintain stability by altering the position of the middle legs. **Figure 8.3** illustrates this change. The robot used a wave gait for these experiments. Walking speed was unaffected by the limb loss; Boadicea maintained its normal wave gait speed of 2 in/sec.

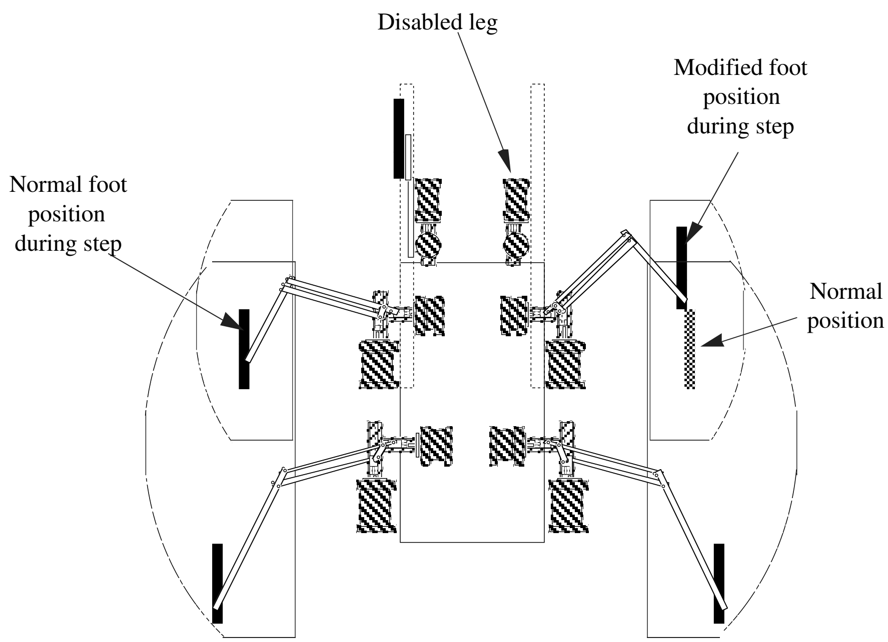


Figure 8.3: Effect of disabling a leg on foot position

When the right front leg is disabled, the right middle leg moves to support the front of the robot. This is the same type of behavior roaches use to maintain stability when legs are amputated **[Hughes 57]**. Boadicea is better equipped for this compensation because its legs have overlapping workspaces; most other legged robots do not.

8.3. Uneven terrain

The tests I have performed with Boadicea on uneven terrain demonstrate advantages of its design. Boadicea uses the same climbing strategy demonstrated by cockroaches **[Yamauchi 94]**. Boadicea can walk on moderate terrain with approximately 6" undulations with occasional missteps. The robot can climb over 4" obstacles, and can reach its front legs onto an 8" step. The actuation system is capable of more difficult terrain, but the robot's high center of gravity and limited vertical workspace restrict its mobility.

Moderate terrain

I performed some experiments with Boadicea walking on slightly rugged terrain in the Mobile Robotics Laboratory sandbox. The terrain for these tests consisted of loose gravel (approximately 1 in^3 rock size) with approximately 6" undulations. Boadicea was able to walk over this terrain somewhat successfully. The robot's progress was hampered because occasionally the feet would not touch the ground or clear an obstacle because the robot did not sense the terrain, or altering its gait to navigate over the obstacles. These missteps and blind scrambling were very similar to Genghis' climbing behavior.

These tests revealed a useful capability. Because Boadicea's front legs are designed to produce large decelerating forces, they often kicked most of the gravel out of the robot's path during the recovery phase. Obviously this strategy is not effective on large obstructions, but it does demonstrate a supplementary advantage to improving the robot's force production capabilities: an ability to modify the environment.

Two factors limited Boadicea's mobility in this environment. First, because the robot has low ground clearance, and a limited vertical workspace for the legs, the feet are not able to step very far down into a depression or hole. Second, Boadicea's small feet are not well suited to walking in loose gravel. Instead of getting good traction, the feet tend to slice through the gravel. For walking on this type of surface, larger feet would be more appropriate.

Climbing

Boadicea was designed with insect like legs to produce a robot with more practical kinematics. The cockroaches that were the inspiration for Boadicea's legs can climb over virtually any surface. I predicted that a robot with similar legs would also have good climbing abilities. Because Boadicea's high-level software is rather primitive, I performed climbing tests under manual control. The robot was executing the position servo loop, but I supplied goal positions for the legs manually.

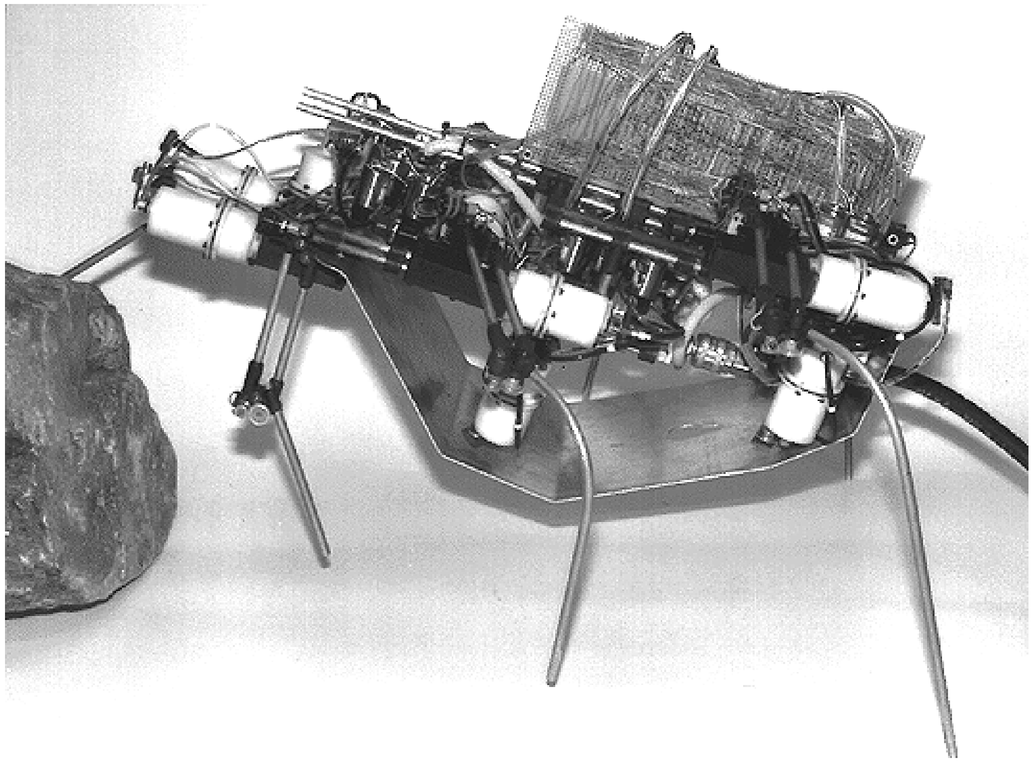


Figure 8.4: Photograph of Boadicea climbing onto a rock

The rear and middle legs support the body and lift the front legs until they can reach the top of the step.

Boadicea's climbing strategy

One measure of climbing ability is the size step the robot can surmount. Cockroaches climb by pitching their bodies up, then vaulting forward with their rear legs **[Yamauchi, et al 93].** To see if Boadicea could also employ this strategy, I tested its ability to execute a similar maneuver (see **Figure 8.5**). Using its middle and rear legs for support, Boadicea can raise its front end. Lifting the rear legs allows the robot to roll back on its belly because the center of gravity is aft of the middle legs. From this posture, Boadicea can use its rear legs to lift the front further. Once the body is pitched up sufficiently for the front legs to clear the step, the supporting legs must push the body forward, then lower the front end so the front legs rest on top of the obstacle.

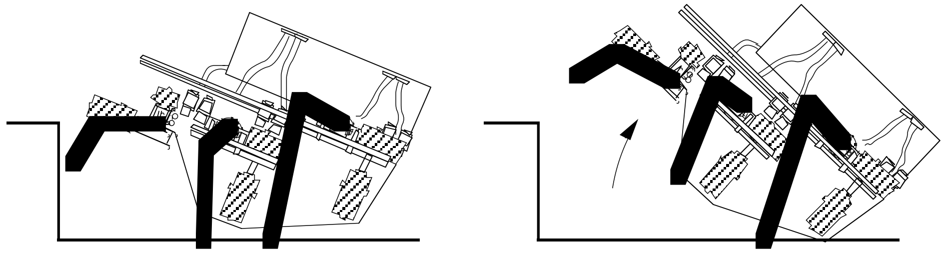


Figure 8.5: Boadicea lifting its front legs to climb a step

Boadicea can lift its front end slightly using the rear and middle legs for support (left). To climb large steps, the robot rests on the aft end of its belly, and uses the rear legs to produce the correct level of pitch.

Climbing test results

Boadicea has successfully surmounted four inch steps, as shown in **Figure 8.6**. With an eight inch step, Boadicea can lift its front legs high enough, and propel the body forward enough to get them on the upper surface. When it reaches the orientation shown in the right half of **Figure 8.6**, however, the robot is unable to proceed. In order to reach this position, both rear legs are at their aft-most position, so they are unable to propel the robot further, and the middle legs cannot reach the ground. Both rear legs are required to maintain static stability; the robot cannot lift either leg to take another step.

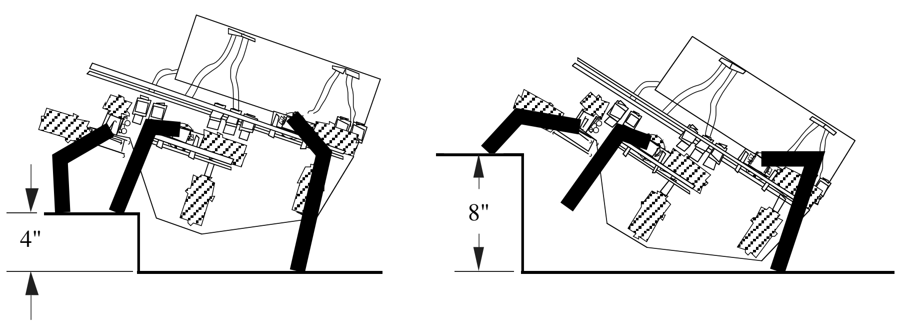


Figure 8.6: Boadicea's step climbing capability.

Boadicea can climb up a four inch step without much difficulty. The robot can get the front legs up onto an eight inch step, but is unable to proceed further. In this situation, the middle legs cannot reach the ground, and both rear legs are required to support the body.

Figure 8.7 illustrates another limitation of this climbing approach. Because Boadicea's center of gravity is high off the ground, at steep angles the rear feet are forward of the center of gravity. In this configuration, the robot is unable to propel itself forward without increasing the pitch angle.

With a strong push from the rear legs, Boadicea can roll onto its back, as shown on the right side of **Figure 8.7**. This ability is of dubious value, but it does demonstrate a range of motion and force capability much greater than other small walking robots. Genghis, Attila, and Hannibal do not have sufficient workspace or actuator torque for this type of maneuver.

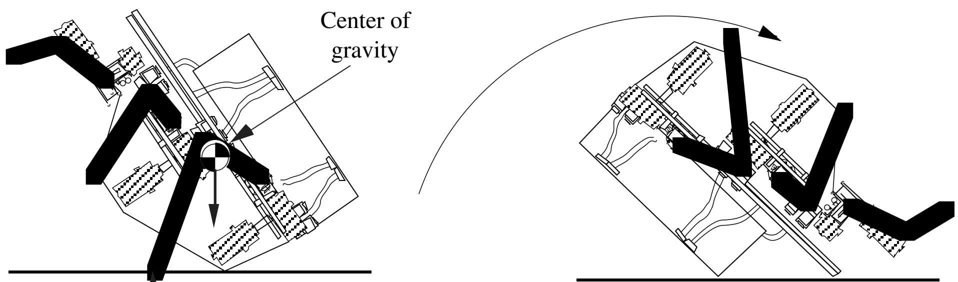


Figure 8.7: Boadicea rolling onto its back

For steep angles of ascent, Boadicea's rear legs will be forward of the center of gravity. In this configuration, the robot is unable to propel itself forward without increasing the angle of pitch. Boadicea can continue to pitch its body up until it passes vertical and rolls onto its back. Although this ability is not a useful, it does demonstrate a range of motion and force capability much greater than other small walking robots.

Boadicea can climb on slopes up to 20°. The biggest difficulty it has in this endeavor is generating sufficient traction. Smooth surfaces, or loose gravel, do not provide enough purchase to support the robot. On steeper slopes, the legs can provide enough force to propel the robot. Boadicea's center of gravity is too high for climbing at these angles, however. On steep slopes, the projection of the center of gravity will fall behind the polygon of support, and the robot topples over backwards. This limitation could be solved by using a fourth DOF on each leg like Attila **[Angle 91]** or by lowering the center of mass.

Boadicea's rough terrain and climbing capabilities could be greatly improved if the robot's body were not so tall (see Section 9.2). A lower center of gravity would allow walking and climbing at steeper angles. Increasing the vertical workspace of the feet would permit locomotion over larger obstacles, and would allow the robot to perform more elaborate contortions when climbing on rugged terrain.

8.4. Payload capacity

One of the primary goals of this project was to build a robot with substantial payload capacity. With a 4 lb payload, Boadicea can still walk at 4 in/sec on level terrain. With a 5 lb payload, 25% greater than the design target, the robot can still walk, although its belly does touch the ground frequently. For both of these tests, Boadicea was using the tripod gait.

9. Conclusions

Previous walking robots, especially small ones, have been limited by the capabilities of their mechanical systems. For example, Hannibal was programmed with a myriad of rough terrain and fault tolerant behaviors **[Ferrell 93]**. The robot's limited kinematics and actuators prevented full utilization of this programming. The Boadicea project was an attempt to develop a capable mechanical system. My goal was to build a robot where the mechanics were capable of performing any task the programming required.

Using this criterion, Boadicea was successful in most respects. The pneumatic actuation system and insect-like legs are capable of carrying more payload, walking faster, and traversing more rugged terrain than previous robots. Currently, the robot's mobility is limited by servo performance, a high center of gravity, and insufficient vertical workspace for the legs. With modifications to remedy these shortcomings, Boadicea's capabilities could be more fully demonstrated.

9.1. Boadicea's accomplishments

The premise for the Boadicea project was that existing legged robots, especially small ones, lack the mechanical performance necessary to meet their goals. Most walking robots were much slower than their wheeled or tracked counterparts. They also had limited payload capacity. Finally, the workspace and force capabilities of their legs were generally inadequate for traversing very rugged terrain.

Boadicea was built to address these shortcomings. Its performance offers improvements over the prior robots by combining pneumatic actuators, lightweight materials, and an insect-like design. These innovations provide higher force and power density, which allows the robot to walk faster and carry larger payloads. Boadicea can also climb on more difficult terrain than previous small walkers.

Pneumatic actuators

Pneumatic actuators offer several advantages for mobile robots, most importantly a higher force density. Actuator force, or torque, density determines a robot's ability to support its weight. Electric motors cannot produce an acceptable torque density because of gearbox limitations. Pneumatic actuators can weigh much less than gearmotors with comparable power and speed specifications.

Table 9.1 compares the performance and weight of Boadicea's pneumatic actuators to a similarly sized DC gearmotor. The DC Gearmotor listed is a MicroMo 2842 motor with a 34G gearbox (90:1 ratio) **[MicroMo 93]**. The weight of the pneumatic system includes the valves and actuator; the gearmotor weight includes both motor and gearbox. The performance numbers for Boadicea's pneumatic actuators are measured values; numbers for the DC motor are based on manufacturer specifications. For the electric motor, foot force and speed calculations assume a 6" moment arm from the motor to the foot; this is the length of Boadicea's legs. The performance of the pneumatic system is clearly superior, especially the force density which is 20 times greater than for the motor.

	Pneumatic	**DC gearmotor**
weight (oz)	5	15
Max. power output (W)	7.6	4.2
Force at foot (lbf)	15	2.2
Max. speed at foot (in/sec)	35	16

Table 9.1: Comparison of pneumatic and electric actuators

The weight of the pneumatic system includes the valves and actuator; the gearmotor includes the motor and gearbox. Foot force and speed calculations assume a 6" moment arm from the actuator. The DC Gearmotor listed is a MicroMo 2842 motor with a 34G gearbox (90:1 ratio). The performance of the pneumatic system is clearly superior, especially the force density.

In addition to their excellent mechanical performance, pneumatic systems make it easier to implement force and impedance based control. Advanced composite pressure vessels can store energy as compressed air with approximately the same energy density as batteries. Therefore, self-contained pneumatic and electrically powered robots would have similar operating lifetimes. Finally, the compressibility of pneumatic actuators can be used to store elastic energy to improve walking efficiency **[Alexander 90]**.

Lightweight materials

Besides pneumatic actuators, Boadicea's power to weight ratio is improved by lightweight materials. Almost all structural parts on the robot are glass or carbon fiber reinforced composites. Boadicea's body is a lightweight frame of carbon fiber and aluminum tubes joined by molded plastic parts. This structure provides a stiffness to weight ratio greater than metallic construction.

Plastic components also allow easier mass production by injection molding. The time saved in manufacturing allows a robot designer to build more frequent prototypes. Also, once a basic set of parts and components has been developed, it is easy to build machines with new configurations. Boadicea's body, for example, has only six different types of parts and one tubing size. Manufacturing and assembly for the entire structure took only a few days to complete.

Insect-like design

Boadicea has demonstrated several benefits to its insect-based design. First, the large, overlapping leg workspaces allow stable locomotion when one or more legs are inoperative. Boadicea can walk with one leg disabled without changing its wave gait speed.

Boadicea's climbing abilities are also enhanced by insect inspirations. The large workspace for the legs, and their orientation allow it to climb larger obstacles than previous walking robots. Boadicea can climb up a 4" step without much difficulty, and can reach onto an 8" step with its front legs. For comparison, Genghis could climb 2" steps. Hannibal could also climb up a 2" step, and could reach up to a 5" step **[Ferrell 93]**.

9.2. Did Boadicea meet its goals?

The primary goal of the Boadicea project was to build a legged robot that is faster and can carry more payload than previous robots. The comparisons in **Table 8.1** and **Figure 8.2** show that this goal was achieved. Boadicea has the largest mass-specific payload capacity of any of the robots, and it is also one of the fastest. The amount of mechanical work the robot can perform is double that of its closest competitor, the ASV.

The most serious limitations of Boadicea's performance are the servo controller and the low reliability of the pressure sensors. These area were not the emphasis of this project, however. Future work on legged robots will address these problems.

Speed

With no load, Boadicea's feet move at maximum speeds of 35 in/sec and 14 in/sec for propulsion and recovery strokes, respectively. I designed Boadicea's legs for a 6" nominal step length and a stride frequency of .5 Hz. With these parameters, the feet must move (relative to the body) at 6 in/sec on both the recovery and propulsion strokes. Boadicea's mechanical system is clearly capable of meeting these requirements. The servo performance, however, is not.

Sensor and servo system limitations determined the maximum speed for Boadicea. Control instability limited step length and stride rate to less than their nominal values. As a result, Boadicea's top speed was 4 in/sec. Although less than the 6 in/sec design target, this speed is a marked improvement over other small walkers; Boadicea is 3 times faster than Genghis and nearly 4 times faster than Attila. Experiments with Boadicea demonstrate the performance advantages of pneumatic actuators for locomotion. Future robots will indubitably solve the problems I encountered and will walk faster.

Force

Boadicea cannot climb slopes steeper than approximately 20° because the center of gravity is too high; on steep slopes, the robot cannot maintain static stability. The actuation system and leg mechanism is capable of producing sufficient force for the climbing goals in **Table 1.5**. To meet these goals, the legs propelling the robot must produce 3.5 lb in the direction of motion. Boadicea's legs can propel the robot with 4.5 lb each, enough to climb a 64° slope. Although the robot's climbing abilities are limited, the actuation system is not the culprit.

Performance targets

	Design goal	Actual Result
Robot weight	10 lbs	10.5 lb
Maximum payload	4 lbs	5 lbs
Normal walking speed	6 in/sec	4 in/sec
Wave gait speed	3.6 in/sec	2 in/sec
Maximum joint torque	42 in-lb	90 in-lb
Maximum actuator power	6 W	7.5 W
climb a 45° slope with the tripod gait		*
climb a 45 ° slope with payload with the wave gait		*

Table 9.2: Design targets and actual performance

* Boadicea's actuators and leg mechanism can produce enough force for these goals. Because of the robot's high center of gravity, however, it falls over backwards on slopes steeper than 20°.

Table 9.2 summarizes the performance targets listed in **Table 1.5** and the actual capabilities I measured. In terms of these measurements, Boadicea is a successful robot. Although the robot is slightly overweight, the force and power capabilities of the actuators are sufficient to support the extra mass. The only area where Boadicea's performance did not meet design goals was walking speed. Although the actuation system is fast enough to meet these criteria, the relatively poor performance of the servo system limited step length and stride frequency.

Servo system

The major limitation on Boadicea's performance is the accuracy of the servo system. The front legs especially make occasional missteps, hindering forward progress. With a more robust and well behaved control system, Boadicea would be able to take larger strides, increasing locomotion speed. The finer details of the sensory, electronic, and servo system, however, are beyond the scope of this project. The servo performance, while less than ideal, was sufficient to demonstrate the capabilities of Boadicea's pneumatic actuation system, lightweight construction, and insect-like design.

Reliability

Another goal I had for Boadicea was to build a robot that was more reliable than Attila and Hannibal, the previous walking robots our lab constructed. Although Boadicea does have some parts which are somewhat failure-prone, the robot did meet my reliability goal; Attila and Hannibal had a sensor, motor, or other failure approximately once per week **[Ferrell 93]**. With the exception of the pressure sensors, Boadicea experiences a component failure approximately once per month. There have been only a handful of failure modes, however, so a small redesign effort could probably solve most of the problems.

9.3. Future work

There is much work that can still be done with legged robots. This project has demonstrated the benefits of fluid power systems for smaller robots. Despite the apparent complexity and controllability problems with pneumatic actuators, the force and energy densities available make them a good choice for small mobile robots.

Improving Boadicea

Boadicea is definitely a prototype robot. The experiments I performed with the robot have indicated several aspects of the design that can be improved.

Performance

Boadicea's gait is dynamic, although the dynamics are unmodeled, unmeasured, and uncontrolled. With more elaborate sensors and better control software, the robot could probably be programmed to run dynamically, greatly increasing its top speed.

Leg design

Boadicea has different front, middle, and rear legs. I predicted that the robot's performance could be improved if each leg were optimized for different tasks. Although the preliminary results of Boadicea's locomotion experiments are encouraging, the robot has not demonstrated capabilities that can be directly attributed to specialized leg designs. Part of the reason for this lack of evidence may be that the legs are not specialized enough.

The saggital orientation of the front legs does seem to be a good idea. This arrangement makes the front of the robot more compact, which could be useful for exploring narrow passages or caves. Having the front legs produce decelerating forces allows the robot to kick small obstacles out of the way; this ability could also be useful in an outdoor environment.

Boadicea's middle and rear legs, however, are not specialized enough for the roles they play in climbing. The middle legs should be modified so they have a larger vertical workspace. In particular, they need to reach lower down to touch the ground when the robot is climbing a step. The rear legs should be able to reach further aft, and also produce more force than they currently can to improve the robot's step and slope climbing abilities.

Reliability

Extensive testing has revealed a few parts on Boadicea which are structurally inadequate for the loads they experience. Some minor redesign to strengthen these parts would be the first way to improve the robot's reliability. The one reliability problem that has been especially frustrating is the pressure sensor failures. The fragility of these sensors prohibits Boadicea from operating in a force-based control mode, although the robot is still able to function. In all, Boadicea has demonstrated better reliability than the previous walking robots at the Mobot Lab, Attila and Hannibal.

On-board power

If a robot like Boadicea is going to operate outside a laboratory environment, its usefulness would be greatly enhanced by making the robot self-contained. Currently, Boadicea operates autonomously; all of the software required for locomotion runs on the 68332 microprocessor. Umbilicals supply the robot with compressed air and electrical power. These power sources could easily be placed on the robot, however.

Because Boadicea requires electrical power only for electronics and the valves, the power requirement is relatively small. A 9 oz rechargeable NiCd battery could power the robot for an hour or two. Mechanical power for locomotion is supplied as compressed air at 100 psi to the robot. A composite pressure vessel could store air at a much higher pressure and supply the 100 psi through a regulator. The calculations in Chapter 2 indicate that a 1 or 2 lb tank could power the robot for up to one hour. Boadicea's payload capacity is 5 lb. Even carrying its own power supplies, the robot would still be able to carry an additional 2 or 3 lb payload.

Ground clearance

Figure 9.1 shows a side-view of Boadicea. The robot is much taller than I had originally envisioned, mostly because of the middle leg lift actuators and the vertical mounting of the circuit board. The circuit board is not a serious problem; because it is light, it does not raise the center of gravity much. When the robot rolls over, however, it is more susceptible to damage.

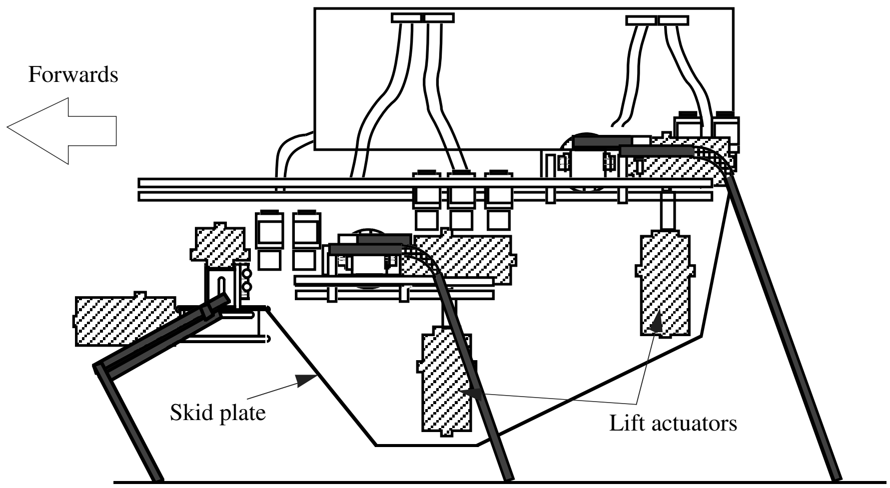


Figure 9.1: Side view of Boadicea

The robot is much taller than I had originally planned. The two main culprits are the middle leg lift actuators and the vertical mounting of the circuit board. The lift actuators reduces the robot's ground clearance, which limits rough terrain mobility.

The lift actuators are a more serious handicap. They reduce the robot's ground clearance, which makes rough terrain locomotion more difficult. Not only will the robot have to climb over small obstacles, it is unable to lower itself to step off a ledge, or into a hole.

Figure 9.2 shows how repositioning these actuators would improve ground clearance. This option was not feasible with the actuators I built for Boadicea, however. With the lift actuator mounted above the leg pantograph, the piston extends to support the body. Because I used the rolling diaphragm seals and a differential jack arrangement, my actuators produce large forces only during retraction. To build a similar actuator with a strong extension movement would require modifying the actuator design to reverse the diaphragm and including a spring. I did not feel this was a practical challenge to undertake given the limited time available, and the late stage in the project when this problem became apparent.

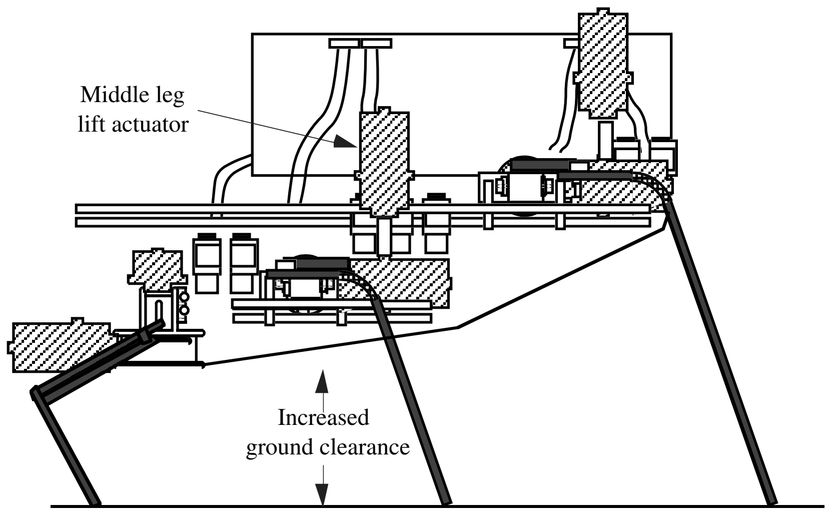


Figure 9.2: Moving the leg lift actuators

If these actuators could be mounted above the pantograph mechanism, the robot would have much greater ground clearance. The actuators I used on Boadicea, however, are unsuitable for this mounting arrangement.

Moving the lift actuators offers additional possibilities, primarily the option of lowering the robot's center of gravity. This change would improve the robot's rough terrain stability because it could maintain static stability on steeper slopes. Also, the circuit board could be redesigned to fit in the interior of the body, instead of riding on top like it does now. **Figure 9.3** shows one idea of how these modifications could be made to Boadicea.

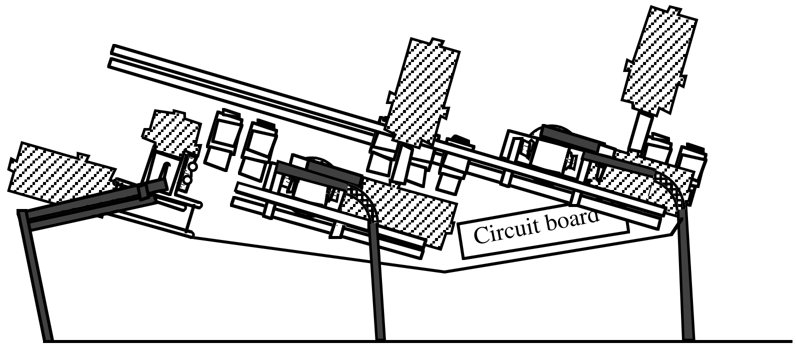


Figure 9.3: Lowering Boadicea's center of gravity.

Moving the lift actuators and circuit board would provide a lower center of gravity, which would improve the robot's slope climbing ability.

Sensors and software

There are many improvements that could be made to Boadicea's sensor system which would improve servo system performance. A more exacting design for the electronics would reduce noise in the sensor signals. Using linear potentiometers could also provide more accurate position sensing, although there are size and reliability problems with these sensors (see Section 6.3). Third, reliable pressure sensors would allow force based control, which was my original intent. All of these improvements would provide more accurate and reliable inputs to the servo controller.

The servo system could also be improved with a more elaborate control law. The feed forward term I used was simple, and did not include the nonlinear dynamics of the actuators. Nonetheless, it did provide much better response. Including feed forward terms which do account for system nonlinearities would likely have a similar beneficial effect.

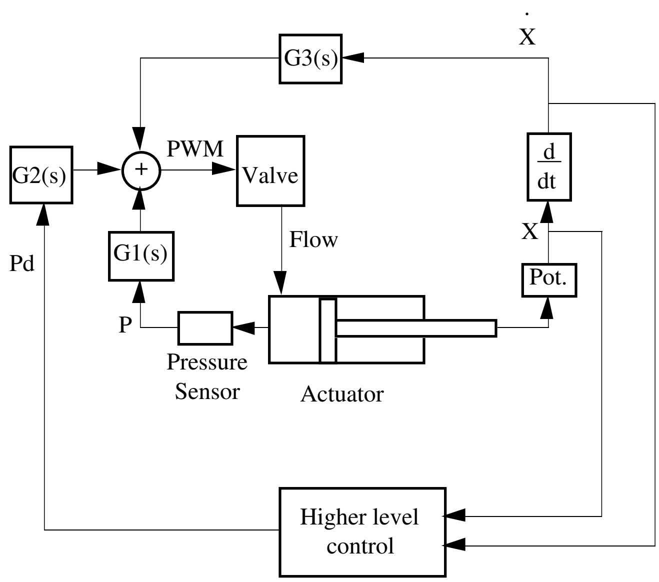


Figure 9.4: A more sophisticated controller for Boadicea

This system uses pressure-based control as an inner control loop. The two feed forward terms, The two feed forward terms, G2(s) and G3(s), anticipate the flow required by changes in V and P, respectively. The higher level control provides a position-based outer control loop.

Figure 9.4 illustrates a controller design we considered, but were unable to implement because of sensor limitations. This system provides force control based on pressure measurements and an outer, position based control loop. In addition to pressure feedback, $G_1(s)$, a feed forward term, $G_2(s)$, compensates for the flow required by actuator motion. A second feed forward term, $G_3(s)$, adjusts the PWM signal for changes in the desired pressure without waiting for an error to accrue and propagate through the feedback controller. This controller design agrees well with the equation that describes actuator dynamics:

$$\frac{\dot{m}}{m} = \frac{\dot{P}}{P} + \frac{\dot{V}}{V}$$

The two feed forward terms, $G_2(s)$ and $G_3(s)$, anticipate the flow required by $\dot{V}$ and $\dot{P}$, respectively. The transfer functions for these terms would include the appropriate compensation for P, V, and m. The feedback control law, $G_1(s)$, compensates for errors in the feed forward model and external disturbances. Unfortunately, on

Boadicea, the position measurements were too noisy to provide a meaningful velocity measurement and the pressure sensors were unreliable.

Future legged robots

For legged robots to provide better mobility than wheeled or tracked vehicles, more emphasis must be placed on their mechanical design. Many legged robots have been built with simple mechanical systems to demonstrate software and control innovations. These robots tend to have limited mechanical capabilities. In the future, however, more capable mechanical designs will be created.

Fluid power

Boadicea has indicated the performance advantages pneumatic actuators provide for small legged robots. The force, power, and energy density possible with fluid power are worth the added complexity and unfamiliarity. Furthermore, compressibility may not be as serious a liability as many robot designers have considered it. Future legged robots should use fluid power actuators to improve their mobility.

Future legged robots should also make use of force and impedance control modes. These control modes could simplify controlling body velocity and orientation; forces exerted by the legs directly determine body motion. Practical dynamic locomotion strategies will likely require force or impedance control. Although Boadicea was unable to explore these possibilities, its pneumatic actuation system would make them easier to implement compared to an electric system.

New assumptions

Insects and other multi-legged animals do not operate under the assumptions normally made by robot designers. These assumptions include maintaining static stability, moving the body horizontally at constant velocity, and making each leg identical. Studies of animal locomotion reveal advantages that can be achieved by dispensing with these constraints **[Full, et al 89]**. Boadicea demonstrates some of these improvements.

The data listed in **Table 1.3**, and results from studies of insect locomotion **[Full and Tu 91]** illustrate the speed advantages of dynamic locomotion. Energy efficiency can also be improved with dynamic gaits; storing energy as gravitational or elastic potential energy allows it to be recovered on the next stride **[Cavagna, et al 77]**.

For these reasons, future robots should exploit dynamic stability as much as possible. Generating dynamic motion in a small robot like Boadicea would require more detailed modeling of leg, body, and actuator dynamics. Higher performance sensors would also be required. Results from dynamic robot experiments to date have been encouraging. Future legged robots should continue in this direction.

Like an insect, Boadicea does not have six identical legs. I attempted to incorporate some of the optimizations found on insect legs to improve the robots capabilities. Boadicea's leg designs offer some mobility advantages, although not as significantly as I expected. Climbing experiments with the robot indicate that the rear and middle legs are not specialized enough. The middle legs need to lift the body more, and the rear legs should provide more propulsion.

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