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Biomimetic Small Walking Machine

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I. Abstract

The goal is to design and construct a biologically inspired, small, robust, and fast walking machine. This paper explains how two important observations from cockroaches can be employed as design guidelines to design and build small walking machines.

The first observation is the fact that cockroaches use very little feedback and control results from the properties of their parts and their morphological arrangement. This observation leads to our hypothesis that a robust and simple electromechanical walking machine should have implicit feedback control only within its hardware. The second observation is that the optimal walking frequency of a cockroach is close to the natural frequency of the cockroach. This observation leads us to hypothesize that the walking frequency of an electromechanical cockroach also needs to be the natural frequency of the machine. These two design guidelines do not dictate any architecture for an electromechanical cockroach. An architecture that involves the mimicking of the trajectory of a cockroach's footpath was arrived at later in the design process. Two small 4-legged walking machines (HEL-Roach I and II) are built to verify the hypotheses. The first machine (3" x 5.25") weighs 0.7-lbs. and can travel with a speed of 3" per second. The second machine (2" x 1") weighs 0.17-lbs and its speed is 5" per second.

II. Introduction

The walking mechanism of insects is very simple. The following passages containing information about the findings on the walking of insects are directly quoted from MURI's abstract [2]. "Dr. Bob Full's PolyPEDAL Lab [3] has shown that a substantial portion of locomotor control can reside in the mechanical design of the system and be simple. The control algorithms are embedded in the form of the animal itself [2][3]." "Control results from the properties of the parts and their morphological arrangement. ... And legs do much of the computations on their own by using segment mass, length, inertia, elasticity, and damping as "primitives" [2][3]." "There is no precise foot placement, no follow the leader gait, and a leg does not have time to react to tactile sensory feedback within a step. Position control using reflexes is improbably if not impossible [2][3]." "During climbing, turning, and maneuvering over irregular terrain, animals use virtually the same gait as in horizontal locomotion – an alternating tripod [2][3]." "The mechanical system – the morphology – can determine the extent of self-stabilization. In other words, there is no explicit feedback control of global variables such as hopping height, posture, or speed. The only control is local, at the joints [2][3]." These findings suggest that

- The dynamics of walking is determined by the hardware and no other feedback control is needed to alter the dynamics.
- The system performance is solely a function of physical properties.
- No sensors are needed and the control should be open loop.
- One degree of freedom actuation is sufficient for walking.
- The control space (i.e. trajectory) is limited.

These findings say that insects have highly sophisticated hardware that can be operated by non-intelligent users. In the same way, the new walking machine needs to embed clever hardware and avoid intelligence so that the walking machine can be simple, small, and fast.

III. Footpath and Leg Coordination

3.1 Footpath

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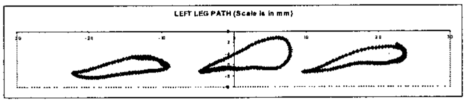


Figure 3.1 Typical left footpath of a cockroach.

Figure 3.1 shows a typical footpath of a cockroach moving forward and to the right of this page (i.e. the right-most path is the path of front leg). This footpath traces out the movement of the tips of the left feet with respect to the center of mass, located at the point (0,0). The flat line on the bottom demonstrates the smooth motion of the center of mass while the legs on the ground push the body forward. This plot is taken from 3D kinematics of cockroaches given by Full [4]. In fact, this path is a desired path according to our specific requirements and preferences of effective footpath stated as follows:

- The starting point and the ending point have to be very close to each other so that every revolution of the footpath is repeated in the same place with respect to the center of mass. In this way, one degree of freedom is guaranteed.
- It has to be tall for high clearance.
- It has to be long for faster walking.
- Bottom of the gait is flat so that the center of mass moves smoothly while the body is being pushed.
- It must contain very few unnecessary motion to be energy efficient.

Considering these specifications, the cockroach footpath in Figure 3.1 seems to have a suitable shape. The HEL-Roach series use gaits similar to this cockroach footpath. (See figures 4.2 and 4.3)

3.2 Alternating Gait

All insects have 6 legs and most of them use those legs to achieve tripod stability during walking. Cockroaches (Figure 3.2) move three legs that are pointed with arrows simultaneously, while keeping the other three on ground. As soon as one group of legs touches the ground, the other group of legs is lifted. In this way, cockroaches manage to keep at least 3 legs on ground at once, maintaining their static stability.

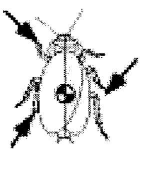


Figure 3.2 Cockroach walking using alternating gait.

3.3 Modified (4-legged) Alternating Gait

When cockroaches walk at moderate speed, they use alternating gait. However, when they walk very fast, they do not need this static stability to avoid falling, as long as they keep the dynamic stability. Another effect of high speed walking is that the speed of the cockroach is impeded because too many legs need to be synchronized. In fact, when cockroaches run very fast, they use only 4 legs and leave the front 2 legs up in the air [4]. They still use alternating gait, alternating 2 sets of 2 legs instead of 3. Thus, 4-legged walking machine was designed so as to make the machine much smaller, faster, and simpler in design.

IV. Leg Mechanisms

4.1 Four-bar Linkage

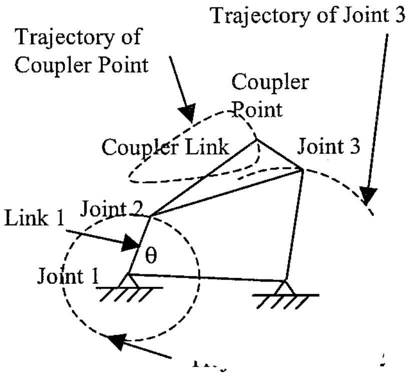


Figure 4.1 Four-bar linkage and its terminology.

The four-bar linkage (Figure 4.1) is a classic mechanism that involves 4 links connected by pin joints creating a trajectory when the input link (Link 1) is turned about Joint 1. Joints 1 through 4 are pin joints and the coupler point (tip of triangle) is a point attached to the coupler link. The main idea is that as the input link simply turns, the coupler point traces out a trajectory. The trajectory is solely determined by lengths of the 4 bars. Therefore, by using the correct link lengths, a footpath-like trajectory can be created by the coupler point. This mechanism is a single degree of freedom system because the input to

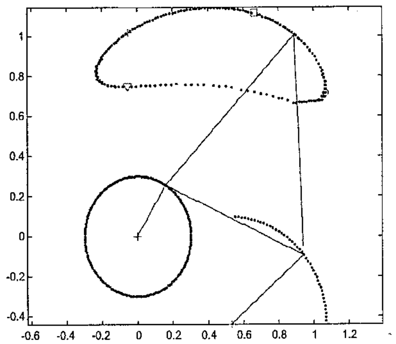


Figure 4.2 MATLAB Simulation of HEL-Roach I Footpath

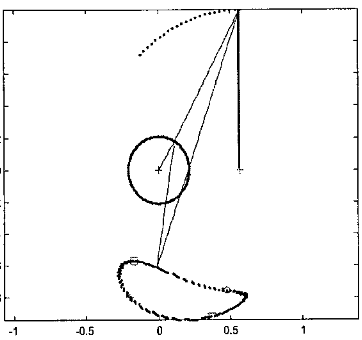


Figure 4.3 MATLAB Simulation of HEL-Roach II Footpath

the mechanism is a simple turning link; such motion can easily be created using one motor. Thus, with the use of this mechanism, only one actuator is needed to generate a footpath. Figures 4.2 and 4.3 show MATLAB simulations of the footpaths used for HEL-Roach I and II.

V. Frequency Matching

5.1 Frequency Matching

The mechanism of jumping can be modeled as a spring-mass system as shown in Figure 5.1. The oscillating mass, m, represents the bouncing body.

The equation of motion of this oscillator is

$$\ddot{x} + \frac{K}{m}x = g$$

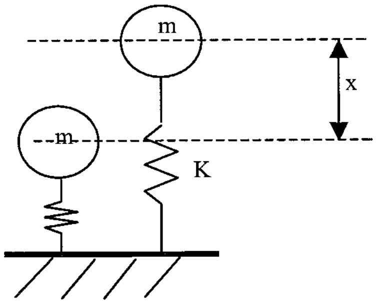


Figure 5.1 Spring Mass System – Jumping Model

where K is stiffness constant of the spring, m is mass of the body, g is the gravitational constant, and x is the displacement of the mass.
And the natural frequency is

$$\omega_n = \sqrt{\frac{K}{m}}$$

During running action, the body undergoes a vertical motion as well as a translation in space. The translation, modeled here as a pendulum-like oscillation, can be combined with the jumping model to form the model of running. The compliant inverted pendulum model is shown in Figure 5.2.

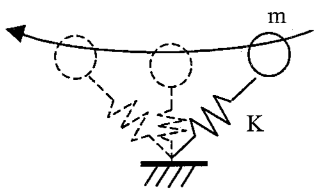


Figure 5.2 Compliant Inverted Pendulum – Running Model

The inverted pendulum model shown in Figure 5.2 is the model for a running insect proposed by Full [3]. The spring contracts when the mass is in the middle of the pendulum creating a smooth motion for the center of mass. While the leg moves from right to left, the spring goes through one cycle and the pendulum completes half a cycle. This shows that the frequency of the contracting spring is twice as much as the frequency of the swinging pendulum. If these two frequencies are not coordinated, it seems to cause interference and impedance in their motion.

The study shows that the cockroach's running frequency matches almost exactly with the natural frequency of their compliant legs [5]. The experiment shows that impedance of cockroach leg decreases significantly when it is excited at its walking frequency [3]. Therefore, the walking frequency must be near their natural frequency.

Above observation suggests that the walking machine should also walk at the machine's natural frequency. To implement this idea, several compliant legs will first be created and their stiffness constants will be measured. The natural frequency of the system can then be easily determined from the stiffness constant. Then, based on the frequency, the desired motor and its speed reducers will be chosen.

5.2 Efficiency

By matching the natural frequency and walking frequency of the walking machine, the efficiency (power in to power out ratio) should increase. To test out this hypothesis, the power out to power in ratio is recorded for different walking frequencies. The efficiency is

$$\eta = \frac{P_{out}}{P_{in}} = \frac{Fv}{VI}$$

where F is the force out, v is velocity of the machine, V is input voltage, and I is input current. Assuming F is constant, the efficiency is proportional to

$$\eta \alpha \frac{v}{VI}$$

The calculated v/VI value will be graphed against voltage so that most energy efficient voltage and speed can be identified. The results will be given in Chapter 7.

5.3 Measuring Compliance

5.3.1 Experimental Measurement by Applying Force

The stiffness constant, K, for HEL-Roach II can be measured in the following manner. Consider the following expression,

$$F = m\ddot{x} + c\dot{x} + kx$$

F is the applied force, m is the mass, c is the damping constant, and x is the displacement of the system. The stiffness constant, K, of the system can be measured in the following manner.

Step1: To simplify the equation, let x be constant in time so that the equation is F=Kx. This assumption is true if the value of F was measured while x does not vary with time.

Step2: For several values of F, measure x.

Step3: Plot the measurements and find the slope, K.

To actually measure K of Springy Legs, first all 4 Springy Legs were attached to the body. Knowing the mass of the body, the first measurement is taken by measuring the deflection of legs. Then, the known mass is added to take another measurement. This process is repeated several times to obtain the average K. Since the 4 legs are attached to the body in parallel, the measured slope is 4K. So the value needs to be divided by 4 to obtain K for a single leg.

5.3.2 Experimental Measurement by Excitation

The alternative to the above method is to measure the compliance by exciting the body. The body of the machine is to be excited by an external vibration with a certain frequency while it stands on 3 legs. By varying the frequency of vibration and seeing the reaction, the natural frequency of 3 legs can be identified when the body starts vibrating at the same frequency. From this experiment, the natural frequency of a single leg can be determined by,

$$f_{2legs} = \sqrt{\frac{1}{3}} f_{3legs}$$

VI. Design and Construction

6.1 Leg Design

The 3D model of a leg that is used for HEL-Roach I is shown in Figure 6.1.

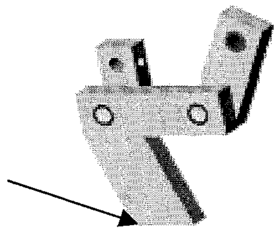
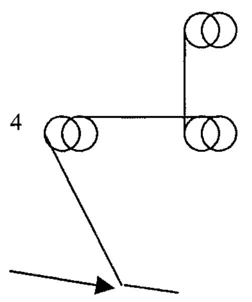


Figure 6.1 Solid leg constructed using aluminum, bushing, and shafts.

Each link is made out of a machined aluminum block. The joint is made using plastic bushings, a shaft, and retaining rings that keep the shafts in place. The input link is coupled to the shaft (not shown) using set screws, so that the motor is able to transfer torque to the legs. The input link rotates about hole #1. An arrow is used to indicate the coupler point (in Figure 6.1), where the footpath is generated.

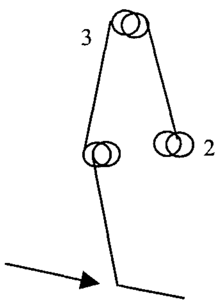
6.2 Springy Leg Construction



In HEL-Roach I, the mechanism shown in Figure 6.1 is directly coupled with the motor via the input shaft. Such a mechanism creates a firm system that contains no compliance. To provide some compliance in vertical direction, a set of "Springy Legs" is introduced. Springy Legs consist of a collection of torsion springs made out of one long piece of music wire. Figure 6.2 shows the model of a Springy Leg.

Note that the hole numbers correspond to the hole numbers in the original leg. Also note that the input link will still be made out of an aluminum block (not shown). The arrow shown in Figure 6.2, again, indicates the coupler point location. With the use of these Springy Legs, the bulky joints can now be removed all together and thus, further simplifying the design.

Since a torsion spring is used instead of a smooth bearing joint, the motor needs to provide extra torque to turn legs. To compensate for the large k value at hole number 3, the lengths of link 2 and 3 are increased so that the force required to oscillate the spring decreases. For



these two links to avoid touching the ground, they are inverted and extended upward instead of downward. Refer to Figure 4.3 for the modified four-bar linkage simulation. The final Springy Leg design for HEL-Roach II is shown in Figure 6.3.

The stiffness constant of a Springy Leg, K, is measured to be 379.8 N/m. Assuming that two legs are on the ground at a single instance, the natural frequency of the legs is as follows.

$$\frac{1}{2\pi}\sqrt{\frac{2k}{m}} = 7.17Hz$$

Also, by exciting the body by hand, the body seems to resonate at around 5Hz.

6.3 Body Design

Once legs with the desired footpath are successfully designed, they need to be coupled with the desired coordination discussed in chapter 3. Such coupling is done so that nothing more than one motor, 2 shafts, and a shaft coupler (either a gear train or a timing-belt) are used to provide the translation of torque in the system. Figure 6.4 shows the chassis and body design for HEL-Roach I.

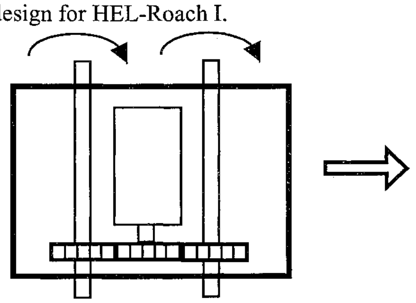
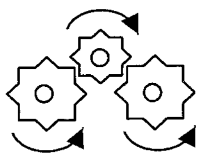


Figure 6.4 Power Terrain of HEL-Roach I

The input gear attached to the motor is placed in between 2 gears attached to shafts, turning both of them in the same direction (see Figure 6.5). This coordination allows the motor to turn both shafts in the same direction at the same speed.



For HEL-Roach II, the motor is coupled to a worm gear pair that is used to drive the front shaft. This worm gear pair is used so that the motor could be mounded parallel to the walking direction. This way, HEL-Roach II becomes significantly narrower than HEL-Roach I whose motor is mounted in sideways (see Figure 6.4). The front and back shafts for HEL-Roach II are coupled using timing belt and pulleys.

Going back to Figure 6.4, if the input links are attached to both ends of the 2 shafts, the 4 input links can be rotated at the same speed. The side view of the 4-legged machine's body is given in Figure 6.6.

6.3 Motor and Transmission Selection

	Required Torque
HEL-Roach I	26.3 oz-in
HEL-Roach II	3.9 oz-in

Table 6.1 Calculated required torque.

	Resistance (Ω)	Kb (mV/rpm)	Kt (oz-in/A)	V
I	8.71	1.52	2.05	12 V
II	47	0.346	0.467	12 V

Table 6.2 Motor characteristics of HEL-Roach I and II motors.

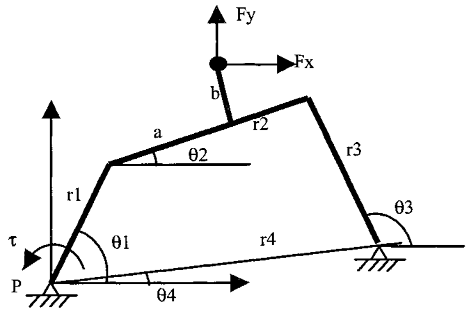


Figure 6.7 Four-bar linkage torque calculation

To choose the motor and transmission pair, the required torque needs to be calculated. Figure 6.7 is a four-bar linkage labeled for torque calculations. Torque at the input link (point P) due to forces at the tips of the feet is determined by the following equation [6].

$$\tau = r_1(F_x \sin\theta_1 - F_y \cos\theta) + [(F_x a + F_y b)\sin\theta_2 + (F_x b - F_y a)\cos\theta_2]\,\frac{r_1 \sin(\theta_3 - \theta_1)}{r_2 \sin(\theta_2 - \theta_3)}$$

where Fx and Fy are horizontal and vertical forces applied at the tracer point. The above equation gives the torque at one particular angle of the input link given Fx and Fy. In order to

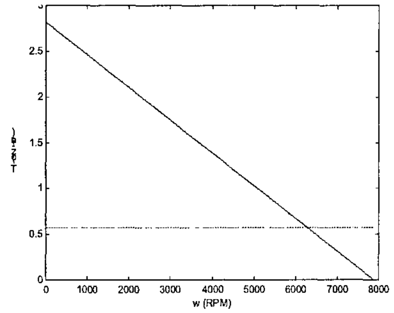


Figure 6.8 HEL-Roach I Motor Performance Line

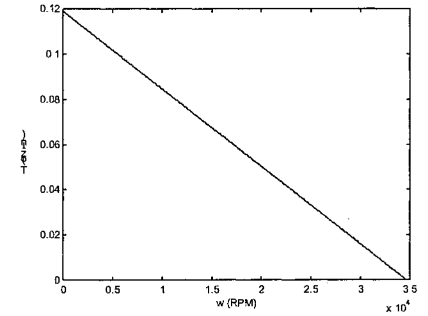


Figure 6.9 HEL-Roach II Motor Performance Line

find the maximum torque needed, this equation

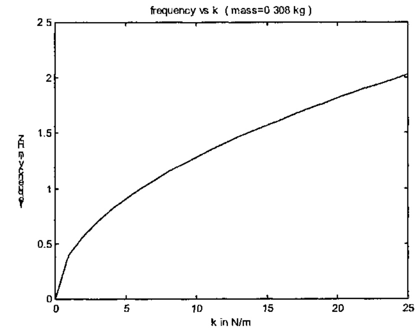


Figure 6.10 Relationship between frequency and stiffness of a leg

has to be solved for {θ2: 0<= θ2 <= 2π}. Among the torque calculated, the largest value is considered to be the required torque at the shaft. The calculated required torque values for the HEL-Roach series are tabulated in Table 6.1 and 7.1. For HEL-Roach II, an additional 2.4 oz-in is added to the calculated value due to the pre-load of timing belt.

Once the required torque is calculated, a motor and a speed reducer are chosen accordingly.

The winding line of the motor is plotted using the following equation,

$$\tau = -\frac{KbKt}{R}\omega + \frac{Kt}{R}V$$

where Kb is back EMF constant, Kt is torque constants, R is resistance of the armature, and V is the voltage applied. Motor constants for HEL-Roach I and II motors are tabulated and their performance curves are plotted.

To check if some motor is suitable, the calculated required torque in Table 6.1 and desired output speed are used. These values correspond to the values after applying the transmission and therefore, they need to be converted to the values before the transmission. The conversion is done in the following manner.

$$\omega_{beforetransmission} = \omega_{aftertransmission} * GearRatio$$

$$\tau_{beforetransmission} = \tau_{aftertransmission} / GearRatio$$

Gear ratios in these equations are the gear ratios for the transmission that came from the motor multiplied by the ratio due to the gearing that is used to couple the motor. Therefore, the speed reduction ratio for HEL-Roach I is 23*2=46 and for II, it is 4*30=120. According to Table 6.1, HEL-Roach I requires 26.3 oz-in torque after transmission. The required torque before transmission is 26.3 oz-in / 46 = 0.57 oz-in. This torque value, τ=0.57, crosses the winding line at $\omega \approx 6300$ in Figure 6.8. Then the maximum speed after transmission will be 6300/46=137 rpm or 2.3 revolutions per second. In the same manner, the maximum speed for HEL-Roach II is approximated. The result is in Table 6.3.

	Maximum Speed
HEL-Roach I	137 rpm, 2.3 Hz
HEL-Roach II	208 rpm, 3.5 Hz

Table 6.3 Maximum Speed Achievable

Knowing the stiffness constant K of a leg, the frequency of operation is calculated to be

$$\omega_{operation} = \sqrt{2k/m}$$

where m is the mass of system and 2k implies that 2 legs are on floor at once. From this, the motor's operating speed is calculated to be

$$\omega_{motor} = n\,\omega_{operation}\ rad/\sec$$

where n is an integer. If this value is smaller than the maximum speed calculated above, the impedance could be matched by varying the speed. Figure 6.10 shows the relationship between the frequency of operation and the stiffness constant for m=0.17 lb system (HEL-Roach II).

In practice, it is impossible to know the mass of the body when the motor and the transmission have not yet been chosen. The above calculation was performed by assuming that the body weighs 3 times more than the weight of the motor and transmission combined.

VII. Results

7.1 General Results

	Length (inch)	Width (inch)	Weight (lb)
I	3	5.25	0.69
II	2	1	0.17

	Four-bar linkage (inch, degree)					
	Link1	Link2	Link3	Link4	Link5	θ
I	0.3	0.81	0.54	0.69	1.05	70
II	0.21	0.9	1	0.567	0.6	-160

	Transmission (oz-in)		Total Gear ratio	Battery
	Max τ	Gear ratio		
I	99.13	23:1	46:1	12 V
II	17	4:1	120:1	12 V

	Motor (oz-in, rpm, volts)			
	company	Max τ	Max ω	Rated Volt
I	Micromo	0.708	8000	12
II	Micromo	0.02	13000	6

	Natural Frequency (Hz)	Actual Frequency	Speed (inch/sec)	Speed (body lengths/sec)
I	-	-	3	1
II	7.17[1]	2.4[2]	5	2.5

	Torque	Speed
I	26.3 oz-in	137 rpm
II	3.9 oz-in	208 rpm

Table 7.1 Specification of Walking Machine and Its Components.

Table 7.1 shows the resultant dimensions and specs of HEL-Roach series. Refer to Figures 4.1 and 6.7 for notations. Figures 7.3 and 7.4 are the pictures of final design.

7.2 Frequency Varied Performances

[1] This value comes from measuring 'k' of the system (method 1). By tapping the system with finger (method 2), the natural frequency was determined to be 5Hz.

[2] This value is not the same as the natural frequency determined by method 1.

The graph (Figure 7.1) shows the variance of efficiency and speed of the walking machine while the voltage applied to the motor is changed.

Figure 7.1 is a plot of v/(VI) vs. input voltage. v/VI is proportional to efficiency (Pin/Pout). It shows that efficiency increase the most when 11 volts is applied. From Table 7.2, 11 volts across the motor gives 2.4 Hz and speed of 3.33 in/sec.

Voltage (V)	Frequency (Hz)	Velocity[1] (in/sec)
9		2
9.5		2.67
10	1.6	2.86
10.5	2	3.2
11	2.4	3.33
11.5	2.4	3.33
12	2.5	3.64

Table 7.2 Walking Frequency and Velocity of Machine at Certain Input Voltage

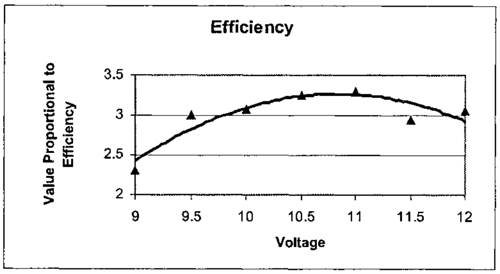


Figure 7.1 Value proportional to Pin/Pout ratio vs. Input Voltage

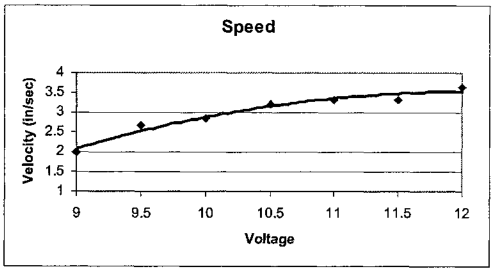


Figure 7.2 Speed vs. Input Voltage

VIII. Conclusions and Future Considerations

8.1 Conclusions

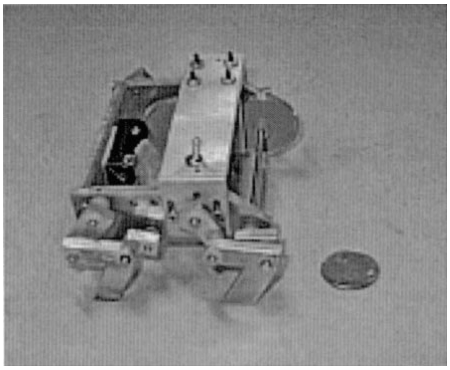


Figure 7.3 HEL-Roach I

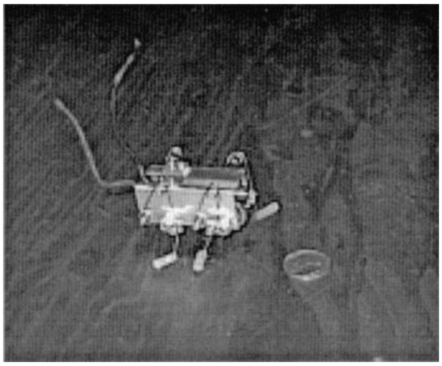


Figure 7.4 HEL-Roach II

Two walking machines are successfully constructed and both walk at reasonable speeds. Some insects' locomotion characteristics that are essential for walking are extracted to create very simple machine. For example, control of walking is wholly embedded within hardware as suggested by nature. The machines do not require any sensors or computers for walking. Also, the spring-mass system model is successfully applied using frequency-matching techniques and the energy efficient frequency was found. If intelligence were to be added in the future, the whole computer can be dedicated to additional tasks instead of having to use large amounts of memory and resources for walking itself.

However, because of the simplicity, the machines do have some limitations. The next section describes what are the limitations and gives some suggestions to solve these problems.

8.2 Future Considerations

8.2.1 Turning

One of the major drawbacks of these machines is that they can only go straight; they cannot turn. Turning of HEL-Roach series is not a simple task because of the coordination of the legs and shaft coupling. It is impossible to steer with the front 2 legs because they are directly coupled to the back shaft by a timing belt or a gear train. It is also impossible to reverse the direction of the input link on only one side because both input links are attached to the same shaft.

The method of a swinging mass is proposed to solve this problem. The idea is to spin a motor on top of the machine with a little load attached to it. The inertia created by the swinging mass makes the body turn left and right depending on the direction of rotation of the motor.

8.2.2 Reversing

Another major shortcoming of HEL-Roach series is that they do not go backwards. Unlike wheel-based machines, going backwards is not so trivial. If the machine needs to go backwards, it needs a decent footpath going in reverse as well. Therefore, if the machine were to be designed to go back and forth, the gait needs to be almost symmetric.

8.2.3 Natural Frequency Matching

The calculated natural frequency and the observed value do not match.

HEL-Roach II was not tested above 12 Volts (2.4Hz) because of the physical limitations of motor. The calculated natural frequency value (7.2Hz and 5Hz) could not be tested for the same reason. However, the increase in efficiency at 2.4Hz may imply that the lower mode for calculated natural frequencies was caught. In fact, 2.4Hz*2 = 4.8Hz ≅ 5Hz and 2.4Hz*3 = 7.4Hz ≅ 7.2Hz.

In order to test out the calculated frequency, stronger motor that is capable of making the machine move at around 7Hz, needs to be used. However, using a larger motor makes the body heavy and contradicts with the purpose of the machine. The trade off can be compromised depending on which feature is more important.

Reference:

[1] Data obtained from walking machine web site. http://www.fzi.de/ids/WMC/walking_machines_katalog/walking_machines_katalog.html
[2] MURI- Biomimetic Walking Machine Project - UC Berkeley's Human Engineering Lab, PolyPEDAL Lab, Stanford University's Dexterous Manipulation Lab, Microstructures and Sensors Lab, Harvard University's BioRobotics Lab, and John Hopkins University's Laboratory for Human Motor Learning Lab. Quoted from the proposal/abstract of this project.
[3] Bob Full, UC Berkeley, Department of Integrative Biology, PolyPEDAL Laboratory
[4] 3D Kinematics of Cockroach Walking - Bob Full, UC Berkeley, Department of Integrative Biology, PolyPEDAL Laboratory.
[5] Full and Blickman
[6] Compliant Mechanisms, Larry Howell, Mechanical Engineering Department, Bringham Young University