The Recti-Blob: A conformal shape-changing robot for robust locomotion over rough terrain

George E. Homsy, Andrew R. Allen, Gill A. Pratt
MIT Leg Laboratory, Cambridge, MA 02139
http://www.ai.mit.edu/projects/leglab/

Abstract

We present a novel robotic architecture suitable for locomotion on rugged terrain. For the moment existing only in a two dimensional incarnation, it consists simply of an external skin which, by changing shape, rolls over itself so as to produce motion. Since all exterior surfaces are active in locomotion, "falling over" has no meaning. Simple, modular, and versatile, the architecture can not only conform to rough terrain, but can also perform various feats of acrobatics.

The current implementation is discussed, along with plans for future improvement of control and efficiency, and generalization to three dimensions.

Results of physics based numerical simulations are presented, and the efficiency of a simple eight link incarnation in nominal octagonal configuration is compared with that of a rolling, rigid, inelastic octagon.

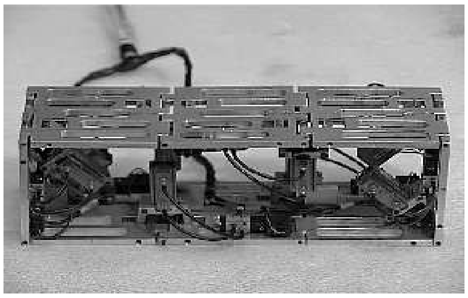

Figure 1: The Recti-Blob as it is currently implemented

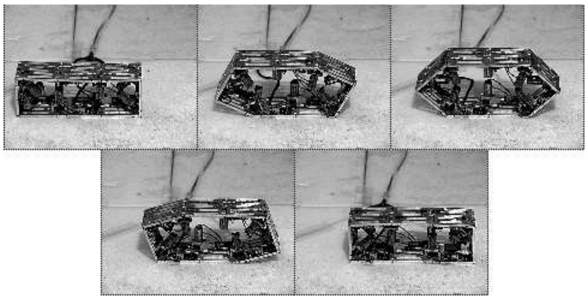

Figure 2: The Recti-Blob, taking a simple step

1 Introduction

Perhaps the most difficult problem facing the designers of robots for rough terrain is that of "getting stuck". With most conventional architectures, including wheeled and legged, there are many configurations from which the robot will not be able to extricate itself. Accordingly, much work has been done to build robots which can successfully avoid such situations. In fact, such an idea forms a large part of the impetus, either implicit or explicit, for building legged robots.

The Recti-Blob (fig. 1) is a robotic architecture currently under development at the MIT legged locomotion laboratory, as an architecture for robust locomotion over rough terrain. By "robust" we mean there are very few combinations of terrain and configuration out of which the robot is unable to maneuver itself. Unlike conventional robots for rough terrain, which try to avoid stuck conditions by careful planning, the Recti-Blob avoids getting into stuck conditions simply by eliminating most such conditions. This is accomplished by using a shape-changing approach to locomotion, in which the design of the robot is such that there is no "right way up", and no fixed "foot" size or "wheel" size. The robot simply reshapes itself to conform to, and move through, its environment.

The current architecture of the Blob is a closed loop of eight identical flat links[1] reminiscent of a Caterpillar track. In contrast to a track, though, the Blob has no internal structure providing shape, support, and power. Instead, each joint is fitted with an independently controlled actuator. This allows it, by cycling its joint positions, to "roll over" itself in much the same way as a track (fig. 2). Clearly, this architecture is well suited only for navigating a two dimensional world. The basic principles hold for a three dimensional world, though; the actual design has yet to be completely thought out (see section 4).

But while the Blob bears a superficial resemblance to a track, it differs in several respects:

1) It uses gravity in conjunction with changes in its own shape to effect movement. Thus, it belongs to the

[1] There is nothing magic about the number eight, except that it is minimal for producing interesting and useful shape changes. Blobs with more links can and will be built.

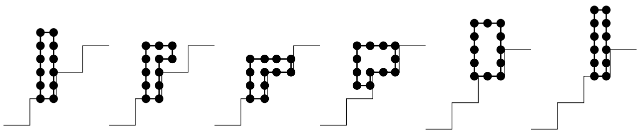

Figure 3: A 12 link Blob climbing stairs.

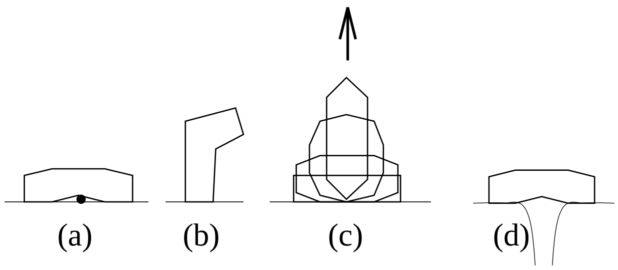

Figure 4: A number of tricks that a ten link Recti-Blob can perform.

class of "shape changing robots", along with legged robots. Contrast this with wheeled robots, including tracks, which rely on friction between environmental surfaces and wheel surfaces to move. This distinction is most clearly demonstrated by the illustration (fig. 3) of a twelve-link Recti-Blob climbing stairs almost as tall as half its extended length; something a wheeled robot is unlikely to do.

2) Since the Blob's actuators are independent, it can also change its static shape to conform to the shape of the underlying terrain (fig. 4a). Also it can tailor its shape to a variety of different acrobatic tasks such as reaching, jumping, bridging, etc. (fig. 4b - 4d). In this sense it more closely resembles a legged robot than a wheeled one.

3) Since the links are coarse in size, the center of mass of the Blob is vertically displaced during execution of a gait. Assuming non-regenerative or imperfectly regenerative actuation, the Blob dissipates energy during motion on a flat surface. This is again similar to a legged robot. But taking clues from biology and from past experience with legged robots, we see several avenues for future work to ameliorate this problem. These are discussed in section 4.

The final and perhaps most interesting distinguishing feature of the Blob is the uniformity of its surface: There is no correct up or down, the "foot" is not static in size, and "falling over" has a very different (and less catastrophic) meaning in this context than in that of a legged robot. For want of better terminology, we say that the robot has "active skin", meaning that all its outer surfaces are, or can be, active in locomotion.

It is these features of the Blob which we believe make it a promising architecture for robust locomotion over rough terrain. After a short review of related work in the area of shape changing robots, the remainder of this paper will focus on the current implementation of the Blob, improvements in progress toward the next generation Blob, strategies for control, and simulation results for the next generation Blob, including efficiency results.

2 Previous Work

We know of surprisingly little research in the field of shape changing robots. One notable exception is the class of robots, developed independently by Forrest Bishop [1] and Joseph Michael [4], consisting of large rectilinear agglomerations of independent cuboidal structures. These cubes cooperate by sliding over each other in an interlocked fashion, thereby changing the shape of the agglomeration to effect motion and manipulate objects. In addition, an agglomeration may fission to divide a task, or fuse with another to form a larger agglomeration for cooperation on a large task.

Also of interest is the work by Mark Yim [7] on Polypod, a reconfigurable modular robot built from chains of independently controllable shape changing wedges attached to each other and to cubic "nodes".

Both Polypod and the robots of Bishop and Michael are dynamically reconfigurable (at least in concept), and thus have extreme generality. They should both be able to perform very complex tasks. However, their speed and rigidity may be problematic at larger scales. Also, at this point in time, they rely on statically stable gaits.

By contrast with these proposed architectures, the Recti-Blob must be regarded as a less general intermediate between dynamically reconfigurable shape-changing robots, and nonmodular, nonreconfigurable robots. The Blob is also fast and can easily perform dynamic tasks, such as flips and jumps.

3 Current Construction

General The current construction of the Blob is simple: It consists of eight aluminum flat links, drilled for lightness, and eight joints of the form diagrammed in figure 5. The joints are staggered alternating from left to right, so that actuators of adjacent joints do not collide. Pneumatic cylinders are used as actuators in this prototype, and the joints are restricted to forming only convex angles. There is nothing about the joint design, however, which precludes concave angles in future implementations. One must only increase the actuator throw or bring the insertion point of the link rods closer to the joint, as shown in figure 6.

The power source and control are currently off-board. Compressed air is supplied through a single tube. The control valves are on-board, one per link, with control signals coming from a PC parallel port.

The existing design emphasizes modularity and expandability. All links are identical, and new links can easily be added. There are many drawbacks though: In addition to the restricted range of joint motion,

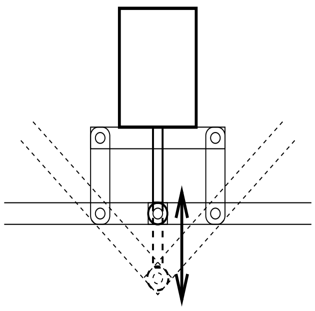

Figure 5: The Recti-Blob joint design

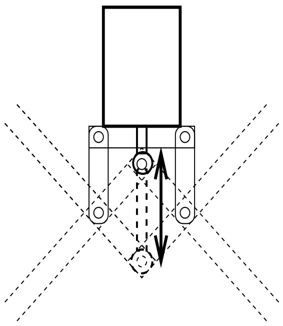

Figure 6: A slightly modified joint, with the link rods moved closer to the joint. Note the capability for concave angles.

there is no ability to hold joints at intermediate angles between the two extremes. This is because simple three way pneumatic valves are used, and there is no joint angle feedback. Nonetheless, we have been able to perform many of the complex acrobatics mentioned above with just this simple prototype, thus proving the concept and clearing the way for improvements.

Future models will use series elastic actuation [5] [6] with feedback control to greatly improve the versatility and efficiency of motion, as discussed in the next section.

Actuators The geometry of the Blob places certain demands on the actuators used. They must be small enough to clear each other when an inside tight corner of the Blob is rolling past itself (fig 7), yet also deliver enough force to lift the top half of the Blob (fig 8). In order to choose a good actuator, consider the following figure of merit:

First, let n be the number of links and l be the length of each link. Let m be the mass of each link. Now consider the actuator to be inscribed in a cylinder coaxial with the joint. Let r be the radius. For any given "tightest corner", such as that shown in figure 7, r must be related to the link length, l, by some constant factor. Call it k_1:

$$r = k_1 l. \tag{1}$$

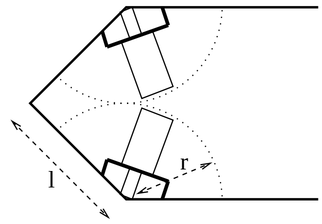

Figure 7: Three joints of the Blob, rolling through a tight corner. The actuators, each inscribed in a cylinder of radius r, are not colliding.

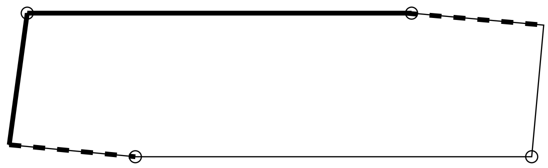

Figure 8: A ten link Recti-Blob starting to execute a step. The solid bold lines are links being lifted. The dashed bold lines are links being half lifted. The circles indicate the joints doing the lifting.

This constraint is so that the actuators don't collide with each other during a step. Now, during a step, some portion of the Blob is lifted some distance by some number of actuators. The exact distance and number of actuators doing the work both depend on the gait being used, but for any given gait we may write the work done per actuator per step:

$$W = Mgk_2 l = nmgk_2 l, \tag{2}$$

where M is the mass of the robot, and k_2 is a proportionality constant which captures the gait geometry. That is, what fraction of mass M is being lifted what fraction of distance l, by how many actuators. We have made explicit the dependence on M and l so that k_2 depends only on the chosen gait, not on the absolute size or mass of the robot.

We may also write the work done per actuator per step in terms of the capabilities of the chosen actuator type:

$$W = F\Delta X, \tag{3}$$

where F is the maximum force delivered and ΔX is the actuator excursion. And finally, since we are considering only a two dimensional Blob in this analysis, we may write the mass of a link in terms of a one dimensional mass density ρ:

$$m = \rho l. \tag{4}$$

Combining these four relations and grouping properties of the actuator on the left side, and properties of the Blob geometry on the right, we obtain:

$$\frac{F\Delta X}{r^2} = \frac{n\rho g k_2}{{k_1}^2}. \tag{5}$$

Hence, $F\Delta X/r^2$ is a figure of merit for any actuator being considered for use in any Blob, with higher numbers being better. Let us call this figure ν.

Interestingly, for a pneumatic actuator running at a given pressure, ν is directly related to the volume of the actuator cylinder, divided by the cross sectional area of the cylinder in which it is inscribed as in figure 7. This suggests that for pneumatic Blobs, cylinders are best chosen whose radius is of the order of their length. In the section on future plans, we discuss what sort of actuator is best chosen for the next generation Blobs.

4 Future Plans

Actuators The next step in the development of the Blob is to fit it with better actuators and feedback. We plan to use miniature lead-screw/nut actuators fitted to stepper motors, with a series elastic element. The advantages of series elastic actuation are manifold, and are well documented elsewhere [5] [6].

The primary advantage in this case is that the series elastic elements have the potential to store and release energy almost without loss. This will allow executing gaits in which the Blob's center of mass oscillates vertically, without requiring the motors to deliver a large amount of work. This is *necessary* for efficient operation of the Blob because it is not round; the energetics of locomotion are more similar to a legged robot than to a wheeled one (see section 6).

Control Stratiegies The similarity with legged robots is poignantly illustrated by the problem of designing control strategies. It has become apparent during the course of simulating the next generation Blob, that motion will be efficient only when operating within one of a set of distinct "gaits". These gaits are distinct regimes of operation, each with its own characteristic relation between speed and efficiency, and each requiring its own control strategy. We expect that each gait will have optimal efficiency at some speed, and that speed will be related to the resonant frequency of some mode of the spring-mass system. This again is extremely reminiscent of legged locomotion [2].

Shape vs. Efficiency A different approach entirely might be to simply "round off" the links of the Blob so that, when it is in nominal position with all joint angles equal, its exterior forms a circle instead of a regular polygon. While this might appear attractive at first, offering hopes of higher efficiency and simpler control strategies, it also suffers from a host of drawbacks:

1) The design will be no longer expandable in a modular way, since now each link must be an arc of some angle, and that angle is uniquely determined by how many links are in the Blob.

2) The acuteness of corners producible by the Blob skin would also be reduced. Intuitively this is bad, because sharp corners may be important at times for gripping the features of rough terrain, so as to increase effectiveness of moving over obstacles, climbing hills, etc.

3) The efficiency gain is not as great as it would appear: We have evidence (see section 6) that the flat-edged Blob's efficiency of locomotion approaches unity as speed increases. The inefficiency is therefore a problem *only* at low speed. But whereas the round-edged Blob may be more efficient at low speed, being much more like a wheel, it is also unable to produce much force with which to move itself. Consider for instance the flat-edged and the round-edged Blob, each trying to walk *slowly* up a gradual incline. The round-edged Blob must displace its joints further than the flat-edged to move successfully.

Distributed Energy Source and Control Other future plans include building Blobs with distributed energy source and control systems. In this model, each link would have its own power source and its own microcontroller on board. The links would then plug together in a truly modular fashion, and the controllers would communicate via a token passing ring-network protocol. Each controller would then only have local information: Which way is up, what is the state of its joint, what are the states of its neighboring joints, and which of the links on either side of its joint are touching the ground. This opens up interesting ground for the design of novel control strategies.

Three Dimensional Blobs Perhaps the most important of future objectives is to make the Blob more usable in a three dimensional environment. This involves either providing some mechanism for turning, or making a more general Blob architecture which is inherently 3D. Several turning schemes have been proposed, including methods for introducing camber, and several different schemes for bending or turning individual links when viewed along a vertical axis. None of these is as desirable, though, as having a Blob design which is inherently 3D. This is a difficult geometrical problem, and one which bears further thought.

5 Simulation and Control

We have performed a number of physics-based, dynamic simulations of the robot both in its current form and with the proposed series elastic actuation. Various gaits and control strategies were tested and their efficiencies compared.

5.1 Current Implementation

Our initial simulation was of the current implementation of the Blob. We modeled the actuators as constant force generators which were either on or off, corresponding to the piston being "in" or "out." The joints were given joint-stops which limited their travel between 180 degrees (flat) and 90 degrees (a corner). The control of the simulation also matched that of the

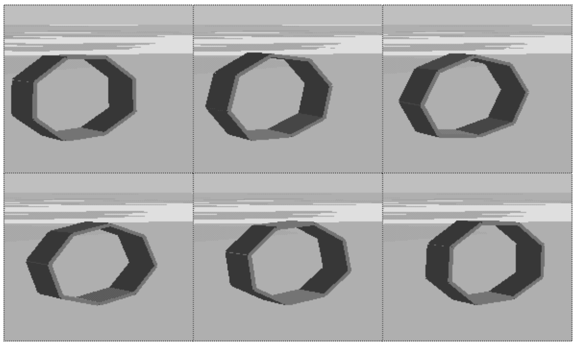

Figure 9: Six frames from a simulation showing a "step." Note that only the two joints on the ground change angles.

Blob; an open loop strategy which either rotated or inverted the 8 bit pattern initially set for the actuators.

These initial patterns could include any number and combination of the pistons being on or off and in essence formed the "gait" of the robot (see fig. 2). We found that having less than 3 of the actuators firing didn't provide enough force for the robot to actually lift its own weight and move, while having more than 4 was wasteful. Thus, most gaits used some combination of four of the pistons firing and four returning to rest position. All the gaits took the form of polygons, some being more "round" than others. This strategy is inefficient for it cannot take advantage of the "wheel-like" properties of the Blob, and in essence, is like trying to "roll" a rectangle.

5.2 Proposed Implementation

We then moved to a model of the Blob that replaced the force generators with series elastic actuators. We retained the joint-stops and current size, however a next generation robot could very well be larger since the actuator figure of merit should be enhanced by using motors rather than pneumatics. Using this model we have currently tested two control algorithms/gaits, however we have at least two more which we would like to test and believe will further enhance efficiency.

Open Loop, Rotation Algorithm The first control strategy is a parallel to the currently implemented algorithm using position control rather than a fixed force to dictate joint positions. We set the inital desired positions just as we set the initial bit pattern to the force generators. These desired positions are then rotated at regular intervals and the Blob "rolls over" itself. Thus, the gaits are equivalent and we obtain a correspondingly low efficiency.

Octagonal, Joint Position Feedback Algorithm The second algorithm is also based on a simple strategy, but it increases the efficiency of the robot substantially. Rather than have 3 or 4 of the joints active at any one time and thus give the Blob a rectangular shape, it is possible to use all the actuators at once to form the Blob into an octagon (fig 9). Then by changing the two joint angles nearest the ground, it is possible to shift the weight of the robot onto the next link.

This strategy incorporates some basic feedback into the control loop. Like the first strategy, we rotate joint angles to perpetuate the forward motion, however, we use the current joint angles to dictate when the rotation should occur. If the Blob's forward motion is hindered, this usually translates to a joint not reaching a certain level. Using feedback, we can sense this and attempt to begin rolling again. Such a control strategy automatically adjusts itself to the speed of the robot, for as the momentum builds and the Blob rolls faster, the angles are being cycled more quickly.

Future Algorithms The next algorithm we will explore uses foot switches for feedback rather than current joint angles. With correctly placed switches, it should be possible to monitor forward motion much like the joint angle algorithm, but with the added benefit of being able to detect collisions with objects. Also, by using foot switches we will have an absolute measure of which link is on the ground and not have to rely on the fact that not attaining a given angle *usually* means the robot has failed to shift to the next link. It will also prevent the problem of "tripping" where the Blob rotates faster than the joint angles rotate. This quasi-static scheme should prove to be substantially more reliable as well as efficient.

The final algorithm which we will like to study is a dynamic scheme. As with the second currently tested algorithm, we will monitor joint angles. Then, using these measurements and given some initial information, we will calculate the forward momentum and center of mass of the Blob. We will then use this information to determine whether the current momentum will carry the Blob to its next step. In the case that the momentum is insufficient, the joint angles can be adjusted accordingly and forward momentum increased.

Using one, or perhaps a number of these control strategies, in addition to some of the other modifications mentioned earlier, should make the Blob extremely effective at covering a variety of terrain. In addition, the various improvements which we have proposed (see section 4) should make it possible to devote a higher processor to active gait selection and planning. In the case of flat ground, the Blob can assume an almost round shape and simply tweak joint angles to maintain a forward momentum. When confronted with rough terrain, the Blob will be able to shift gaits to something less energetically efficient, yet able to surmount obstacles.

6 Efficiency

An advantage of the Blob is that on relatively flat ground it should be nearly as efficient as a wheel. The ability to vary the angles between the joints can make the Blob (at least energetically) look like it has substantially more sides than it does, and in the limit, this is a circle (which ideally has 100% efficiency).

Let us look first at the energetics of an inelastic, rolling, rigid octagon and calculate the efficiency[2] of such a structure. McGeer [3] gives us a formula for the efficiency of a rimless wheel with N spokes. In the case where our structure has flat sides, this is exactly the case of a rimless wheel with a number of spokes equal to the number of sides of the polygon. We have for any polygon,

$$\eta_v = 1 - \sigma^2(1 - \cos 2\alpha_0), \tag{6}$$

where, η_v is a ratio of the velocities before and after a "step,"

$$\sigma^2 = \frac{1}{1 + r_{gyr}^2}, \tag{7}$$

and $2\alpha_0$ is the angle between spokes. For an octagon, $2\alpha_0 = 45^o$.

Here, r_{gyr} denotes a dimensionless radius of gyration, which in this case is the moment of inertia, normalized by ml^2. In our case, we approximate a hollow cylinder which gives us a value of $r_{gyr} = 1$.

Since η_v is a ratio of velocities, we must square it in order to get the efficiency in terms of energy. For the octagon, we get a value of approximately .72 or 72%. Thus, an inelastic octagon will retain 72% of the kinetic energy of a given "step" as it moves to the next side.

In order to find a similar efficiency for the Blob, we had to first determine how much energy we are putting into it per step. This is simple since the necessary quantities are accessible in the simulation. We settled on the following equation as an estimate of the energy added per step to one joint of the Blob,

$$W_{joint} = \int_0^{t_0} \mid v_{joint}\tau_{joint} \mid dt, \tag{8}$$

where v_{joint} is the velocity of a joint and τ_{joint} is the torque experienced by that joint. Because we're interested in the amount of energy put into the actuator, we use the absolute value to make this a conservative estimate, even in the case of a nonregenerative actuator.

We sum these values over all the joints to obtain the total work per step. This is then divided by the kinetic energy and the total number of steps. We get the following value for η_e:

$$\eta_e = 1 - \frac{\sum_{joint=1}^{n} W_{joint}}{steps_{tot} KE}, \tag{9}$$

where we subtract from one to give the energy *retained* on each step (where a step is a transition from one link to the next sequential link).

We are now in a position to directly compare the values of the efficiencies mentioned in section 5. Figure 10 and 11 show graphs of efficiency versus time from two simulations.

[2] In this case, efficiency can be defined as the percent of energy maintained from one "step" to the next where a step consists of moving from one side to the next.

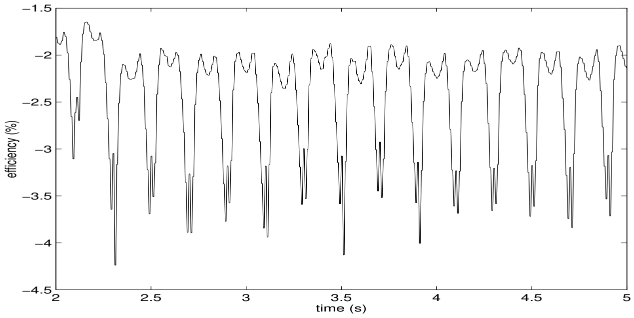

Figure 10: Efficiency versus time during a simulation using the open loop, rotation control strategy.

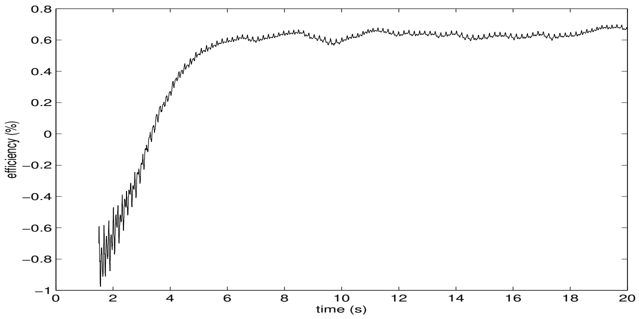

Figure 11: Efficiency versus time during a simulation using joint-position feedback algorithm.

Figure 10 was taken from a simulation of the series elastic actuated Blob using the open loop, rotation algorithm. The time between steps is .18 seconds and the total number of steps for the simulation was 25. The initial gait was that of a rectangle three links wide by 1 link high (see fig 2). We can see that the average efficiency is on the order of -2. This means that almost 2 times the energy of each step was *added to* the Blob for every step[3]. This is due to the fact we are losing almost all the forward momentum and kinetic energy of the system every time we take a step.

Figure 11 shows the efficiency of a simulation run with the series elastic actuated Blob under the octagonal, joint position feedback algorithm. We see that the efficiency reaches a maximum value of .70 for a run of 144 steps. This value is very close to that of the octagon. Thus, with even the simplest of control strategies, a reasonable efficiency can be obtained. The lack of sophistication in the control is evidenced by the long term fluctuations in efficiency which correspond to the "tripping" behavior mentioned previously. We feel that with some fine tuning and refine-

[3] A negative value here is not as strange as it may appear. We know a value of 0 would mean that all the energy is lost from one step to the next. Thus, a negative value simply means that energy is put in and dissipated; in this case, approximately 2 times the amount lost on a step.

ment, even this simple control strategy should raise efficiency above that of the octagon, and it is clearly better than that of the initial open loop system. We feel that the more sophisticated control strategies can only improve upon this figure and should be able to achieve efficiencies of above 90%.

7 Conclusions

The Recti-Blob is a unique design for a robot capable of negotiating rough terrain. It sucessfully combines the advantages of both legged and wheeled locomotion. It will be able to surmount obstacles impossible for a wheel to get over, while on flat ground achieving nearly the efficiency of a wheel (something a legged machine is unlikely to accomplish).

The current implementation of the Blob has been extremely reliable both mechanically and in terms of control. We believe that this reliability will carry over to the proposed modifications and should provide a solid platform from which to explore the various proposed gaits as well as different control hardware.

Our initial simulation results are encouraging, for even with a simple control strategy and a minimum of fine tuning we have achieved reasonable efficiency. With the development of more sophisticated control and the addition of series elastic actuation to the Blob, we feel that a robust, efficient and reliable method for locomotion over rough terrain can be successfully implemented.

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