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MEDIC: A Legged Millirobot Utilizing Novel Obstacle Traversal

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Abstract—
This work presents the design, fabrication, capabilities, and obstacle traversal mechanics of MEDIC (Millirobot Enabled Diagnostic of Integrated Circuits), a small legged robot able to overcome a varied array of obstacles. MEDIC features a hull that keeps its body in contact with the ground at all times, and uses only four actuators to move forward, turn, mount obstacles, and move in reverse. The chassis is fabricated using a Smart Composite Microstructures (SCM) approach and the robot is actuated by coiled Shape Memory Alloy (SMA). MEDIC also features a camera which will be useful for navigation in the future.

I. INTRODUCTION

When presented with obstacles of an unknown nature, legged locomotion is often highly effective at navigating varied terrain. Many robots use other morphologies (wheels, whegs, etc.) to traverse difficult terrain [1] [2]. Additionally, some robots that use legs may rely on highly sophisticated control algorithms and many degrees of freedom to achieve mobility [3] [4]. At the small scale many of these solutions are impractical, as friction forces start to dominate inertial forces and processing power becomes limited.

MEDIC uses nearly frictionless flexure joints, shape memory alloy actuators, and open-loop control to move through difficult terrain. This is done by using a “hull” body design. The hull allows MEDIC to have all four feet off of the ground at the same time and still remain stable. This feature enables turning (simply protract the legs on one side and retract the other side) and obstacle traversal with little computation or feedback (simply walk toward an obstacle).

MEDIC has been designed and built to be able to traverse horizontally mounted computer motherboards. The robot is designed not to cause shorts, as it is constructed of non-conductive material, and its own electronics are not exposed unless it somehow rolls over during ambulation. The ability to crawl on motherboards may, in the future, allow MEDIC to diagnose problems on a motherboard that a human could not reach, such as in a computer on a satellite in space. Many motherboards are mounted vertically, and navigating these is a more difficult goal that may be addressed in the future as adhesive technology improves.

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A computer motherboard is a terrain that presents varied challenges, in both obstacle morphology and in size constraints. To navigate a motherboard with a physical robot, the robot must be capable of forward motion, turning, and mounting obstacles. Furthermore, being able to move in reverse is advantageous if a route turns out to be more difficult than expected. Small spaces demand a turning radius that is as small as possible, and gaps between components mean legs must not become stuck mid-stride. MEDIC's design addresses many of these challenges and results in a small, light, and capable robot. Previous SMA driven small robots such as RoACH [6] were not capable of reverse, and had a turning radius of 25 mm.

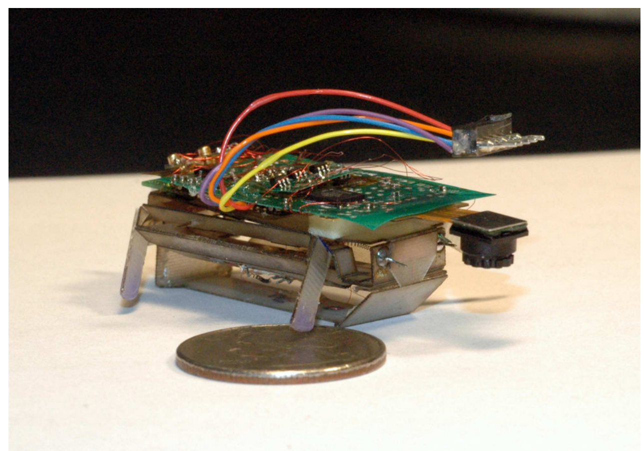

Fig. 1. MEDIC over a US Quarter.

II. FABRICATION

The robot chassis is fabricated using the Smart Composite Microstructure process. This process enables rapid iteration, the use of lightweight and stiff composite materials, and the use of nearly frictionless flexure joints. Due to these and other advantages, this process has been used successfully to develop many millirobots [5] [6] [7] [8]. The chassis is constructed using G5 fiberglass and 12.5 μm PET in a manner similar to that described in [9] and [10]. For this robot, the main body starts as a single structure, which is folded to form the chassis. This single-piece folding design avoids problems associated with aligning multiple parts, since most of the alignment is enforced by the structure itself. At this scale, alignment is crucial, since an error of even a millimeter can be significant. The single-piece design is also very compact by nature, which saves a significant amount of material. This is a large advantage for mass production.

For a robot of this size wiring is a significant time investment and is error-prone. The more wires suspended freely about the robot, the higher the chances that one of these wires will break. To address these concerns, MEDIC features embedded copper wiring, where copper wires backed with Kapton^{TM} are sandwiched between the fiberglass and PET layers to form wiring for the robot, similar to the method detailed in [11]. Pads are cut out of the fiberglass on one side of the sandwich to expose copper for final wiring to the CPU board. This process not only saves hours of wiring time for each robot produced, but makes wiring failures less likely, saving potential repair time as well. The embedded wiring goes through several 90 degree joints in the chassis, but these are fixed joints that do not bend dynamically.

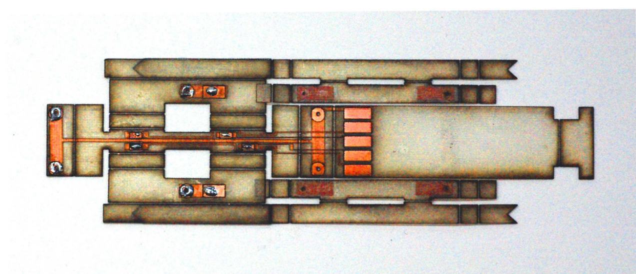

Fig. 2. Copper wiring is embedded directly into the chassis.

III. Mechanical Design

A. Ambulation

MEDIC walks by a rowing motion, implemented using four degrees of freedom. The kinematics are symmetric left to right, and each body side has an abduction/adduction degree of freedom, and a protraction/retraction degree of freedom. To move forward, first the adduction actuators are activated, bringing the feet low towards the ground. Next the protraction actuators are activated, sweeping the legs backwards and pushing the feet against the ground. This causes the robot to vault forward. Due to the weight of the robot and the power available, this usually results in a sliding (as opposed to vaulting) motion. This process is shown in Fig. 3 and detailed in Table I. In reverse the same cycle is used, but in the opposite order. Turning left is done by moving the left legs using the reverse primitive and moving the right legs using the forward primitive. This causes the robot to pivot on its hull. This process is shown in Fig. 4 and detailed in Table III. A right turn is performed in the opposite manner. Fig. 7 shows the activation pattern for the SMA actuators when the forward gait is employed.

B. Actuation

At the small scale actuation choices are limited. Several millirobots [6] [7] use SMA because of its high energy density, light weight, and ease of integration into the SCM process. We use coiled SMA similar to that described in [12]. The coiled SMA avoids complicated routing of SMA wire and difficult pre-tensioning. An actuator may have to

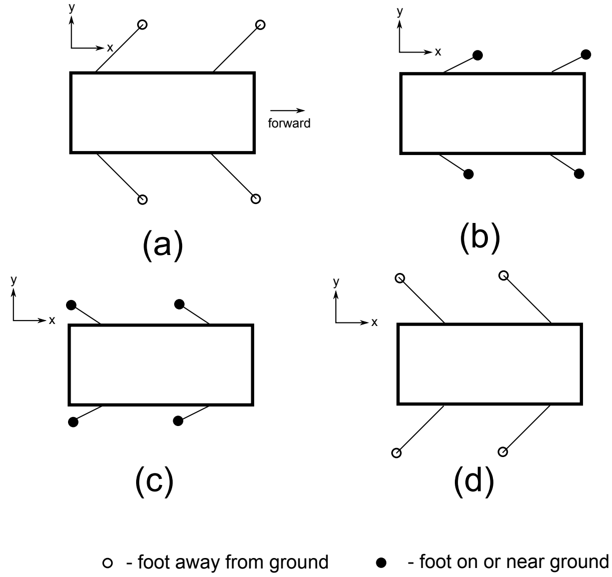

Fig. 3. To move forward, the robot progresses in the order a,b,c,d. In a, all actuators are relaxed. In b, the adduction actuators are turned on, moving the legs near the ground. In c, the protraction actuators are turned on (the adduction actuators remain on), moving the robot forward. In d the adduction actuators are turned off, raising the legs. To move in reverse, the robot progresses in a, d, c, b.

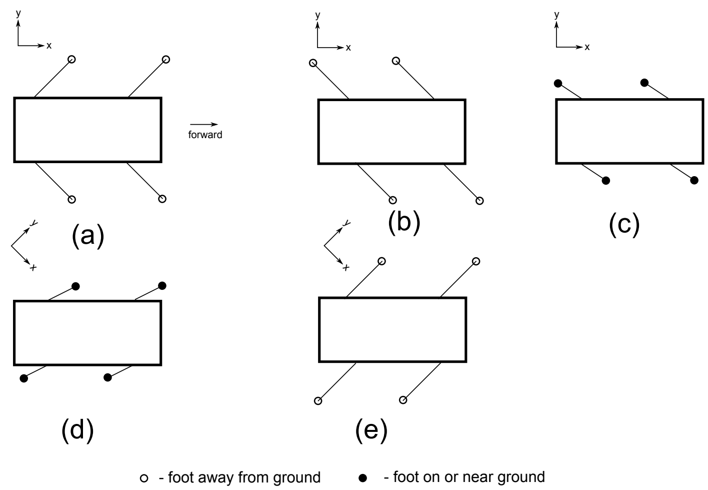

Fig. 4. To turn left, the robot progresses in the order a,b,c,d, e. To turn right, the robot progresses in a, e, d, c, b.

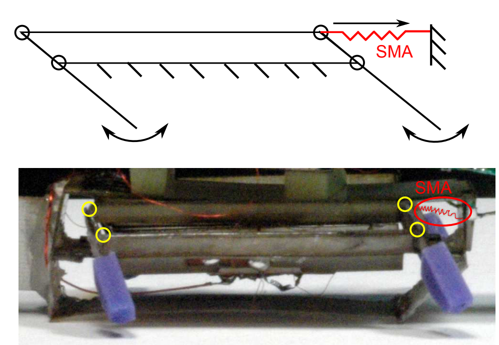

Fig. 5. Protraction/Retraction Joint Kinematics (Side View of Robot)

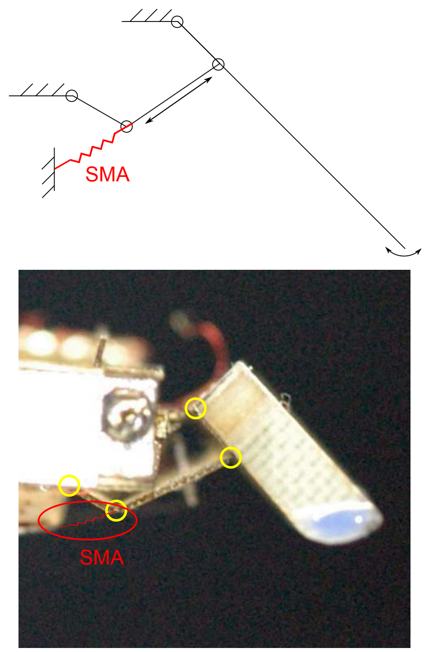

Fig. 6. Abduction/Adduction Joint Kinematics (Front View of Robot)

produce 10 mm of stroke and fit inside of an envelope less than 15 mm long. The coiled SMA used here allows that. At a displacement of 4 mm, the actuators can produce 7 grams of force. The legs act as a lever arm and, assuming no losses, deliver approximately 2.6 grams of force to the ground at the bottom of their stroke.

TABLE I
MAP OF ACTUATOR STATES TO GAIT POSITION IN FIG. 3 FOR FORWARD MOVEMENT

Position	Adduction	Protraction
a	OFF	OFF
b	ON	OFF
c	ON	ON
d	OFF	ON

TABLE II
MAP OF ACTUATOR STATES TO GAIT POSITION IN FIG. 3 FOR REVERSE MOVEMENT

Position	Adduction	Protraction
a	OFF	OFF
d	OFF	ON
c	ON	ON
b	ON	OFF

C. Specific Resistance

Specific Resistance is often a useful metric for mobile robots, as a way of measuring energy efficiency [13]:

$$\varepsilon = \frac{E}{Mgd} \tag{1}$$

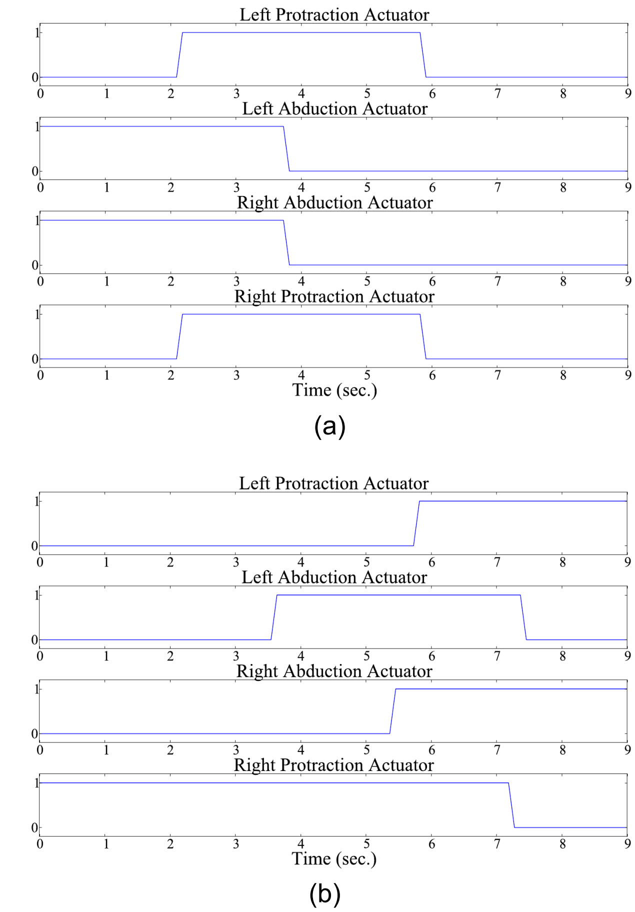

Fig. 7. (a) Actuation pattern for forward motion. (b) Actuation pattern for a right turn. Overlap occurs because time must be allowed for the SMA actuators to heat up and cool down.

TABLE III
MAP OF ACTUATOR STATES TO GAIT POSITION IN FIG. 4 FOR A LEFT TURN

Position	Left Adduction	Left Protraction	Right Adduction	Right Protraction
a	OFF	OFF	OFF	OFF
b	OFF	ON	OFF	OFF
c	ON	ON	ON	OFF
d	ON	OFF	ON	ON
e	OFF	OFF	OFF	ON

where ε is the specific resistance, E is the energy consumed, M is the robot's mass, g is the gravitational constant, and d is the distance the robot travels. Over a battery charge, MEDIC uses approximately 20 mAh of current at 3.8V. It can take about 80 steps of 5 mm each to move about 400 mm. This gives a specific resistance of over 12,000. This is far from the ideal, which would be about 0.36 (equal to the measured coefficient of dynamic friction). SMA actuators have high power-to-weight ratios, but are very inefficient. The slow cycle speed of the actuation leads to high power dissipation. Short bursts for quick heating as used in RoACH [6] are more efficient.

D. Return Springs

Because SMAs are only tensile actuators, a return spring is necessary to complete a movement cycle. The abduction/adduction degree of freedom relies on the stiffness of the flexure joints to serve as a return spring once the SMAs have cooled.

In the retraction/protraction degrees of freedom, a buckling beam is fabricated from 12.5 μm steel shim to serve as a return spring for the robot. The springs must be stiff enough to allow a return action that will move the robot (to implement reverse) but must be compliant enough to allow the SMA actuators to move the robot forward. To date, spring tuning has been done empirically.

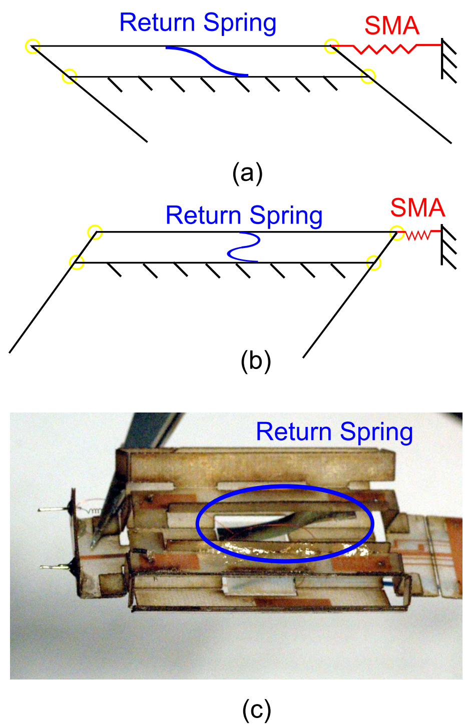

Fig. 8. (a) shows the return spring configuration when relaxed (b) shows the return spring when the actuator is on (c) shows the return spring as mounted on the MEDIC chassis.

While antagonistic SMA actuators may also be used, return springs were chosen to reduce the total number of actuators to four. The actuators are built by hand and eliminating some of them decreases the total fabrication time. In addition, eliminating actuators simplifies the wiring significantly. The current embedded copper wires must be a minimum size to be assembled without deforming. Due to the small size of the robot and these constraints, the embedded wiring could not support six actuators.

IV. Obstacle Traversal

A. Hull Design

Climbing is an active area of research in legged robotics. Several robots use gecko-inspired adhesives for vertical climbing [14] [15], while others use claws [16]. Our goal is not to climb vertical surfaces, but to mount obstacles that exist on a computer motherboard. Due to the size of MEDIC, simplicity of design and implementation is a key factor. Minimal actuation is required to reduce complexity and power consumption. Furthermore, control capability is limited, making simple movements appealing. These considerations led to the design of a hull to help MEDIC overcome obstacles and stay stable while turning and walking.

The hull is a simple inclined plane, which allows MEDIC to mount short obstacles by reducing the force necessary to surmount a plateau. Additionally, where other legged robots may get a leg or legs caught between two obstacles, the hull allows MEDIC to traverse gaps shorter than its body length with relative ease. If MEDIC encounters a surmountable obstacle, simply walking forward will force it over the top. When an obstacle is encountered a special protocol is not needed.

B. Obstacle Mechanics

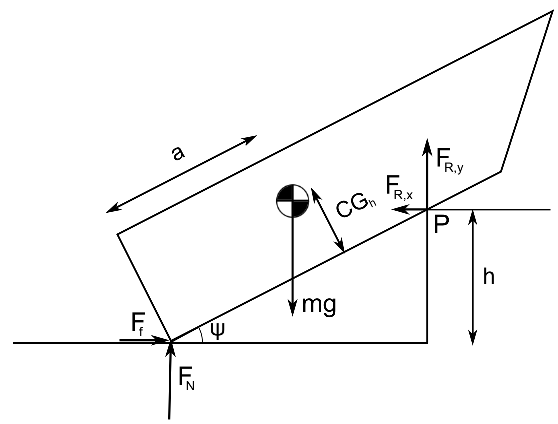

Fig. 9. The position of the center of mass of the robot will limit the height of obstacles it can overcome.

$$\max_{\psi} \quad \{a\sin\psi - CG_h \sin\psi \tan\psi\} > h \tag{2}$$

It is worth noting that this condition is only a function of the mass distribution of the robot. Moving the mass low and forward is highly advantageous for obstacle traversal. For MEDIC, the center of mass is located approximately 15 mm from the rear of the robot longitudinally and about 15 mm above the ground. This currently limits the obstacle height to a theoretical maximum of 3.5 mm.

The second condition is that the thrust force applied to the robot must be sufficient to initiate motion. We calculate a required thrust force by using a static analysis. We assume that the reaction forces at the top of the obstacle are normal to the hull.

$$\begin{bmatrix} 1 & -\mu & -\mu cos(\theta) - sin(\theta) \\ 0 & 1 & cos(\theta) - \mu sin(\theta) \\ 0 & -l & h(\mu cos(\theta) + sin(\theta)) \end{bmatrix} \begin{bmatrix} F_t \\ F_{N,r} \\ F_{N,h} \end{bmatrix} = \begin{bmatrix} 0 \\ mg \\ mg(acos(\psi) - CG_h sin(\psi) - l) \end{bmatrix} \tag{3}$$

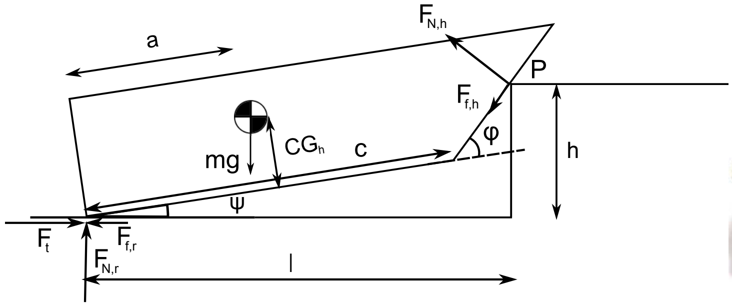

Fig. 10. Thrust force (F_t) depends on robot and geometry and friction.

where

$$l = c\cos(\psi) + \frac{(h - c\sin(\psi)}{\sin(\theta)}\cos(\theta) \tag{4}$$

and

$$\theta = \phi + \psi \tag{5}$$

From here, using the measured $\mu = 0.36$ we can estimate the thrust force needed to move the robot up an obstacle. For 3 mm, we calculate this to be 3.1 grams. It is important to note that the feet and hull do not have to have the same coefficient of friction. The feet on MEDIC are dipped in silicone rubber (Smooth On Inc. SO # 84160) to increase their friction coefficient.

C. Dimensions and Weight

MEDIC measures 55 mm long, 35 mm wide at the legs, 25 mm wide at the hips, and is 18 mm high. Its total mass is 5.5 grams, including onboard battery. A breakdown of the mass is shown in Table IV.

TABLE IV
MASS OF MEDIC BROKEN DOWN BY COMPONENT.

Item	Mass
Battery	1.76 g
Chassis	1.5 g
CPU Board + Radio	0.88 g
Camera	0.33 g
SMA Driver Board	0.14 g
Legs	0.09 g
Battery Connector	0.07 g
Actuators	0.02 g
Glue/Solder/Wire/Misc.	0.71 g
Total	5.5 g

V. ELECTRONICS AND SOFTWARE

A. Electronics

The robot's electronics packaage consists of a microcontroller (dsPIC33FJMC706A) interfaced to six power MOSFETs for switching the SMA actuators, a CMOS imaging sensor (OmniVision OV 7660) for capturing grayscale images of the environment, and an IEEE 802.15.4 compliant radio (Atmel AT86RF231) for providing low-power wireless communications with a PC or laptop. Fig. 11 depicts the two printed circuit boards populated with these components.

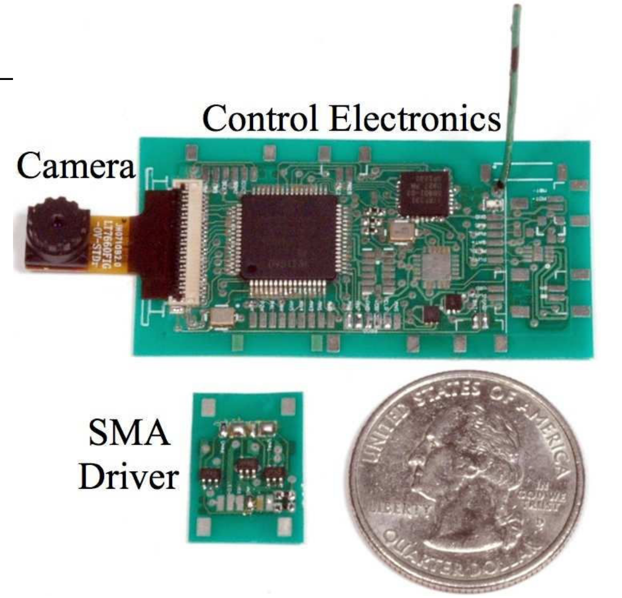

Fig. 11. The power (below) and control, communication, and imaging (above) electronics for the MEDIC robot.

B. Software

The robot firmware is written in C and uses a function queue scheduling architecture [17]. Locomotion, configuration, and image capture commands are sent from a laptop via a Python interface (command line or GUI) and scheduling is handled by the robot firmware according to the diagram in Fig. 12. The SMA actuators are driven using a PWM signal configured and controlled by the firmware. A single timer drives the switching of all four SMA actuators, and the duty cycles of the actuators are arranged such that no two actuators are on simultaneously. Although it limits the maximum duty cycle of any given actuator to 25%, the relatively high current draw of each actuator requires this approach to avoid resetting the PIC due to exceeding the maximum discharge rate of the battery.

VI. RESULTS

A. Walking and Endurance

MEDIC was tested in a series of trials on a paper surface to determine its baseline performance. It is operated from a wireless connection to a laptop PC and powered by an onboard Full River 50 mAh Lithium-ion Polymer battery. MEDIC averages 5 mm per step when walking forward, and 2 mm per step when walking in reverse. It can turn in either direction at 9 degrees per step (see Fig. 13 with a turning radius of 27 mm (for the Center of Mass). On a single battery charge it will last approximately 80 steps (whether the steps are forward, reverse, or turning), though in some tests a battery charge has lasted over 100 steps. A step takes 9 seconds, which is necessary to allow the SMA actuators to heat up and cool down. MEDIC has taken over 1000 total steps.

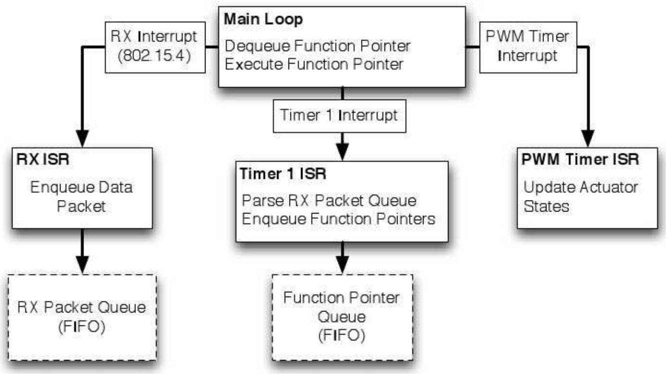

Fig. 12. Functional diagram of the firmware used to run the MEDIC robot. The firmware uses a function queue scheduling architecture in which command packets (to configure actuator timing, step forward and back, take and transmit pictures, etc.) are received and parsed asynchronously and pointers to their corresponding firmware functions are queued. The main loop checks the length of the function pointer queue every iteration, dequeueing and executing the oldest function pointer if the queue is not empty.

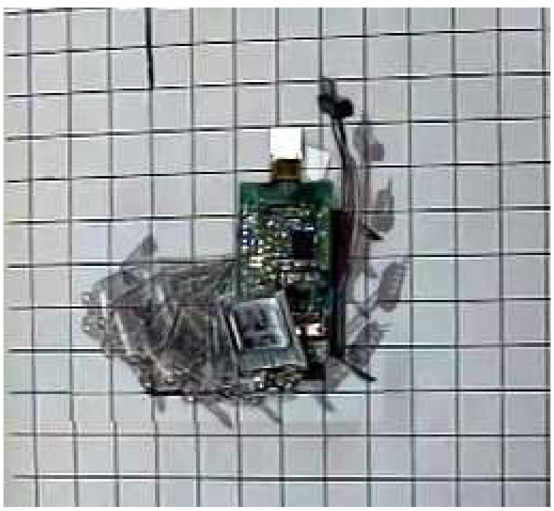

Fig. 13. Frame Capture of MEDIC executing a left turn. 10 steps results in a 90 degree turn.

B. Obstacle Traversal

An adjustable obstacle course was constructed out of acrylic to test MEDIC's ability to overcome obstacles. Obstacle heights were adjusted in 1 mm intervals, and the surface of the acrylic was covered with paper for consistency among tests. MEDIC was able to navigate obstacles 3 mm and lower. This shows good agreement with the model in section IV-B. Its mass distribution is such that it cannot traverse 4 mm obstacles.

C. Comparison to Other Climbing Methods

Body-supported obstacle traversal faces different limits than other methods of climbing. Many other modes of climbing are limited by the size of their propulsion mechanisms (wheels, whegs, legs) whereas body-supported climbing is mainly limited by the hull height and mass distribution.

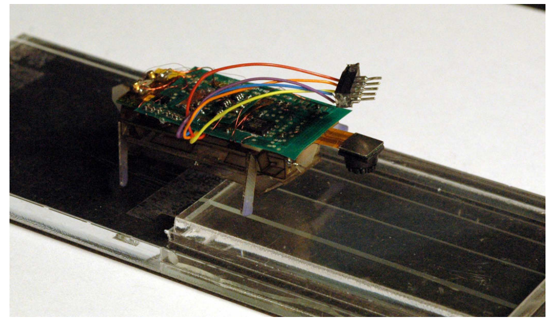

Fig. 14. MEDIC's hull will propel it up an obstacle as it walks forward.

Assuming enough thrust is available, the size of the legs for body-supported climbing is irrelevant. This may be advantageous depending on design constraints. As robot size decreases axles may not be desirable due to the effects of surface forces, making body-supported climbing appealing. In addition, as robot size decreases it becomes ever more difficult to add degrees of freedom and actuators. MEDIC's body-supported climbing allows it to climb obstacles using only four degrees of freedom and four actuators, as opposed to over a dozen of degrees of freedom exhibited by other larger robots [4] [3]. The differences in these climbing methods are illustrated in Fig. 15.

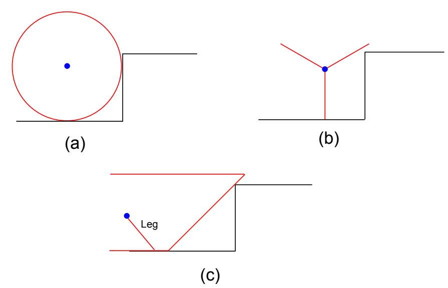

Fig. 15. (a) A wheel can only climb obstacles lower than its axle height. (b) A wheg can climb obstacles 1.5 times its axle height. (c) Body-supported obstacle traversal may mount obstacles far above its hip height, but is limited by body height and weight distribution, as shown in (2).

D. Navigation and Mobility

MEDIC is able to navigate sections of a Supermicro MBD-X7SLA-L-O motherboard (see Fig. 16). It can cover approximately 25% of the board under teleoperation.

E. Comparison to Similar Robots

MEDIC excels at navigating tight spaces. While its maximum obstacle mounting height is relatively low, its turning radius is very small. This is shown in Table V.

VII. Conclusions and Future Work

This paper has presented the mechanical and electronic design, obstacle traversal mechanics, and experimental performance results for the new robot MEDIC. Body-Supported obstacle traversal is a novel climbing mode in millirobots that is useful when continuously rotating joints may not be desirable. The robot is able to execute tight turns and

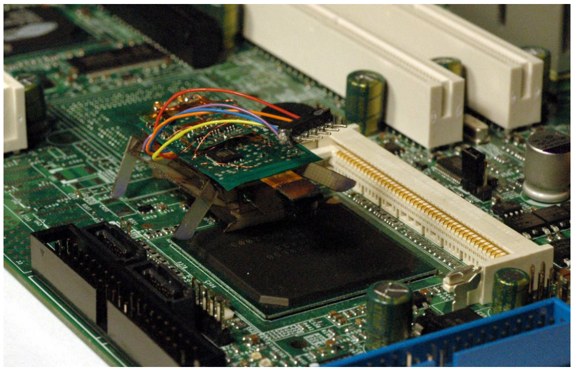

Fig. 16. MEDIC in its natural environment.

TABLE V
A COMPARISON OF SIMILARLY SIZED LEGGED ROBOTS.

Robot	Size	Mass	Turn Radius	Climbing Height
RoACH [6]	3 cm	2.4 g	2.5 cm [1]	0.1 cm
DASH [5]	10 cm	16 g	20 cm	5.5 cm
Hexbug Ant [18]	6 cm	21 g	-	> 1 cm
Mini-Whegs [1]	9 cm	146 g	17.8 cm	5.4 cm
MEDIC	5 cm	5.5 g	2.7 cm	0.3 cm

climb over obstacles. It is also able to take pictures and navigate varied terrain. The climbing models show good agreement with the experimental results and will be useful when considering future design changes.

Future work includes improving the climbing potential of the robot by moving the center of mass and using the camera for localization and navigation. In addition, the development of automatic gait tuning of the robot would be an interesting and useful learning and optimization problem. Stronger actuators would allow the robot to vault instead of slide across the ground, improving movement efficiency. Weight reduction through the use of lighter composites for the chassis would enable higher performance as well. In the more distant future, the addition of a probe to gather signals from the motherboard environment may be added.

VIII. ACKNOWLEDGEMENTS

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