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A Multi-Material Milli-Robot Prototyping Process

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Abstract— **Photo-patternable adhesives and silicones are introduced for use in centimeter-scale robotics. Traditional approaches to making robots at this size scale require the use of expensive start-up equipment and/or precise machining, and generally yield fragile and costly robots in small numbers. The multi-material milli-robot prototyping process uses Loctite® polymer products and photolithography to rapidly fabricate robust, inexpensive, and compliant robots only centimeters in size. In this paper, the process flow is described and characterized with minimum feature sizes of 0.25 mm in polymer layers 0.18 mm thick. Both commercial and ink-jet printed masks are used for the photolithography steps. Finally, a functional inchworm robot and a small gripper have been designed and demonstrated with Nitinol shape memory alloy (SMA) used for actuation. The gripper is 1.2 g and costs $3.21 in small numbers while the inchworm robot is 7.4 g and costs $7.76 in small numbers. Building a functional robot from a computer design takes less than 1 hour.**

I. INTRODUCTION

Interest in fabricating large numbers of small robots has grown recently due to applications ranging from mobile sensor networks to search and rescue. However, realizing these applications is difficult due to the extended fabrication time, cost, and fragility of current robot manufacture and design. Several mobile robots have been demonstrated at the centimeter-scale [1], [2] but they have not demonstrated robust integration and cannot currently be manufactured in large numbers. These robots also have high one-time equipment costs and can require long assembly times.

We present a multi-material milli-robot prototyping process to quickly fabricate large numbers of inexpensive, robust and compliant robots. In this work, milli-robots are defined as centimeter-sized robots with millimeter-scale features. The final goal of this project is to use the multi-material milli-robot prototyping process to test new ideas for even smaller microrobots that to this point have required a clean room and expensive silicon processing equipment to fabricate [3], [4]. In addition to the expense, these millimeter-scale mobile robots also suffer from fragile mechanisms as a result of traditional MEMS processing materials and techniques. This new process targets improved robustness through the use of polymers and compliant mechanisms.

In addition to fabrication difficulty, cost, and fragility, another challenge for small robots is moving through unpredictable environments [5]. As the robots grow smaller, obstacles around them grow proportionally larger with respect to the robot size. Combining polymers with varying material properties allows for creation of complaint mechanisms that have proven successful in overcoming obstacles and unpredictable environments at large scales [6], [7]. However, little has been done to demonstrate this in small-scale robots. In addition, polymers can be used to embed other robot components such as actuators and wiring which eliminates the danger of damage and having these components fail due to contamination (Figure 1). Similar ideas have been demonstrated successfully in larger robots using shape deposition manufacturing [8].

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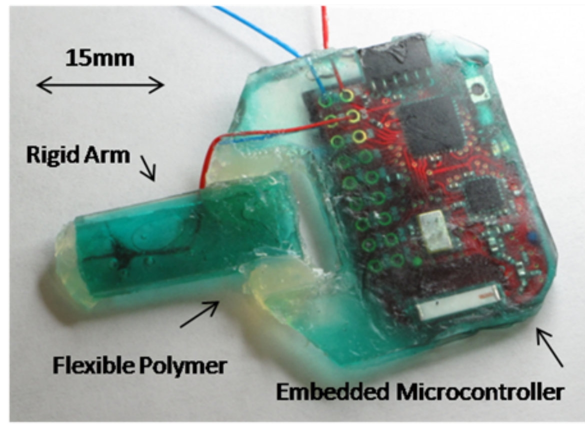

Fig. 1. Mockup of an inchworm robot with embedded radio and microcontroller (TI EZ430-RF2500) to wirelessly monitor and control the robot. The green layer is a rigid polymer while the clear is more elastic.

The process outlined in this work uses inexpensive, compliant photo-patternable materials to combine the benefits of small-scale robots with the robustness and compliance in larger-scale robots. Compliant mechanisms will improve the mobility and robustness of robots on the centimeter and millimeter-scales and can also be used to add mechanical energy storage for improved efficiency. Finally, the use of these polymers will allow many milli-robots to be fabricated in less than an hour on a benchtop instead of several weeks in a clean room or after many hours of assembly. While this process is currently limited to planar structures, separately constructed components can be stacked and folded to create more complex robots.

In Section II, we present the procedures used to create multi-material compliant robot flexures using our process. In Section III, we discuss process characterization including achievable feature resolution. In Section IV, we describe the integration of actuation into the process, and Section V describes the design, fabrication and testing of an inchworm

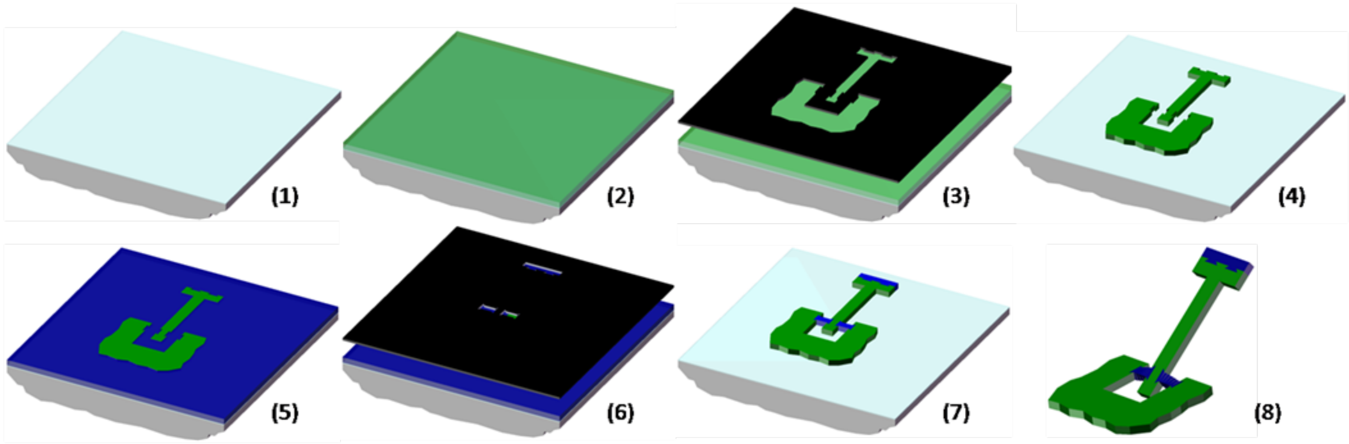

Fig. 2. The multi-material prototyping process. The different color components represent materials with different Young's Moduli - green represents a more rigid polymer and the blue is a soft, flexible silicone.

robot and a robotic gripper.

II. FABRICATION PROCESS

The goal of this research is to develop a fabrication process that is fast, inexpensive, and allows for the creation of many functional and robust robots that can be made at the centimeter and eventually the millimeter-scale. To keep the process quick and inexpensive, it should take place outside of a clean room, without expensive equipment, and all materials need to be easy to work with. For eventual use with millimeter-scale robots, the process should also be scalable to smaller sizes. Finally, batch fabrication techniques will allow for large numbers or robots to be fabricated at once.

Loctite® photo-patternable adhesives and silicones are available with a range of material properties. This paper will focus on Loctite® 3525, an adhesive, and Loctite® 5084, a silicone product. Loctite® 3525 is a modified acrylic and was chosen for its stiffness and moderate modulus of 175 MPa [9]. Loctite® 5084 is an Alkoxy silicone that has high strength and is extremely flexible [10]. These products do not have adverse health effects, so no additional protection or equipment is necessary. Choosing materials of drastically different Young's Moduli allows for investigation of robotic flexures made from both rigid and compliant parts. These materials have not been used before to create multi-material mechanical components, although Loctite photo-patternable adhesives have been used to create microfluidic devices [11].

A. *Process*

The process flow is described in Figure 2. In step 1, uncured Sylgard® 184 silicone elastomer base (without the curing agent) is spread evenly in a thin layer over the substrate. This ensures easy release of the structure after patterning is complete. This step can be avoided if using a non-stick substrate such as a surface with cured poly dimethylsiloxane (PDMS) silicone. The first polymer to be patterned is then applied in step 2. Desired thickness of the polymer is achieved by the use of spacers of known thickness such as glass slides or coverslips. For the purpose of this research, thicknesses of 180, 350 and 1100 μms were used. A given thickness can also be achieved by spin coating on a flat substrate. The exact final thickness of the cured polymer can be determined using a profilometer or calipers for thicker samples.

After the first polymer is deposited at its desired thickness, it is then patterned using an inexpensive transparency mask in step 3. The polymers used for this demonstration were negative resists so all masks were dark field. The masks used were also coated with a thin layer of Sylgard® 184 elastomer base to prevent the polymer from bonding to it. The polymer is then cured directly under the light from a portable UV lamp (Spectroline®, EN-180, 365 nm). Cure times for the polymers at each thickness are displayed in Table I and are generally a couple minutes long, depending on layer thickness.

After curing, the mask is removed. Uncured polymer is washed away mechanically with water, followed by a solvent such as acetone. After this, the polymer is given a final rinse with water to remove any re-deposited polymer and excess acetone in step 4. In step 5, the second polymer is applied. It is flattened to the desired height using spacers or the height of the first cured polymer. This second polymer is patterned with its respective mask in step 6, and cured and rinsed using the same technique as noted previously in step 7. More polymers can be patterned in subsequent steps, although only two are used in this paper. Finally in step 8, the entire structure is peeled from the substrate with the resulting fabricated structure shown in Figure 3. All parts of this process were carried out under normal lighting conditions and can be done outside of a clean room environment. The process and final results are shown in the attached video.

Although fabrication is limited to a planar process, this process can be used to make mechanisms that are not limited to planar structures. Layers can be stacked or folded to create three dimensional structures similar to those in [1], [12] as seen in Figures 4 and 5. However, this added design

TABLE I
CURE TIMES FOR POLYMERS (MIN:SEC)

Thickness (μms)	Loctite® 3525	Loctite® 5084
180	0:50	2:20
350	1:40	4:70
1100	7:30	8:00

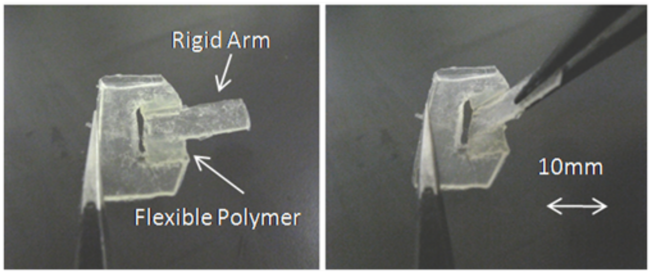

Fig. 3. A 0.3 g bi-material torsion hinge produced with the multi-material prototyping process.

complexity limits the ability to batch fabricate components.

B. Process Considerations

Several additional process steps can be used to add to the basic functionality described in the multi-material prototyping process. For example, embedding components as seen in Figure 1 needs to take place before the polymer is cured. The components, e.g. the controller or actuators, can be placed in the uncured polymer, pushed down or covered with additional polymer and the process can continue as described above. In addition, a diluting material can be added to create thinner layers with viscous polymers. This has been demonstrated with silicone using n-heptane to dilute and spin-coat a material that otherwise would not be capable of producing consistent layers [13]. During the curing process, the polymers must be covered to protect from oxygen exposure. In the process previously described, the mask served as an oxygen barrier, however if contact lithography is not used, it is necessary to cover the polymer separately or create a nitrogen environment. Without this, the polymer will react with the oxygen during crosslinking and leave a layer of uncured polymer [11].

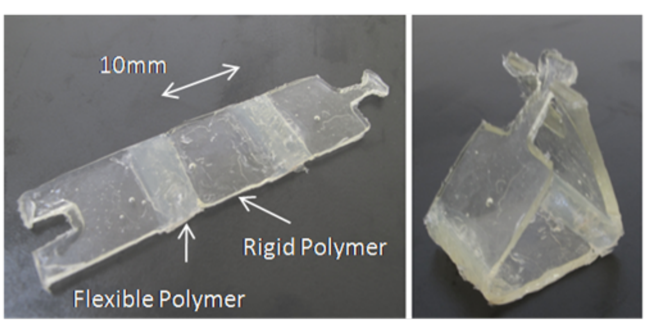

Fig. 4. Planar bi-material features can be fabricated, folded, and secured out-of-plane to build 3-D structures.

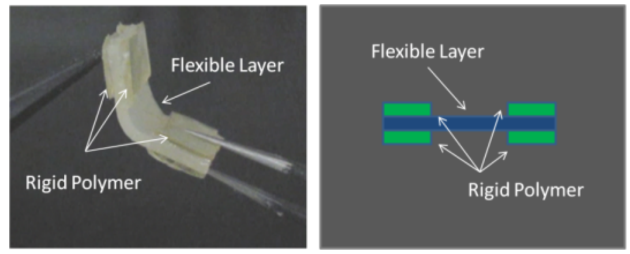

Fig. 5. Layers can be fabricated on top of each other or stacked to form complex 3-D structures.

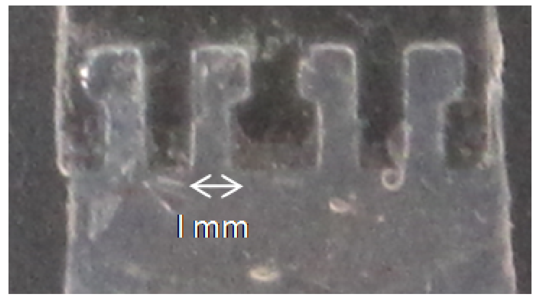

Fig. 6. Adhesion enhancement structures.

The cured polymer, particularly in thicker samples, will often get small bubbles of trapped air. These have not seemed to affect the functionality of our components; however, at a smaller scale it is feasible that they may become a more significant problem. This can easily be managed by placing the setup in a vacuum to pull the bubbles out. It is also important to note that the cured polymer will appear cloudy even in the absence of such bubbles and regardless of the cleaning process.

Determining the order in which polymers are applied can also be important. The first polymer to be applied is typically the one with better feature resolution, although reversal of this order is possible and will still yield results. However, smaller features and improved designs were seen by defining the smallest features first.

Finally, the device will release from the substrate more easily when it is allowed to cure for a bit longer in ambient air and light after all excess polymer has been removed. A few hours will allow it to completely finish curing and the result can be easier to work with. However, this step is not necessary and similar results are obtained without taking this extra time.

III. PROCESS CHARACTERIZATION

To support usability and scalability in the multi-material prototyping process, bond strength between polymers and feature size resolution are both characterized. Initial characterization by manually pulling apart two attached polymers has demonstrated strong adhesive bonds between Loctite® 3525 and 5084 by simply curing the polymers in contact with each other. However, this result does not occur

TABLE II

RESOLUTION WITH COMMERCIAL MASK

Thickness (μm)	Loctite® 3525	Loctite® 5084
180	250 μm	1250 μm
350	500 μm	1250 μm
1100	2000 μm	3750 μm

TABLE III

RESOLUTION WITH INK-JET MASK

Thickness (μm)	Loctite® 3525	Loctite® 5084
180	750 μm	2000 μm
350	1000 μm	3000 μm
1100	2000 μm	20 mm

with all Loctite® photo-patternable adhesives. For example, Loctite® 3108 does not adhere well to 5084. Bonding can be enhanced by use of structures to increase bond surface area when using products that do not bond well together or when there is only a limited surface area for bonding. Finger-like protrusions and other mechanical shapes have been demonstrated to increase surface area and bonding between polymers (Figure 6). Future research is still needed to test the strength of the bonds and their durability over spans of time and number of uses.

Minimum feature sizes are shown in Table II and Table III and were measured using the resolution test in Figure 7. For the purpose of this research, resolution was defined as the smallest feature that could be resolved without growth surpassing ten percent of the intended feature size. Growth is defined as fabricated feature expansion beyond the feature drawn on the mask. These tests were carried out using commercially purchased laser printed masks (˜$25/mask) as well as extremely inexpensive masks made with an ink-jet printer (Canon Pixma iP4500, 9600x2400 dpi) on inkjet film (AccuBlack® from Chromaline®). At less than a dollar per sheet, and immediate turnaround, the process time and cost is further reduced by printing the mask instead of out-sourcing it. However, one drawback of inkjet printing is lower resolution.

As seen in Tables II and III, feature sizes increase with increased thickness regardless of the mask type. There is significantly more growth when a thicker layer of polymer is used, so the minimum feature size becomes much larger. Loctite® 5084 minimum feature sizes are larger than those of Loctite® 3525. Loctite® 5084 also becomes very weak at thicknesses less than 300 μm. As a result, it is difficult to achieve freestanding and defined features at this size with Loctite® 5084. To solve this problem, a stronger polymer should be used at these thicknesses. In addition, smaller feature sizes do not retain full layer thickness. This is likely due to exposure intensity and polymer chemistry, although further testing is needed to determine exact cause.

IV. INTEGRATING ACTUATION

Once compliant mechanisms have been designed, the next step is to integrate actuators with the prototyping process. Shape memory alloy (SMA) wires were chosen for the robot actuators (Flexinol® Nitinol 0.0100" dia) due to their simplicity and robustness. SMA has also been processed and demonstrated at the micro-scale [14], [15], [16]. These metal wires have the ability to "remember" a predetermined shape and return to it when heated. The popularity of using SMA as an actuator is growing due to its several advantages including high-power to weight ratio and the large deformation capacity.

Shape memory alloys are also relatively easy to work with. For actuation of the robot flexures in Section II, large displacements were required. For this reason, SMA was trained into tightly wound coils. The untrained SMA was wrapped around a metal rod of desired diameter (Figure 8) and placed on a pre-heated hot plate at 540 °C (Fisher Scientific Isotemp Ceramic120 V, 60 Hz). The SMA was then removed after 20 minutes, at which point it was quenched in water to ensure swift cooling. This step is necessary to avoid brittleness in the SMA. After removing the SMA from the metal rod, it is ready to be integrated into the polymer robot.

Once trained, it is important not to over stretch the actuator because this will deform the SMA plastically and it will not retain its shape memory. It is also important that the SMA is not heated much higher than the activation temperature. This will result in the SMA working poorly or failing to work at all. In addition, it has been shown that the coils, if left in tension for long periods of time on the order of several

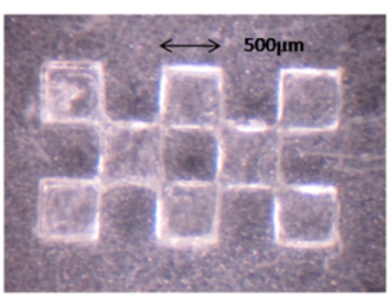

Fig. 7. Resolution test of 180 μm thick Loctite® 3525. Feature sizes are 500 μm.

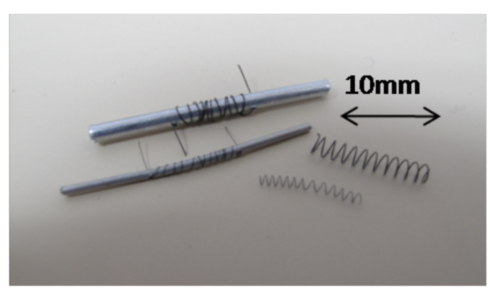

Fig. 8. Setup for training shape memory alloy (SMA) into tightly wound coils for robot actuation. Heating after deformation will return the springs to their trained position.

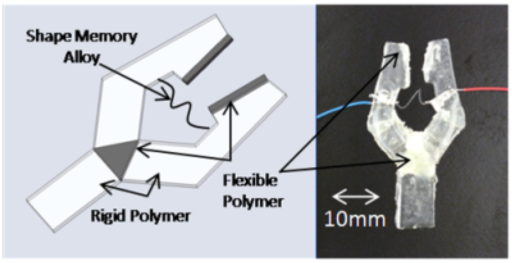

Fig. 9. Gripper made using the multi-material prototyping process.

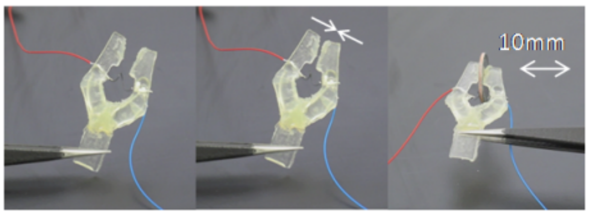

Fig. 10. Frame shots of gripper actuation. In the last frame, the gripper holds a dime.

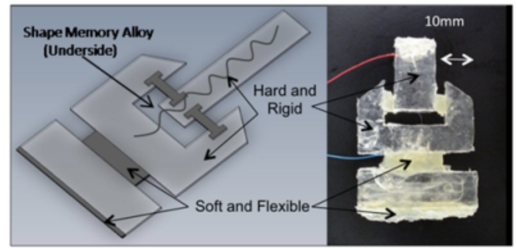

Fig. 11. Design of a 7.4 g inchworm robot with a 1.2 cm step size.

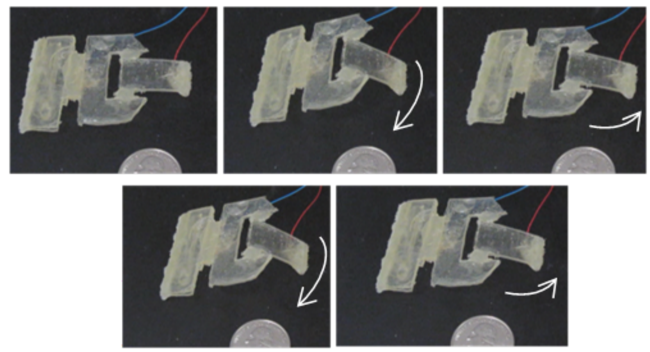

Fig. 12. Frame shots of an inchworm robot walking forward. A quarter is placed for scale.

weeks, will also lose some memory and not fully return to the trained form when heated.

After the SMA is trained and cut to the desired shape and size, metal clips are attached to the ends. Wires cannot be directly soldered to the SMA using traditional solder, so the wires are instead soldered to these clips. The ends of the SMA can then be embedded into the polymer during fabrication and the polymer is cured with the SMA in position.

SMA is a high power actuator. However, it is also inefficient and therefore unacceptable for the final goal of building autonomous robots. For this reason, these actuators will be eventually be replaced with low-power actuators such as electrostatic inchworms, PZT, or dielectric elastomer actuators (DEAs) [17], [18]. The advantage of DEAs is that these could eventually be batch fabricated with the mechanisms since similar compliant polymers are required.

V. Robot Design and Results

A. Gripper Arm Design

Using the process described above, a one degree-of-freedom gripper arm was fabricated using a single piece of shape memory alloy for actuation. The Solidworks® design is shown juxtaposed with the fabricated device in Figure 9. This gripper uses the softer Loctite® 5084 as a compliant joint between the two gripping fingers as well and also provides a softer material on the fingers. This added compliance allows the gripper to grip objects of varying sizes and shapes [6]. The more rigid Loctite® 3525 serves as the gripper skeleton and a single piece of SMA is used to pull the fingers together. This fabricated gripper is approximately 40 mm long, 20 mm wide, and 1 mm thick, and weighs 1.2 grams. In Figure 10 frame shots are shown of the gripper actuating and grasping a dime. This gripper was put through testing to determine its long term durability. After over 5000 cycles and three days, the gripper continued to actuate.

B. Inchworm Robot Design

To further illustrate the capability of this process to fabricate mobile robots, we have fabricated a tethered, one degree-of-freedom crawling robot as seen in Figure 11. The polymers were strategically placed to provide the friction characteristics needed for the robot to move forward in an inchworm-like gait. The soft Loctite® 5084 is placed on the end of the robot to anchor the back of the robot when the leg is released. A separate stacked layer of Loctite® 3525 on the back of the robot allows the robot rear to slide forward when the leg is actuated. This crawling motion from directional friction is possible due to the varying coefficients of friction of the two polymers used.

The current inchworm robot uses a single SMA wire for actuation, and frame shots of the robot crawling can be seen in Figure 12. The final prototype is less than 7 cm long, 4.5 cm wide, 2 mm thick and weighs 7.4 grams. The robot step size is measured at 1.2 cm. While this robot only demonstrates a single degree of freedom leg, the process can easily be extended to fabricate more complex multi degree of freedom robots in the future. Both demonstrations presented in this work have easily survived multiple several-foot drops.

C. Robot Cost Analysis

A primary motivation for this research is to find a cost and time effective alternative to the expensive traditional methods of prototyping small-scale robotics. For this process, there are several one-time costs as well as per-device costs, as

TABLE IV
COST ANALYSIS-ONE TIME COSTS

Product	Cost
Ink-Jet Printer (Canon PIXMA iP4500)	$119.99
UV Lamp (Spectroline EN-180 365 nm)	$157.77
Hot Plate (Fisher Scientific Isotemp Ceramic 120 V)	$232.87
Glass Microscope Slides (Quantity:72)	$49.40
Sylgard 184, 0.5 kg	$51.86
Acetone, 4 L	$98.40
	Total $710.29

TABLE V
COST ANALYSIS-PER GRIPPER COSTS

Product	Cost
Mask Film (assuming ink-jet printed)-one sheet	$0.96
Transparency Substrate-one sheet	$0.60
Shape Memory Alloy (0.01" dia-$35/25 ft)-approx 1 inch	$0.14
Loctite® 3525 ($28/25 ml syringe)-1 ml	$1.40
Loctite® 5084 ($68.75/10.8 fluid ounces)-0.5 ml	$0.11
	Total $3.21

seen in Tables IV,V, and VI. These costs include a printer for mask production, a UV lamp for curing polymers, and a hot plate for training of SMAs. Per device costs include the polymers, transparencies for mask production, and SMA for actuation. The majority of the per-device cost is the polymer materials. These costs can all be reduced by buying in large, bulk quantities. Costs can also be reduced by recycling the masks.

The second advantage of this process is that it allows for prototyping of many designs quickly. Designs can be designed, fabricated, analyzed, and re-designed in short periods of time. Moving from a robot design to a fabricated and functional robot takes less than one hour.

VI. CONCLUSION AND FUTURE WORK

Current small scale robots are expensive and require lengthy fabrication and assembly times. These robots also lack the compliance and robustness to perform well in unstructured environments. This paper has described a new process to rapidly prototype inexpensive and robust centimeter-scale robots without the use of clean room facilities or expensive equipment. The use of Loctite® photo-patternable polymers can create several possibilities in the field of small robotics by eliminating the expense, fragility and complexity of traditional small-scale robots.

Future research will pursue prototyping more complex and efficient robots with reduced feature sizes. Efforts will be made to integrate more efficient actuators such as dielectric elastomers and other actuation techniques as well as explore other methods of locomotion to improve robot efficiency. A future objective is a fully autonomous walking robot with an attached gripper, possibly for multi-robot assembly, with embedded components. Finally, further testing of durability and long term use of the polymer structures are also extensions to this work.

TABLE VI
COST ANALYSIS-PER INCHWORM ROBOT COSTS

Product	Cost
Mask Film (assuming ink-jet printed)-one sheet	$0.96
Transparency Substrate-one sheet	$0.60
Shape Memory Alloy (0.01" dia-$35/25 ft)-approx 2 inch	$0.28
Loctite® 3525 ($28/25 ml syringe)-4 ml	$5.60
Loctite® 5084 ($68.75/10.8 fluid ounces)-1.5 ml	$0.32
	Total $7.76

VII. ACKNOWLEDGMENT

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