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Mass Manufacturing of Self-Actuating Robots: Integrating Sensors and Actuators using Flexible Electronics

Artem Dementyev[1], Jie Qi[1], Jifei Ou[1] and Joseph Paradiso[1]

***Abstract*— Currently, the manufacturing of self-actuating and self-sensing robots requires non-standard manufacturing techniques and assembly steps to integrate electrical and mechanical systems. In this work, we developed a novel manufacturing technique, where such robots can be produced at a flexible electronics factory. We developed the technique using standard industrial machines, processes, and materials. Using a lamination process, we were able to integrate air pouches or shape memory alloy (SMA) inside a polyamide-based flexible circuit to produce bending actuators. The bend angle of the actuators is sensed with a chain of inertial measurement units integrated on the actuator. Air-pouch actuators can produce a force of a 2.24N, and a maximum bend angle of 74 degrees.**

To demonstrate, we manufactured a five-legged robot with the developed actuators and bend sensors, with all the supporting electronics (e.g., microcontrollers, radio) directly integrated into the flexible printed circuit. Such robots are flat and lightweight (15 grams) and thus conveniently compact for transportation and storage. We believe that our technique can allow inexpensive and fast prototyping and deployment of self-actuating and self-sensing robots.

I. INTRODUCTION

Manufacturing robots is a time-consuming task with a steep learning curve. It requires the integration of a large number of mechanical parts, electronics, and sensors. To alleviate this issue, recent research has investigated self-assembling robots [1], [2], [3]. Often starting as sheets, such robots self-assemble into the required shape with the use of external or internal stimuli (e.g., heat, air, magnetic fields). They offer a number of advantages such as easier and faster manufacturing, transportation and deployment. Currently, however, self-folding and self-actuating robots are made using nonstandard manufacturing processes which make difficult to build at scale.

In this paper, we explore how self-actuating and self-sensing robots can be made using only flexible electronics manufacturing processes. This offers multiple advantages such as mass production with standard technology and direct integration of sensors and actuators. Because the assembly can undergo standard pick-and-place surface mount assembly (SMT) and reflow processes, it requires little post-processing and manual assembly. Furthermore, this manufacturing technique does not require any molds or stamps, further allowing for faster production. We were able to develop our process using standard manufacturing procedures and materials during a 1-month residency at a flexible electronics factory in Shenzhen, China.

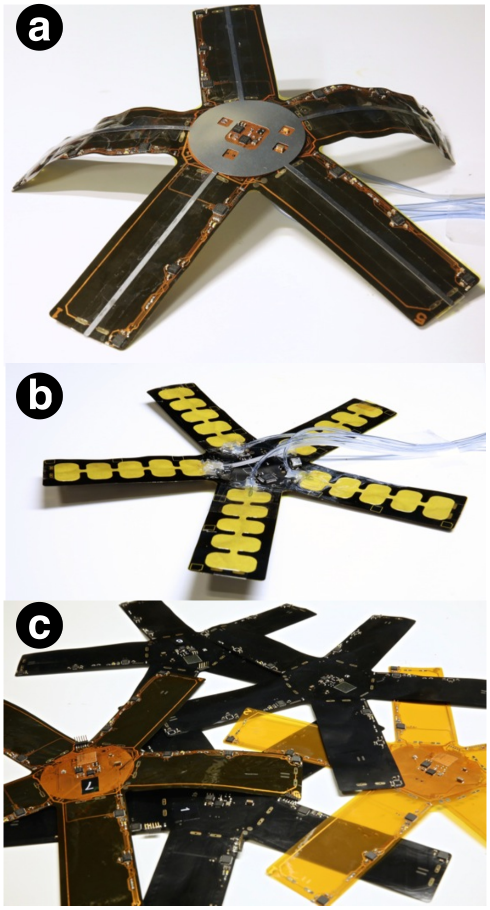

Fig. 1. The 5-legged robot created with the manufacturing technique introduced in this paper. A) The top of the robot with some inflated air-pouch actuators. The electronics and the metal skeleton are visible. B) The bottom of the robot to show the air pouch-based actuators. C) Some of the robots manufactured in the factory. The technique allows for mass production of self-actuating robots.

Flexible circuits are commonly employed in consumer, space and military applications because they are lightweight and can conform to complex shapes. The core is typically made out of polyimide polymer (PI), often called by its commercial name Kapton, and laminated with copper [4]. The PI polymer can resist high temperatures of up to 400^{o}C and is an excellent electrical insulator (dielectric constant=3.4) [5]. In this work we created a process which allows embedding air pockets inside the flexible printed circuit (FPC), enabling

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[1] Artem Dementyev, Jie Qi, Jifei Ou and Joseph Paradiso is with Media Lab, Massachusetts Institute of Technology, USA `artemd@media.mit.edu, jieqi@media.mit.edu, jifei@media.mit.edu, joep@media.mit.edu`

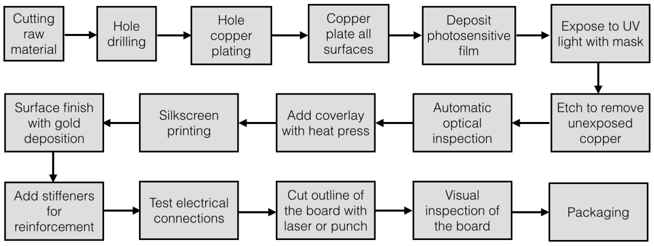

Fig. 2. Process diagram of flexible circuit manufacturing.

Fig. 3. Pictures of selected manufacturing steps in the factory. a) The technician is placing the flexible PCB in a heat press to laminate the coverlay. b) Vinyl cutting the wax paper for creating air pouches c) Manual alignment of the coverlay followed by temporary attachment of the coverlay with a cloth iron. d) The SMT assembly line used to assemble the robots.

pneumatic or shape memory alloy (SMA) actuation.

To facilitate assembly, researchers have explored self-folding mechanisms for robots as well as static objects. One early work named ”Programmable Matter” [6] demonstrated self-folding materials with origami patterns and SMA actuators. More recent works demonstrated robots that are capable of transforming from a flat sheet by heating shape memory polymers [1], [2] or by external magnetic fields [3]. While these robotic assemblies rely on rigid materials for structure, other methods use more flexible materials. A more recent approach demonstrated air pouches using heat sealing [7], to allow air inflation to actuate bending. Similarly, previous research showed that it is possible to heat flexible circuits to produce actuators [8]. However, it is still difficult to produce such mechanisms in large scale quantities because they require unconventional manufacturing materials and techniques.

Soft robotics is another line of research that attempts to create self-actuating robots using compliant materials such as silicone. These typically employ pneumatic actuation and silicone molded actuators [9]. Such robots can even be untethered using onboard pumps [10] or chemical reactions [11] to drive actuation. Other approaches explored include using shape memory alloy actuators [12] or electroactive polymers [13]. Although soft robotics is promising, it is still not compatible with current high volume manufacturing processes, as it requires multiple manual molding steps to create the actuators.

Previous research shows the integration of shape sensing [14] into a flexible actuator using pressure sensors and inverse kinematics. Also, another approach laminated resistive sensors into the robot’s joints, to sense the bend angles [15]. Finally, a string of inertial measurement units (IMUs) on flexible electronics substrates can sense 3D deformations [16]. In this work, we employ a similar IMU-based approach, as it is proven to be compatible with flexible electronics.

In this paper, first, we describe the manufacturing process of integrating two types of actuators into flex circuits: pneumatic and shape memory alloy. Then, we describe how we sense the actuator’s bend angle using inertial measurement units (IMUs). Next, we describe the design and development of a five-legged robot as an example artifact enabled by our process, shown in Fig. 1. The robot contains both the actuators and bend sensors all integrated into one flexible circuit. Finally, we conduct various tests of the process and our example artifacts such as how much force actuators produce. We follow up with a discussion of the limitations and future directions.

The main contribution of the paper is the novel mass production process that integrates actuators and electronics. In this context, we developed a five-legged robot that can sense its shape to potentially provide closed-loop control.

II. DESIGN AND FABRICATION

We describe the fabrication process using the example of the 5-legged robot.

A. *Manufacturing*

The diagram of the standard flexible electronics manufacturing is shown in Fig 2. The process is similar to rigid PCB production, but the flexible polyimide (PI) substrate is used instead of rigid FR4. Also, a laminated plastic coverlay is used instead of a screen-printed solder mask, as solder mask will crack during bending. The coverlay prevents oxidation of copper and electrical shorts during soldering and also makes the flexible printed circuit (FPC) more robust to bending. The coverlay is either die cut or laser cut, depending on the complexity and quantity. The PI coverlay comes with an adhesive acrylic coating and is laminated using a heat press with 12MPa, 180^{o}C for 5 minutes, as shown in Fig. 3. Then, it is baked in the oven for 30 minutes at 170^{o}C to further improve adhesion. Before lamination, the coverlay is aligned by hand and temporarily secured with a clothing iron in the corners.

We found that we could insert non-sticky wax-coated paper on the circuit before the coverlay is added. In locations with a wax paper, coverlay does not stick to the circuit, thus creating an airtight empty space that can be used as an air pocket or for an addition of shape memory alloy. We cut the wax paper with a vinyl cutter (CE6000-40, Graphtec). The coverlay initially came with a wax paper backing that prevents damage to the covelay during handling. Typically

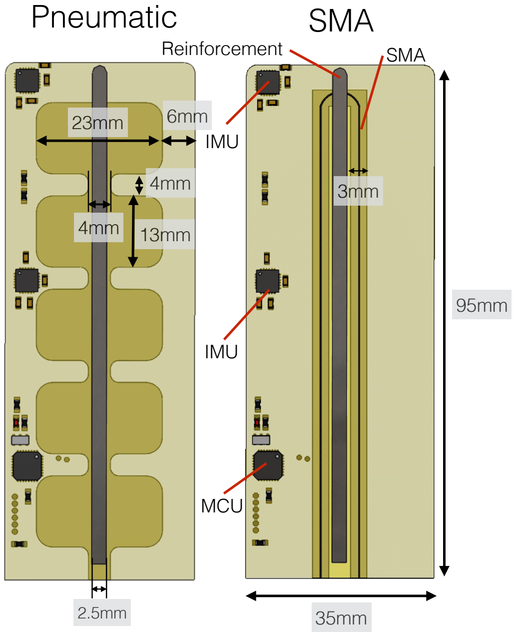

Fig. 4. The design specifications of the pneumatic and shape memory alloy actuators.

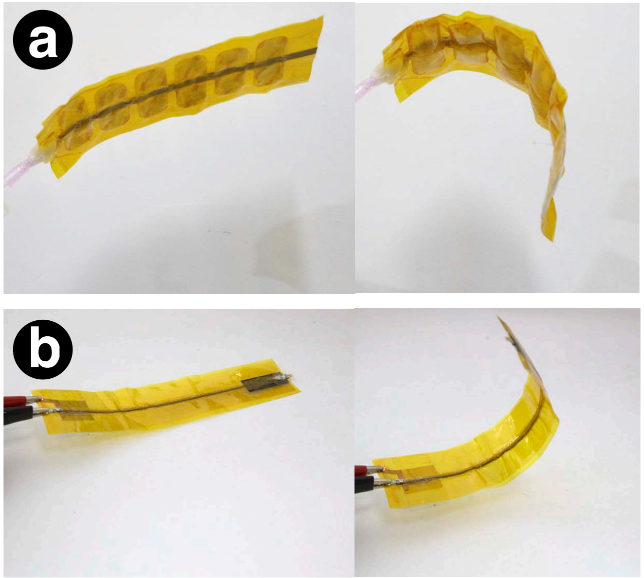

Fig. 5. Testing the two actuator mechanism prototypes. a) Pneumatic actuator before and after inflation. b) Shape memory allow actuator before and after current is applied.

it is thrown out, but we used it to make pockets under the coverlay.

Often the flexible circuits contain stiffeners, for example, to reinforce the area under a USB connector to prevent delamination during plugging and unplugging. Stiffeners are made from thicker PI or stainless steel, and laser cut for small quantities or die cut for larger quantities. We found that stainless steel stiffeners served two essential functions: adding structural integrity to the FPC and working as springs. All the PI materials were too flexible for structural support.

Manufacturing required a few manual post-processing steps. The wax paper still slightly adhered, so a thin piece of metal (0.2mm) was slid under the coverlay to help to release wax paper. Furthermore, the air actuators had to be sealed and connected to a pump with a hose. Currently, we used hot glue to create an airtight seal. The shape memory alloy wire was threaded through the air channel under the coverlay to create a bending mechanism.

All circuit design was done using PCB design software (Altium Designer V18) which allowed us to design the electronics and actuators in the same 2D environment. The electronics were exported as Gerber files for manufacturing. The actuators and reinforcement were designed as mechanical circuit layers and exported in AutoCAD DXF format to the machines (laser and vinyl cutters).

We used a PI substrate that is identical to DuPont's Pyralux AP brand and coverlay identical to Pyralux LF. To save on manufacturing costs, the factories in China used locally sourced materials.

B. *Actuator Design*

We demonstrate two types of actuators: pneumatic and shape memory alloy. Pneumatic actuators are faster and generate more force, but currently, require a tether to external pumps. The shape memory actuators allow an untethered robot but provide lower speed and force. We used diaphragm pumps (KPM27R, Koge Electronics Co.) controlled with relays (SDR-05VDC, Sonole) and pressure sensors (ADP5151, Panasonic). We use NiTi 0.25mm diameter shape memory alloy (Flexinol HT) wire. This wire contracted when heated by electrical current, causing the actuator to bend. Laser cut stainless steel reinforcement (thickness=0.2mm) was added to the top of the actuator to create directional bending and allow the actuator to spring back to its original shape. The detailed dimensions of the actuator are shown in Fig. 4. The principal dimensions of the actuator were chosen to maximize the space used on the standard 240x240mm flexible PCB sheet.

The challenge of the pneumatic actuator is to avoid delamination during inflation. To do so, the 90^o corners of the pneumatic actuator were slightly curved. Also, we found that a minimum seal distance of 4mm around the actuator is required to provide a reliable airtight seal at 40KPa.

C. *Actuator Bend Sensing*

Closed-loop control requires sensing of the deformation of the actuators. We use a chain of inertial measurement units (IMU) for shape sensing. The IMUs are inexpensive and simple to integrate as they require no modification to the mechanical structure and can be picked-and-placed along with other components. Each actuator leg contained 2 IMUs and the center of each robot contained another IMU, providing a total of 11 IMUs. The locations of the sensors are shown in Fig. 4 The deformation of the leg in x, y plane for each IMU node n can be estimated using inverse kinematics

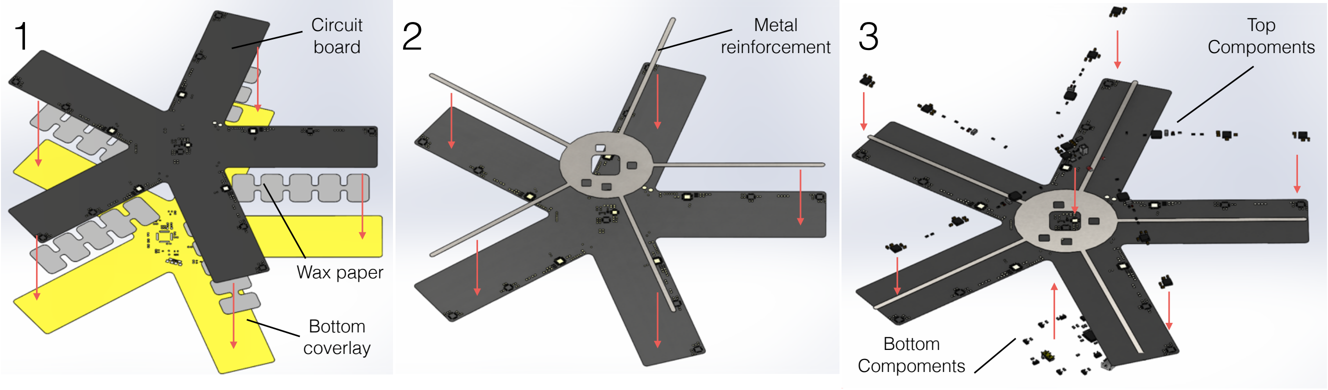

Fig. 6. The main manufacturing steps. 1) First, the air pockets are created by placing the wax paper between the bottom coverlay and the circuit. The previous circuit fabrication steps are standard and are not shown. 2) The metal reinforcement is laminated on top using double-sided adhesive. 3) Finally, the electronics components are populated on top and the bottom of the robot by a pick-and-place machine.

with the following equations:

$$x_n = x_{n-1} + h\cos(\theta_n) \tag{1}$$

$$y_n = y_{n-1} + h\sin(\theta_n) \tag{2}$$

Where θ is the rotation angle, h is the distance between the IMUs. We had to make some assumptions about the deformation model. Namely, that the distance h remains constant and the bending only happens in the x, y plane, without twisting. It is worth noting that this approach scales to an arbitrary number of IMUs, so the accuracy increases with more sensors.

The rotation angle θ can be determined by integrating the gyroscope:

$$\theta_n = \theta_{n-1} + d\theta_n - ct \tag{3}$$

where c is the measured gyro drift constant, t is the elapsed time, and $d\theta_n$ is the gyro rotation rate.

D. Robot Design

We chose the five-legged robot design for its ability to move in any direction using the same curling actuators. The actuators are identical to the ones described previously. The movement is achieved by simultaneously curling and uncurling actuators on the opposite sides. The robot design was inspired by a starfish movement.

Each leg of the robot contained a low-power microcontroller (Atmega328P, Atmel) and two inertial measurement units (IMU), each with a 3-axis accelerometer and gyroscope (MPU6050, Invensense). Also, the robot contained a more powerful 32-bit ARM M0 microcontroller (ATSAMD21G, Atmel) in the middle, that communicated to the legs with the I2C bus to collect orientation data. It also communicated to a radio chip (NRF24L0+, Nordic) to allow wireless control. The center of each robot contained one more IMU to provide the reference angle for the bend measurements.

To solder the electronic components on the robot, a standard factory surface mount technology (SMT) process was used. The solder paste was screen printed using a stencil. Components were populated with an automatic pick-and-place machine and soldered in a reflow oven at a peak temperature of 217^{o}C. We made 15 robots in our first manufacturing run.

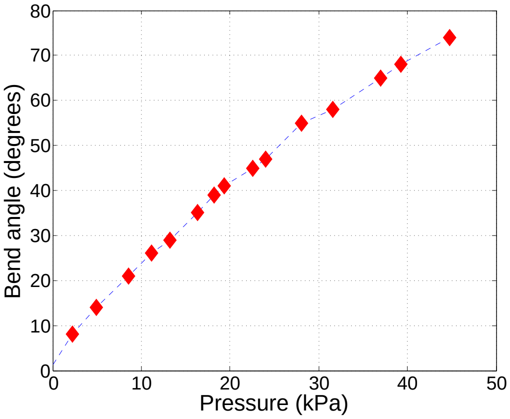

Fig. 7. Measured bend angle of the pneumatic actuator at different air pressures.

III. RESULTS

A. Actuators

The curling of the actuators is shown in Fig. 5. The tested specifications are summarized in Table I. The pneumatic actuators can create a peak force of 2.24N at 41.6kPa and had a maximum bend angle of 74^o. The force is determined by the maximum pressure, as at higher pressure, the actuators burst. The SMA actuator provides a peak force of 0.86N at 3.2V and 1A. The forces were measured using a digital force gauge (DFS20, Nextech). The speed of the pneumatic actuator was 60^o/sec for curling and 420^o/sec for uncurling. The actuator went from 0 to 70^o in 1.17sec and back to zero in 0.168 sec after the air valve was opened to the atmosphere. The uncurling speed is faster, as it is facilitated by the metal spring, made from the reinforcement material. The speed of curling is 6.4^o/sec and uncurling is 3.75^o/sec for SMA actuator. The actuator went from 0 to 30^o in 4.7sec, and back in 8sec. To avoid overheating the SMA wire we used a voltage of 3.2V in the experiments. The pneumatic actuator greatly outperforms SMA in speed, since the SMA actuator speed is limited by the passive cooling and heating. The pneumatic actuator performed better on all tests as well but required an external pump. The speed of the actuators was measured by video analysis with a camera at 50fps (Canon, Mark IV).

The bend detection has a mean error rate of 6.4% as compared to reference angles. In Fig. 7, we show how the bend angle changes with the air pressure. The angle sensed by IMU is proportional to the air pressure. This potentially allows for fine control of the bend angle by adjusting the pressure by cycling the pump on and off.

TABLE I

THE SPECIFICATIONS OF TWO TYPES OF ACTUATORS

Actuator	curl speed	uncurl speed	max angle	peak force
SMA	6.4^0/sec	8.0^0/sec	30^o	0.860N
Pneumatic	60^0/sec	420^0/sec	74^o	2.24N

B. Robot locomotion

Using pneumatic actuation the robot can move at the speed of 1.73cm/sec. Using the shape memory allow the robot can move at the speed of 0.4cm/min. We found that the robot was prone to slippage as it was light and had a small contact area on the feet. To improve traction we weighted down each leg with a piece of metal (10 grams). The weight of the robot was 15 grams without the metal weights.

C. Manufacturing

Our process slightly increases the manufacturing time compared to a standard two-layer flexible PCB. The actuators have to be manually placed and aligned between the PI layers, and secured with a hot clothing iron. This took about 1 minute per device. The price is about \$500 USD per $25cm^2$ for a single sheet (1 robot) as this mostly covers the setup costs (e.g., making masks, stencils). Each additional sheet will only cost a few dollars, as most of the initial cost is for the setup of machines.

IV. DISCUSSION AND FUTURE WORK

There are limitations to this manufacturing technique. The copper traces can crack under repeated bending cycles or large bend angles. Polyimide substrate does not stretch much, which can be a disadvantage in pneumatic applications. Stretching allows for higher air volume inside the pouches, thus providing higher forces. Also, this technique only works with a limited selection of materials, as all the materials have to be able to withstand the high temperature of up to 220^oC and high pressure (12MPa) during lamination and reflow. Furthermore, the lamination process only allows thin and flat materials. In the future, we plan to experiment with other substrates such as polyurethane, which provides a higher degree of stretch and is more robust to bending.

There are other possible applications of this technology, besides robotics. This approach can be used to assemble three-dimensional electronic circuits, without a need for post-processing. In such a case, the actuators would only be used once. Also, this approach can be applied to create new wearable devices that conform to the body and can be inflated on demand to provide more support.

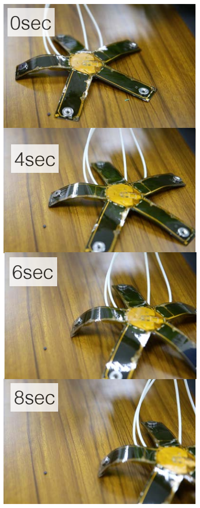

Fig. 8. Snapshots of the air actuated robot moving.

At times, we had a difficult time convincing the factory workers in Shenzhen to try the experimental methods. Understandably, the factories are conservative in their processes, as they don't want to damage the machines or decrease the yield. Widespread adaptation of this technique will require the factories to add this technique to their standard procedures, and this might take time.

We found the design process to be time-consuming since there are currently no tools designed for the integration of electronics and actuators. This also creates a high barrier to entry as circuit design process, mechanics and software have to be well understood. Also, the electronics have to be carefully designed to prevent cracking of copper traces under bending. In the future, we hope to create design software environments that will automatically allow designing actuators and sensors embedded into the flexible circuits. For example, generating actuator shape based on the design requirements such as shape, force, and range of movement. Furthermore, such software will automatically position and route the bend sensors.

V. CONCLUSIONS

In this work, we integrated actuators and sensors by only using standard flexible electronics manufacturing. The key to creating actuators was a modification of the lamination process of the coverlay. As a showcase, we developed a 5-legged robot using this manufacturing technique. The legs of the robot contain a chain of IMUs, that measure the shape of the leg, thus enabling future closed-loop controls. The legs were actuated by either inflating air pouches with external pumps or heating shape memory alloy, which allows the robot to be untethered.

We believe that our scalable process allows the creation of self-actuating and self-sensing robots using standard manufacturing techniques. Such robots are manufactured flat and lightweight (15 grams), thus easy to pack and transport. We hope that this manufacturing technique will bring a wider adaptation of robotics technology, as it allows one to quickly manufacture thousands of robots. We imagine that the robots will be able to one day walk out directly from the factory.

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