Towards Automatic Assembly of Sub-Centimeter Millirobot Structures

Ranjana Sahai, Jusuk Lee, Ron Fearing
EECS Department, University of California, Berkeley, Berkeley, CA 94720

Abstract

We describe new fabrication methods using fixtures and milli-robots (orthotweezers) to fold pre-cut stainless steel sheets into microstructures, bond them, and attach strain gages. The fixture developed for folding triangular structural elements, with the angles for sequential folding chosen through a theoretical analysis, as well as the steps taken to automatically assemble the beam and attach the strain gages are described in detail. By completing the folding, bonding, and microassembly steps, we plan to build a self-contained desktop rapid prototyping system.

Introduction

This paper describes new tools for rapidly prototyping sub-centimeter mechatronic structures and sensors by combining folding and micro-assembling operations. The tools presented here are designed to be a minimal set of robust primitives that can eventually be combined to make a fully automatic, desktop assembly process for milli-robots. For structural elements, we use hollow triangular beams that serve as building blocks for 2-D and 3-D structures. For sensing, we attach semiconductor strain gages using an orthotweezers micromanipulator.

The present work aims to develop efficient, reliable, and flexible fabrication methods to achieve the final 3-D configurations. Fig. 1 shows a block diagram of the assembly process from a flat sheet to the 3-D structure. Although full automation is the goal, the current work focuses on automating or creating fixtures for those tasks most difficult to perform by hand (folding the small beams and precise positioning in assembly).

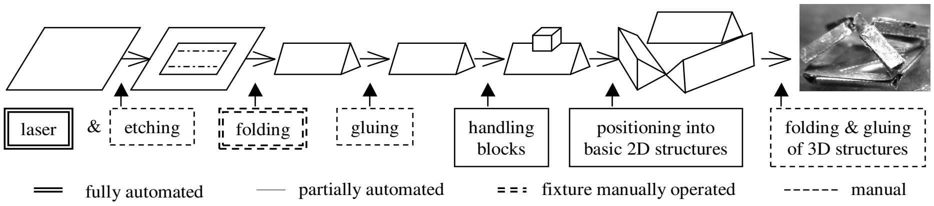
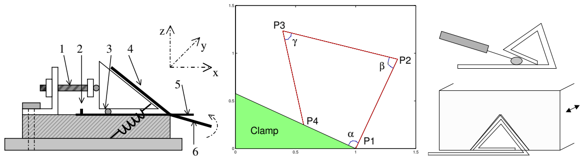


Figure 1: 3-D Structure Assembly Process

This work extends previous efforts in this area as described in [1] and [2]. A description of orthotweezers used in our work for precise positioning may be found in [3]. The following sections present the folding and gluing processes used, a theoretical analysis of the mechanics of bending, the assembly of 3-D structures, and the attachment of sensors.

Triangular Beam Construction

We formed the triangular beams by folding $12.5\mu m$-thick stainless steel sheets. The folding process, although slower than stamping, provides precise bending that is more amenable to small, thin sheets. The stainless steel sheets were pre-cut and pre-scored using the Microlaze laser micromachining station as described in [1]. The process included pre-coating the stainless steel with polyimide, blasting the polyimide with the laser, and etching to produce the cut and score lines. The fixture developed for folding the sheets is shown in Fig. 2(a).



(a) (b) (c)

Figure 2: Triangular beam construction: (a) folding mechanism: *(1)*clamp-position adjustment screw, *(2)*alignment pin, *(3)*clamp point contact, *(4)*upper razor blade, *(5)*stainless steel sheet, *(6)*rotating razor blade (b) folding configuration (c) gluing process

To reduce springback, we designed our folding fixture so that it provides an almost pure bending moment and minimizes the length over which the bending takes place. As shown in Fig. 2(a), a razor blade attached to the clamp applies a line force along the bend line, and a rotating razor blade underneath the piece being folded provides the bending moment. The rotating razor blade is secured to the base using flexures made of tape. The base was molded out of polyurethane with a $200\mu m$-thick steel sheet glued to the area beneath the clamp. It incorporates two alignment pins to ensure accurate placement of the stainless steel sheet each time a fold is made. The clamp design follows the exact constraint design principles (as described in [4]) by using a contact point coupled with a nesting force (provided by tension springs) to hold it in place. Using this method allows the clamp to be removed easily but replaced accurately [4].

The triangular beam cross section that we use requires three sequential bends at P3, P2, and P1 (see Fig. 2(b)) until P3P4 just touches the clamp surface at P4. Further rotation of P1P2 by applying an increasing moment causes the end P4 to move along the clamp surface. To determine the conditions under which the edge P4 will always move down (rather than up, as was observed in some initial trials) the clamp surface to meet edge P1 (thus forming a closed triangular section), we received inspiration from Lu and Akella's work [5] to model each line shown in Fig. 2(b) as a link and determine the angular motion of each link sequentially to guarantee the desired ending configuration. This study led to a static analysis based on the pseudo-rigid compliant mechanism model [6].

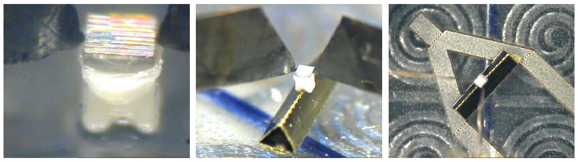
In the pseudo-rigid compliant mechanism model, the compliant structure of Fig. 2(b) is replaced by a four bar mechanism that has rigid links with torsional springs at the joints. The free-body diagrams based on this model and the resulting system of nonlinear equations are similar to those given in [6] and are not presented here. We used the MATLAB function *fsolve* to solve these equations and determine a set of values for the bend angles that will result in the desired ending configuration. Based on this analysis, we used values $\alpha = 89$, $\beta = 101$, and $\gamma = 60$ degrees. Although currently the folding mechanism is operated by hand, the aim is to fully automate it. Thus it is crucial to know a set of angles that work consistently.

After the triangle has been pre-bent into shape, glue is applied with a needle applicator. Then a fixture with 1-mm equilateral triangle channel cut into it is passed repeatedly over the triangle to hold it in place while the glue dries. The fixture is kept in motion with small back and forth movements to prevent the triangle from being glued to the fixture

(See Fig. 2(c)).

The 3-D Structure Assembly Process

The assembly process for transforming the beams into 3-D structures involves a process similar to the one described below for the sensor attachment. The orthotweezers system reliably grasps blocks, thus the grasping of other objects is accomplished by attaching a removable handing block to the object to be manipulated. Thus, the first step in both the beam and gage assembly is to create a pallet of blocks, wax glue, and the objects to be manipulated. A V-groove meta handling block is required to fit over the beam's top edge so that the silicon handling block, manually glued on its top surface, will remain parallel to the horizontal plane, a configuration that allows the maximum dexterity from the orthotweezers. These V-grooves were made from polyurethane cast in a rubber mold. Once the pallet of the blocks, wax ($50\mu m$ thick), and beams is prepared by hand, a semi-automated process starts where the orthotweezers pick up a handling block and dip it in wax glue (Fig. 3(a)) warmed by a heater. Then the handling block is attached to a beam and the heater is turned off to secure the block to the beam. Next, in a second pallet, the tweezers pick up the handling block and beam combination, orient it in the correct position (Fig. 3(b)), and attach it to a faceplate previously cut in the flattened 2-D version of any desired 3-D structure (Fig. 3(c)). The faceplate has a thin layer of UV-cured glue to secure the beams in place. The final step involves bending the faceplate in the appropriate places by hand to form a 3D structure.



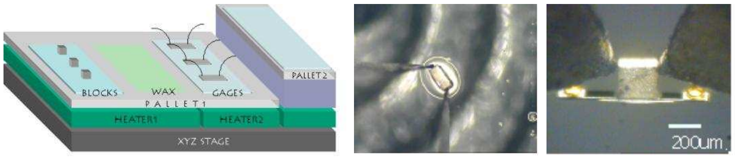
(a) (b) (c)

Figure 3: Steps of the 3-D assembly process (a) meta block dipped in wax, (b) block attached to the beam and lifted, (c) beam placed on faceplate pattern

Sensor Attachment

For force sensing on the milli-robot structures, we automatically attach semiconductor strain gages again using the orthotweezers system. This process also requires two steps. In the first step, customized pallets are created as shown in Fig. 4(a). Pallet 1 has the silicon handling blocks ($200 \times 200 \times 100\mu m$), spin-coated ($15\mu m$-thick) low melting-point wax, and semiconductor strain gages ($1000 \times 150 \times 12\mu m$). The handling blocks and the gages are placed on top of Gelpak (to compensate the sticking force) by using conventional hand tweezers under a microscope. The rest of the first step, however, is completed in an automated fashion using the extensive set of available primitive algorithms of the orthotweezer system.

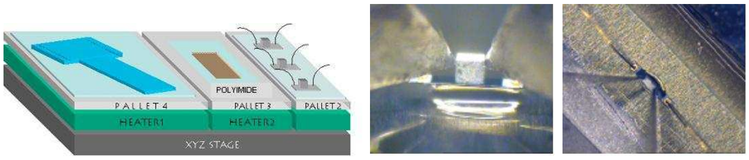
In this automated procedure (after the user first locates the block, wax, and strain gage visually), the following steps are executed. (1) The height of the gage, wax, and the block are measured. (2) The block is grasped. (3) The block is dipped into molten wax (Fig. 4(b)). (4) The block is placed on top of the strain gage and cooled to harden the wax (Fig. 4(c)), and (5) the gage is placed on pallet 2. These steps take about 5 to 10 minutes.



(a) (b) (c)

Figure 4: Attaching handling blocks to strain gages, (a) stage and pallet setup (not drawn to scale), (b) [top view] dipping handling block into wax (as a glue), (c) [side view] attached handling block.

To carry out the second step, the user first locates the strain gage-handling block combination (prepared in the first step), polyimide, and target. The automated process then involves the following steps. (1) The height of the target location, polyimide, and the gage are measured. (2) The block with the gage is grasped. (3) The gage is dipped in polyimide (Fig. 5(b)), and (4) the gage is placed on top of the target and held there while the polyimide cures as it is exposed to a high temperature (Fig. 5(c)).



(a) (b) (c)

Figure 5: Attaching strain gage to PZT actuator, (a) stage and pallet setup, (b) [side view] dipping strain gage into a polyimide (as a glue) well, (c) [top view] attaching the gage.

Conclusion

For flexibility in assembly tasks, pallets customized for each assembly product have been developed. These pallets contain a stock of folded beams, strain gages, handling blocks, and adhesive, which will then be combined into milli-robot structures. By combining the folding, bonding, and microassembly steps, we plan to build a self-contained desktop rapid prototyping system for milli-robots.

References

[1] Shimada, E., et al, “Prototyping Millirobots using Dexterous Microassembly and Folding,” *Symp on Microrobotics, ASME Int Mech Eng Cong And Exp*, Nov. 5-10, 2000, Orlando, FL.

[2] Fearing, R.S., et al, “Wing Transmission for a Micromechanical Flying Insect,” *IEEE Int Conf on Robotics and Automation*, April, 2000.

[3] Thompson, J.A., and R.S. Fearing, “Automating Microassembly with Ortho-tweezers and Force Sensing,” *IROS 2001*, Maui, HI, Oct. 29-Nov. 3, 2001.

[4] Blanding, Douglass L., *Exact Constraint: Machine Design Using Kinematic Principles*, ASME Press, New York, 1999.

[5] Lu, Liang and Srinivas Akella, ”Folding Cartons with Fixtures: A Motion Planning Approach,” *IEEE Trans on Robotics and Automation*, vol.16, no. 4, pp. 346-356, August 2000.

[6] Howell, L. L., and A. Midha, “A Method for the Design of Compliant Mechanisms with Small-Length Flexural Pivots”, *ASME J of Mech Design*, vol. 116, no.1, pp. 280-290, March 1994.