ASSEMBLY OF PLANAR STRUCTURES BY PARALLEL ACTUATION OF MEMS MICROROBOTS

B.R. Donald^{1,2,*}, C.G. Levey³, and I. Paprotny^{4,1}

¹Department of Computer Science, Duke University, Durham, North Carolina, USA

²Department of Biochemistry, Duke University Medical Center, Durham, North Carolina, USA

³Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire, USA

⁴Department of Computer Science Dartmouth College, Hanover, New Hampshire, USA

ABSTRACT

Parallel motion and cooperation of multiple microrobots has many potential applications, including microassembly. In this paper, we present designs, theory and the results of fabrication and testing for an untethered multi-microrobotic system of stress-engineered MEMS microrobots that implements a novel microassembly scheme. Our work constitutes the first implementation of an untethered, mobile multi-microrobotic system. The robots are designed such that multiple devices can be independently maneuvered using a single, global control signal. We used a novel stress-engineering fabrication process to build 15 microrobots and used these to demonstrate microassembly of five types of planar structures from two classes of initial conditions. The final assemblies matched their target shapes by 96% (average), measured as the percentage of the area of the target shape covered by the assembled structure.

INTRODUCTION

Mobile microrobotic devices have many potential applications, including medicine, surveillance, and assembly [1]. This paper presents designs, theory and experimental results for a novel microassembly scheme, which aggregates planar structures from a group of parallel-actuated MEMS microrobots. In this work, parallel-actuated (as opposed to serial) refers to the robots moving simultaneously under the application of a single, global control and power-delivery signal. The robots are $240\text{--}280\text{ }\mu\text{m} \times 60\text{ }\mu\text{m} \times 7\text{--}20\text{ }\mu\text{m}$ in size, and consist of untethered scratch-drive actuators [2] that provide forward motion, and steering-arm actuators that control whether the robots move forward or turn [3]. We present fabrication methods, designs, control algorithms, and experimental results demonstrating the first simultaneous control of multiple untethered microrobots, and report the application of such multi microrobotic systems to the assembly of planar micro-structures. The aggregation and assembly of these structures is controlled and programmed by docking the individual robots, while defect formation is avoided by using non-colliding paths, enabling virtually defect-free assembly.

A system of n of our microrobots operating within the same operating environment is both non-holonomic (robots can only move in the direction they are facing) and highly underactuated, because all the robots receive a single, common control signal. Since all n robots are electrically coupled (and via compliance, intermittently mechanically coupled), the generalization of our earlier work [3] from one to n robots required advances in design, fabrication, control and programming to defeat the coupling and the potentially exponential explosion in complexity due to added degrees of freedom of the configuration space (C-space). In this paper, we present microrobot designs that efficiently demultiplex the common control signal for a group of n microrobots, and a control strategy that implements microassembly, transforming the problem of parallel control of n devices to parallel control of two robots, followed by sequential control of single robots. We used this control strategy to assemble several planar micro-structures. Innovations in designs and fabrication include designs of independently controllable microrobot species, an improved stress engineering process, single-device trimming to further reduce process variability, and a batch transfer mechanism for parallel transfer of robots from the die to their operating environment.

Fig. 1 shows scanning-electron micrographs of five *microrobot species* that we used to implement microassembly. Four of these species are *independent*, i.e. can be maneuvered as independent non-holonomic systems during microassembly. The micrographs of five types of planar structures assembled by these microrobots are shown in Fig. 2. The final assemblies matched their target shapes (portion of the area of the target shape covered by the assembling structure) by 96%, on average. All assembly experiments were conducted within a small (1.5 mm^2) area.

While previous MEMS-robotic systems are assembled from microfabricated components, the dimension of these robots are on the order of millimeters or centimeters [4]. Scaling laws cause power delivery to be challenging as the dimensions of the robots are reduced to the micro-scale. The ability of our microrobot [3] to receive power from its environment [2] allows us to reduce its size by almost two orders of magnitude from other MEMS robotic

Figure 1: Scanning electron micrographs of the five microrobot species used to implement microassembly. Sets of independent microrobot species are: 1,3,4,5 or 2,3,4,5. The snap-down and release voltages of species 1 and 2 are similar, despite different steering-arm designs. Yellow color is used to highlight the areas of the steering-arms covered by the stress layer.

* Corresponding author: D101 Levine Science Research Center, Duke University, Durham, NC.

Figure 2: Optical micrograph of planar structures assembled using microrobot species shown in Fig. 1. The image of structure G_3 was taken using an earlier version of species 5 (lower-right device), with a slightly longer steering-arm actuator than what was used in the assembly experiments reported in Table 1.

devices. Recently, a 950 μm MEMS micro-needle powered by external magnetic fields has also been demonstrated [5].

Most proposed microrobotic applications envision simultaneous operation of many microrobots. Micro-scale multi-robotic cooperation has not been previously attempted; however there are many examples of macroscopic multi-robotic systems that aggregate form or functionality through cooperation or mutual interaction. Coordination of macroscale multirobotic systems is achieved by message passing, implicit communication, or local rules. However, most of these approaches assume the robots have sufficient onboard hardware resources to receive and process sensory inputs and/or communicate with other devices. In contrast, our robots are much simpler and can only partially decode the broadcasted control signal. While the control of such systems have not been previously studied, the concept of selective response to a global control signal (Global Control, Selective Response (GCSR) [6]) is common in micro- or nano-scale biological systems. Our work demonstrates theoretically and experimentally that by designing microrobots so that each responds differently to a global control signal, we can control a group of robots to achieve useful tasks, such as microassembly.

Microassembly is generally performed in one of two ways: robotic manipulation through the use of macro-scale robotic manipulators with micro-scaled end-effectors [7], or self-assembly, where structures are aggregated through stochastic motion and interactions of components [8]. Robotic manipulation is in general inefficient, while defect formation is a common problem in self-assembly. Furthermore, in self-assembly the geometry of the assembly is programmed upon fabrication of the individual components (one set of parts can only assemble one type of structure). Our assembly scheme controls structure aggregation through intersecting trajectories, virtually eliminating defect formation, and allowing us to generate a large variety of structures from the same set of components. This assembly scheme does not require external actuators to maneuver the individual parts, resulting in an efficient, controllable assembly with a yield comparable to assembly using robotic manipulation.

STRESS-ENGINEERED MEMS MICROROBOT

Fig. 3 presents a schematic design of a stress-engineered MEMS microrobot (a detailed description of the robot can be found in [3]). It consists of an untethered scratch-drive actuator (USDA) [2] that provides forward motion, and a out-of-plane curved steering-arm actuator that determines whether the robot moves straight or turns. The robot moves in straight line when the arm is elevated, and turns when the arm is down. A lithographically-patterned stress layer defines the out-of-plane

curvature of the steering arm. The robot operates on a grid of zirconia-insulated interdigitated electrodes. When a voltage is applied between sets of electrodes, the electrodes and the conductive chassis of the microrobot form a capacitive circuit, and an electrical potential is induced on the microrobot. Varying this potential (in the form of a waveform) allows us to control the state of the steering-arm actuator as well as to provide the power to the USDA.

Figure 3: A schematic design of a stress-engineered MEMS microrobot.

The steering-arm actuator consists of an 80–130 μm long cantilever beam (L) attached to a circular pad of 20–40 μm in diameter (D) with a 0.75–1.2 μm deep dimple at the center of the pad to prevent irreversible stiction. Similar to an electrostatic cantilever beam, each steering-arm has two distinct transition voltages at which the arm abruptly changes states. These are the *snap-down* voltage (V_{down}) at which the arm is pulled in contact with the substrate as the robot is commanded to turn, and the *release* voltage (V_{up}) at which the arm is released when the robot is commanded to move straight. These transition voltages are determined by the steering-arm designs. Microrobots with the same steering-arm design are classified as the same microrobot species.

FABRICATION

The fabrication of the microrobot chassis is performed through the surface micromachining MEMSCAP PolyMUMP's foundry process. The chassis is formed from the top layer of polysilicon, referred to as the Poly2-layer, while the bushing is formed from both the Poly1 and Poly2 layers. After the PolyMUMP's process is complete, a portion of each arm is coated with a stress layer of evaporated chromium (stress-engineering). The tensile residual

stress of the chrome-layer curves the steering-arms upward and is one of the factors determining their transition voltages. However, stress-engineered MEMS microrobots are highly susceptible to galvanic attack (GA) because the under-etch bath exposes polysilicon structures to Buffered Hydrofluoric Acid (BHF) prior to chrome deposition, and the release-etch exposes the polysilicon structures to Hydrofluoric Acid (HF) in the presence of metal from the stress layer. Both the BHF-exposure and HF-exposure in presence of metal have been shown to promote GA and corresponding polysilicon degradation. The effects of GA are often localized, and can result in scorching, *viz.* dark and granular silicon surfaces, as well as variations in the thickness of the polysilicon structures. We found that poor chrome adhesion during the release-etch is correlated with such polysilicon scorching. We have also measured significant thinning of the polysilicon layer on die with visible GA-scorching. In some cases, the structure thickness was degraded by up to 100 nm. To reduce the effects of GA, the stress-engineering process from [3] was modified to incorporate two consecutive baths during the BHF undercut stage, as well as the HF release stage. We have found this double bath system greatly reduced the GA-attributed structural thinning.

The microrobots are fabricated attached to larger structures, called *transfer frames*, which are used to move multiple devices from the die to the operating environment. The relative position of the robots is set in design, and the attached transfer frame allows us to move this entire configuration to the operating environment. Fig. 4 shows an optical micrograph of a transfer frame. Microrobots are fabricated attached to the frame through notched sacrificial beams (i). The frame is anchored to the substrate through another set of sacrificial beams (ii). These beams are broken, and the frame is lifted of the substrate, and subsequently transferred to the operating environment, using micro-probes inserted into hinged ears at the perimeter of the frame (iii), or using a vacuum microprobe. Once on the operating environment, the notched beams (i) are broken, and the robots are released while maintaining their designed configuration.

Figure 4: Optical micrograph of a batch transfer structure called a Transfer Frame.

In the infrequent cases when compounding process variability due to GA or other factors causes the transition voltage of the steering-arms to deviate significantly from their design, a novel post-release trimming method can be used to further increase or decrease the curvature of the individual steering-arms. Fig. 5 shows a schematic illustration of the post-release trimming concept (left) and optical micrographs showing device from species 5

before and after the trimming operation (right). A prefabricated fixture (i) is used to immobilize a released microrobot, such that additional chrome can be deposited on its steering-arm. Chrome is deposited on the top surface of the arm to increase the curvature, or on the bottom surface of the arm to decrease it. The fixture is anchored to a handle substrate through a linear spring that provides a normal force immobilizing the microrobot. The handle substrate is subsequently placed in a thermal evaporator for additional chrome deposition. The fixture also functions as a shadow-mask, limiting the chrome deposition to the surface of the steering-arm actuator (ii).

Figure 5: The post-release trimming method used to adjust the deflection of the steering-arm actuators.

The operating environment for our microrobots consists of zirconia-insulated wavy interdigitated electrodes. The electrodes are composed of a 500 Å gold layer, patterned through a liftoff process. They reside on a silicon substrate, covered with a 3 μm - thick layer of thermal silicon oxide. The electrodes are coated with 0.5 μm of reactive-evaporated zirconium dioxide, followed by a 300 Å passivation layer of evaporated silica. A more detailed description of the fabrication process for the operating environments is given in [3].

INDEPENDENT MICROROBOT SPECIES

We designed and fabricated five microrobot species using three separate stress-engineering runs, resulting in 15 fabricated microrobots. Species 1, 3, 4, and 5 are independent and 2, 3, 4, and 5 are independent, *i.e.* can be controlled as independent non-holonomic systems. Our control algorithms ensure species independence if the snap-down and release voltage pairs for all robots are *unique*, *i.e.* either V_{down} or V_{up} is unique.

The design parameters for each of the five species are summarized in Table 1. Species 2 used a 1.2 μm tall dimple, while all other species used a 0.75 μm dimple. Single-device trimming was used to adjust the steering-arm transition voltages of one device from species 2 and one device from species 5. However, damage to the device from species 2 (caused by arcing due to dielectric breakdown) prevented us from fully completing the adjustment, reducing the number of operational devices to 14.

Table 1: Design parameters for the steering-arms of microrobot species 1-5. All dimensions are in μm.

Species	D	w	L	L_C	L_O
1	20	10	120	33.5	9.5
2	40	8	80	59.5	9.5
3	20	10	120	33.5	1.5
4	36	8	107	94.5	1.5
5	30	8	130	91.5	1.5

Fig. 6 illustrates the five control and power-delivery waveforms, called *control primitives*, that are used to control the microrobots. Experimentally-measured trajectories of the microrobots during the

application of each control primitive are presented in Fig. 7. For each control primitive, two trajectories are shown for each stress-engineering run of each microrobot species. A total of 140 such trajectories are shown; 28 for each of the five control primitives. Note that the control primitives are labeled (A-E) and ordered left-to-right such that independent microrobot species progressively switch from turning to straight-line motion. This order is exploited in our strategy for controlling the microrobots during microassembly.

Figure 6: The waveform sequences (first three pulses only) of the five control primitives (A-E) used to control the five microrobot species (1-5 in Figure 1). Voltages may deviate up to ± 10 V from the actual voltages used.

CONTROL STRATEGY FOR MICROASSEMBLY

We implemented microassembly by exploiting the ordering described above. The corresponding progressive change in the behavior of our microrobots allows us to transform the problem of parallel control of n microrobots to a simpler problem of simultaneously controlling two devices, followed by sequential control of single robots. The integrity of the intermediate assemblies is maintained through mutual compliance, and we restrict the structures that can be assembled to those that can be reached via the progressive assembly of *compliant-stable* structures. Compliant-stable structures do not change their configuration while the devices are powered; the sum of forces (including friction) and moments, generated by all the robots and transmitted through compliant interaction, equals to zero.

Consider a system of n microrobots, devices D_i , $i \in \{1 \dots n\}$ belonging to independent microrobot species, and labeled according to increasing transition voltages of their steering arms, and $n+1$ control primitives, P_j , $j \in \{1 \dots n\}$ labeled according to

decreasing number of turning devices. The assembly of n robots takes place in $n-1$ steps:

Step 1: Assembly of the Initial Stable Shape

In step 1, we assemble the initial stable shape, (G_1 from Fig. 2) by simultaneously controlling microrobots D_{n-1} and D_n to dock together using primitives P_1 , P_2 , and P_3 . These primitives invoke both turning and straight-line motion in robots D_{n-1} and D_n , but *only* invoke turning behavior in the remaining devices. Thus, regardless of the trajectory of D_{n-1} and D_n , the remaining $n-2$ robots “idle” by orbiting in circular trajectories. We use simple geometric trajectory planning to simultaneously control D_{n-1} and D_n to dock at an intersecting point of their trajectories. Fig. 9b shows the implementation of this first step of the control strategy on the system of four microrobots.

Steps 2, ..., $n-1$: Subsequent Addition of Single Robots

In subsequent steps, the goal shape is progressively assembled through sequential addition of single robots while maintaining the stability of the accumulating structure. The robots are added in the order D_{n-2} , D_{n-3} , ..., D_1 using the pairs of control primitives (P_3, P_4), (P_4, P_5) ... (P_n, P_{n+1}). For example, primitive pair (P_3, P_4) provides turning and straight-line motion to robot D_{n-2} , while D_{n-3} , ..., D_1 orbit, and D_{n-1} , D_n are immobilized in the assembling structure (see Fig. 9c and d).

Self-Aligning Compliance

Microrobots that dock to form the initial stable shape self-align, reducing any remaining alignment error. The straight front edge of the scratch-drive actuator causes two opposing microrobots to slide relative to one another until both robots reach a stable configuration. Self-alignment is a form of local, pairwise self-assembly. Fig. 8 shows an example of self-aligning compliance between two docking robots. Configurations of the two devices measured four times during a self-aligning experiment are shown, illustrating the reduction in relative misalignment.

Figure 8: An example of self-aligning compliance. Outlines of devices from species 4 (red) and 5 (blue) recorded four times during a self-aligning experiment. The structure rotates by 79° overall.

Figure 7: Experimentally-measured trajectories showing the reproducibility of motion for the five microrobot species (1-5 in Fig. 1) during the application of each control primitive (A-E) in Fig. 6.

Figure 9: Composite optical micrograph of experimental assembly data using devices from species 1,3,4 and 5. The devices are labeled according to the number of their respective species. **a:** Initial configuration. **b:** Docking of device 4 and 5 to form the initial stable shape, while device 1 an 3 orbit. **c:** Docking of device 3 with the initial stable shape, while device 1 orbits. **d:** Docking of device 1 to complete the assembly. Black denotes trajectory segments where both robots that are being maneuvered towards the goal turn, gray denotes segments where one robot moves straight while the other robot turns, while white denotes segments where both robots move straight. A movie of this assembly sequence is available online at: <http://www.cs.duke.edu/donaldlab/Supplementary/HH08/>.

MICROASSEMBLY IMPLEMENTATION

We implemented microassembly using groups of four independent microrobots during five independent assembly experiments generating a total of 14 structures. Fig. 9 illustrates data from one of the assembly experiments. The robots were operated on a 1.5 mm^2 environment, and their position was observed using a digital video-camera attached to an optical microscope with a $6.7\times$ objective lens. The position of the devices was extracted with a precision of $\pm 2.1 \mu\text{m}$. During the operation of the microrobots, the humidity was controlled below 4% RH using a continuous stream of dry nitrogen. The waveforms defining the control primitives were produced using an Agilent 33120A arbitrary waveform generator, and amplified with a Trek PZD700-1 high-voltage power amplifier with a gain of 200.

The table in Fig. 10 indicates the average match (portion of the target structure covered by the assembled shape) for each type of generated shapes. The experiments were conducted starting from two different classes of initial configurations: R_1 - robots are arranged along the corners of a rectangle with sides 1 by 0.9 mm, all devices oriented along the y-axis, and R_2 - robots are arranged in a line with average separation of $360 \mu\text{m}$, and variable orientation. The initial position of the microrobots was set using

microprobes. We used common geometric shapes (a line and a rectangle) to demonstrate the ability to achieve successful assembly from arbitrary different initial configurations. Five types of planar structures were assembled, denoted as G_1 - G_5 (see Fig. 2). Due to the absence of external fixtures that would constrain the position of the assembled structure, we consider the assembly a success regardless of the pose of the assembled structure, as long as the structure is entirely contained within the operating environment.

The average match across all assembled structures was 96%, $\pm 3\%$ (st. dev.). This average does not include completely failed assemblies. We recorded an 11% failure rate during consecutive assembly of nine structures over the course of three assembly experiments: the single failure was due to the loss of stability of an intermediate structure.

The average docking misalignment across all experiments was $5 \mu\text{m} \pm 5 \mu\text{m}$ (st. dev.). In all experiments, compliance was used to self-align the initial stable structures. Two of the five experiments were conducted with the initial shape purposefully misaligned by at least $50 \mu\text{m}$ to test self-alignment. In these experiments, the average misalignment after completed self-alignment was $9 \mu\text{m} \pm 8 \mu\text{m}$. In the remaining three initial

		Target Structure G					Average $G_1 - G_5$
		G_1	G_2	G_3	G_4	G_5	
Initial Configuration	R_1	96 % (4) 3 runs	98 % (3) 2 runs	96 % (2) 2 runs	96 % (na) 1 run	93 % (na) 1 run	96 % (3) 3 runs
	R_2	99 % (2) 2 runs	98 % (na) 1 run	93 % (na) 1 run	89 % (na) 1 run	na	95 % (4) 2 runs
Average R_1 and R_2		97 % (3) 5 runs	98 % (2) 3 runs	95 % (2) 3 runs	93 % (5) 2 runs	93 % (na) 1 run	96 % (3) 5 runs

Figure 10: Summary of the assembly experiments, showing the average match (portion of the area of the target shape covered by the assembled structure) for each of the generated shapes. A total of five assembly experiments were conducted starting from two classes of initial configurations R_1 and R_2 . The standard deviation (in parenthesis) and the number of experimental runs from each class of initial configurations are also shown.

shape docking experiments, precise control was applied to minimize the initial misalignment. In these experiments, the average docking misalignment was $6 \mu\text{m} \pm 7 \mu\text{m}$ before the self-alignment, and $2 \mu\text{m} \pm 3 \mu\text{m}$ after the self-alignment was complete.

When docking a single robot with a stable structure, the average docking misalignment was $3 \mu\text{m} \pm 3 \mu\text{m}$, which is on the order of the minimum feature-size of the fabrication process.

CONCLUSION

In this work we demonstrated the first example of parallel operation of multiple untethered MEMS microrobots. We presented designs and fabrication of independent stress-engineered microrobot species, as well as control algorithms that implement a new microassembly scheme, generating planar structures with a high level of accuracy. The average match between the generated structures and the desired target configurations was 96%, with an average misalignment of $5 \mu\text{m}$ across all experiments, and $3 \mu\text{m}$ in experiments where error correction and self-aligning compliance were fully implemented.

In the presence of a global, broadcast-type control signal, a multi microrobotic system composed of many individual devices will naturally be highly-underactuated, necessitating the type of control algorithms presented in this work. Successful control of highly underactuated systems is likely to be important as the size of the assembling components is reduced even further, since parallel operation, broadcast communication, and selective response are ubiquitous in the architecture of micro- and nano-scale biological systems.

ACKNOWLEDGEMENTS

This work was supported by grant number GM-65982 to B.R.D. from NIH, and 2000-DT-CX-K001 to B.R.D., from the Office for Domestic Preparedness, Department of Homeland Security, USA. The electron micrographs were taken at the Dartmouth Ripple Electron Microscopy Laboratory, with the help of C. P. Daghljan. We would like to extend our thanks to D. Rus for her advice and collaboration. We thank C. McGray for the initial work on the stress-engineered MEMS microrobot. We

thank J. Gibson for the use of equipment in her lab. We further thank D. Balkcom, C. Bailey-Kellogg, A. Lebeck, K. Böhringer, and J. Reif for their advice and suggestions.

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