2-SNESAT: SCALABLE BEHAVIOR-DIFFERENTIATED CONTROL FOR SWARMS OF PROGRAMMABLE MEMS MICROROBOTS

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ABSTRACT

Microscale robotic systems have many potential applications in areas such as medicine, surveillance, or assembly. However, these and other envisioned applications depend on the ability to coordinate actions of large numbers microrobots. Control of large groups of MEMS microrobots, whether using magnetic or electric fields is challenging because by the large degree of under actuation, i.e. the challenge of controlling individual microrobots independently through a single global control signal. In this paper we demonstrate a scalable voltage-based control (2-SNESAT) which uses a sub-linear $O(\sqrt{n})$ number of control voltage levels and constant $O(1)$ number of control pulses to use onboard physical logic to control a group of six (6) independently controlled MEMS microrobots. This control strategy is an important breakthrough that paves the way for swarm control of large numbers of microscale robots.

KEYWORDS

Microrobotics, MEMS, scratch-drive actuators, behavior-differentiated control.

INTRODUCTION

Microscale robotic systems have many proposed applications in areas such as biomedicine, surveillance, or microassembly. These and other envisioned applications rely on the combined actions of many microrobots. However, the high level of underactuation present in such systems, where all robots are controlled by a single global control signal, makes the simultaneous control of several microrobots significantly more difficult than controlling a single microrobot in isolation. In [1,2] we presented a globally controllable 240 µm × 60 µm × 10 µm mobile stress-engineered MEMS microrobot (MicroStressBot for short), which contains an *untethered scratch drive actuator (USDA)* providing forward motion, and a steering-arm actuator that controls when the robot moves in a straight line or turns. Multi-microrobot control of up to four MicroStressBots has been presented in [2] through a concept called ***behavior-differentiated control (BDC)***, where the individual MicroStressBots have different response during portions of the control voltage waveform, and hence can be controlled independently.

STRESS-ENGINEERED MEMS MICROROBOTS

Stress-engineered MEMS microrobot (MicroStressBot) are mobile electrostatically powered microrobotic platform fabricated using a three-layer Polysilicon surface micromachining process. The kinematics of a MicroStressBot are superimposed on the optical micrograph in **Fig. 1** shows the scanning electron micrograph (SEM) of a MicroStressBot situated on a power-delivery substrate. The microrobot has two actuated internal degrees of freedom; an untethered scratch-drive actuator (USDA) that provides forward motion, and a steering-arm actuator that determines whether the robot moves in a straight-line or turns. The steering-arm consists of a cantilever beam with a circular pad and a dimple. The cantilever beam is curved out-of-plane using a stress-engineering process [3], which determines the deflection of the steering arm. The microrobot operates on fields of insulated interdigitated electrodes. When a voltage is applied across these electrodes, the electrodes and the conductive microrobot chassis form a capacitive circuit that couples an electric potential onto the microrobot body. The coupled voltage waveform called the power delivery waveform is alternated over time to provide power to the untethered scratch-drive actuator and to control the state of the steering- arm.

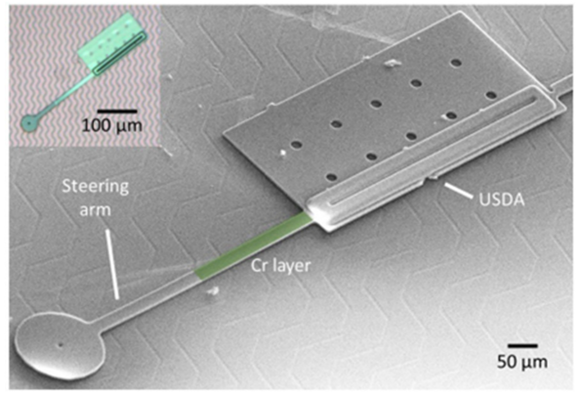

Figure 1: Scanning electron micrograph of a MicroStressBot with USDA and steering arm. The part of the steering arm with Cr deposition is color-coded (green). (inset) Optical micrograph of the same MicroStressBot.

Fig. 2 shows a voltage diagram relating the applied voltages of the waveform to the functionality of a MicroStressBot. During power delivery portion of the power delivery waveform, the voltage that is capacitively coupled to the chassis of the USDA alternates from $V_{SDA,U}$ to $V_{SDA,D}$. The repetitive flexure of the backplate causes forward motion of the USDA. $V_{SDA,U}$ and VSDA,D are equal for all microrobots on the same field.

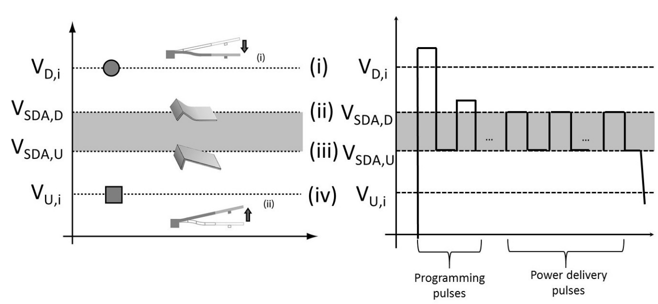

Figure 2: (left)Voltage diagram of a MicroStressBot. (right) Programming and power delivery pulses of a MicroStressBot. (i) $V_{D,i}$ is the snap-down voltage for the steering-arm of MicroStressBot, (ii) $V_{SDA,D}$ is the voltage for SDA back-plate flexure, (iii) $V_{SDA,U}$ is the voltage for SDA back-plate relaxation, (iv) $V_{U,i}$ is the release voltage of the steering-arm of a MicroStressBot.

MicroStressBot's steering arm can either be raised or lowered. When the voltage supplied to a robot R_i reaches the steering-arm's snap-down voltage ($V_{D,i}$), the arm is pulled into contact with the substrate. When the voltage is reduced below its release voltage

($V_{R,i}$), the arm is released from the substrate. These control voltage levels ($V_{D,i}$ and $V_{R,i}$) are a function of the design of the individual steering-arm actuators. These voltages can vary between individual robots, enabling BDC through a global control signal.

For any MicroStressBot R_i, the voltage used to control its steering arms must satisfy the following conditions:

1. **$V_{D,i} > V_{U,i}$:** This is simply enforced by the electromechanics of a electrostatic cantilever beam and can be proven easily from lumped element analysis.
2. **$V_{D,i} > V_{SDA,D}$:** This ensures the USDA flexes sufficiently to achieve forward motion for all valid snap- down voltages.
3. **$V_{SDA,U} > V_{U,i}$:** This ensures that the USDA relaxes to step forward when the microrobot moves in straight line and/or turns.

The steering-arm is used to modulate the behavior of the MicroStressBot to achieve global controllability [1]. Applying the power-delivery cycle (i.e. actuating the USDA) while the arm is lowered causes the microrobot to turn. The robot turns around a fixed radius of curvature, which is defined by the design of the steering-arm actuator. If the power-delivery cycles are applied while the arm is raised, the robot moves in straight line. The kinematics of the MicroStressBot is shown in **Fig. 3**.

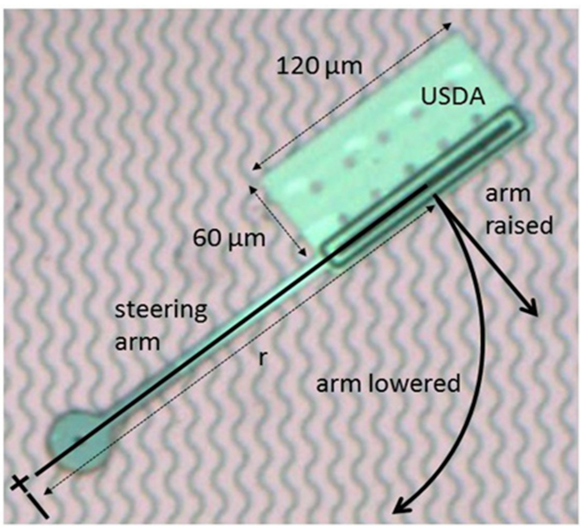

Figure 3: The kinematics of a MicroStressBot.

The $V_{D,i}$ and $V_{U,i}$ control voltages of the steering-arms of the MicroStressBots are a direct function of their geometry, and consequently it is possible to engineer a group of robots to respond to different voltage levels, and exhibit different behavior during parts of the control voltage waveform. This ***behavior-differentiated control (BDC)*** can be used to support independent parallel control of multiple MicroStressBots.

Programing through Stress-engineering

Stress-engineering involves deposition and patterning of a stressor layer (in this case evaporated Chromium) on planar surface micromachined MEMS structures to induce out-of-plane deflection of the respective steering arm, resulting a programmable deflection, and correspondingly steering-arm control voltages. **Fig. 4** shows programmed deflections for identical steering arms but variable stressor layer coverage, resulting in different electrostatic pull-down ($V_{D,i}$) and release ($V_{U,i.}$) voltages. More specifically, MicroStressBot R_1 has stressor layer deposition for length of 45 µm of steering arm whereas MicroStressBot R_2 has Cr deposition for length of 150 µm of the steering arm. A reconfigurable shadow-mask system was used to precisely define the coverage of the deposited stressor layer [3].

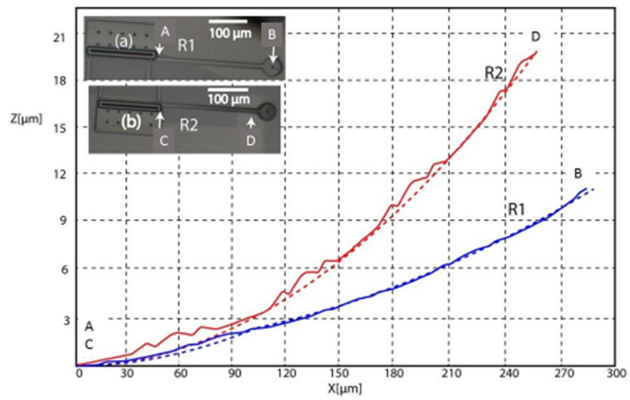

Figure 4: Optical profilometry showing the deflection of MicroStressBot R_1 and R_2 steering arm (see insets (a) and (b)) after deposition and patterning of the stressor Cr layer. Height data is shown for steering arm of R_1 (a) from point A to point B and for steering arm of R_2 (b) from point C to point D.

The Cr coverage, and consequently steering arm deflection is directly transferrable to snap-down and release volatges of the steering arms $V_{D,i}$ and $V_{U,i.}$ A quantitative analysis of snap-down and release voltages for electrostatic actuators, assuming a quasi-static lumped-element model shown in **Fig. 5**(b-c), $V_{D,i}$ and $V_{U,i}$ can be approximated as,

$$V_{D,i} \approx \sqrt{\frac{8kg_0^3}{27\epsilon_0 A}}, \quad (1)$$

$$V_{U,i} \approx \sqrt{\frac{2kg_1^2(g_0-g_1)}{\epsilon_0 A}}, \quad (2)$$

where k is spring constant of the steering arm, distance g_0 is the zero-voltage gap between the pad at the end of the arm and the underlying electrode and distance g_1 is the air gap between the pad and the substrate when the arm is in the snap-down position. A represents the area of the circular pad at the end of the steering arm. The angle between the steering arm and the electrodes are considered small justifying a parallel plate approximation where the distance g_0 represents the end deflection of the steering arm. As shown in [3], the estimation of $V_{D,i}$ and $V_{U,i}$ can be improved through numerical integration (1D FEM).

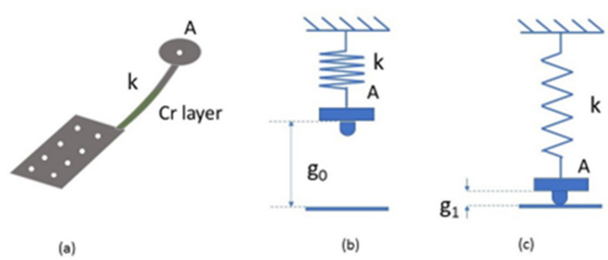

Figure 5: (a) MicroStressBot with spring constant k and steering-arm area A. Simplified spring-force model for the (b) snap-down voltage and (c) release voltage.

MULTI-ROBOT CONTROL USING BDC

Behavior-differentiated control (BDC) can be best described as a set of control strategies for multi-microrobotic systems controlled using a global control signal where the behavior, i.e. motion, of individual robots is differentiated by temporal changes to the globally broadcast control signal. These differentiations to the trajectories of the individual microrobots can be used to construct the trajectories of the individual robots between initial and goal configurations subject to the motion constraints confounding all the individual microrobots. In essence, BDC generates trajectories of all the robots simultaneously actuated such that all the robots reach the goal configuration at some point in time, subject to the motion constraints.

A control matrix relates the motion of individual robots to the broadcast control signal. Let n be the number of MicroStressBots, and m be the number of control primitives, i.e. control voltage waveforms that can elicit different behavior in some robots. Idealized system behavior can also be analyzed using hysteresis matrix H, which is a $(m \times n)$ matrix that describes the state of the steering-arms for each robot, where each entry $(j, i) = 1$ if the robot i arm is down during control primitive j (the robot is turning) and zero otherwise (the robot moves in straight line).

Several BDC schemes have been presented, such as Nested Hysteresis Gap (NHG) and STRIctly Non- nested hysteresis Gap (STRING). These control strategies all scale differently with respect to the number of microrobots that can be controlled simultaneously. ***Control voltage bandwidth*** ξ of a MicroStressBot system can be defined as the number of independent electromechanically addressable voltage levels (V_D and V_U) that can be used for control. Let the control voltage bandwidth requirement ξ_n of BDC for a n microrobot system be defined as the number of independent voltage levels necessary to achieve independent control during microrobotic application. To achieve independent control, it must hold that $\xi_n \leq \xi$. It follows, that for the system to achieve swarm control, ξ_n has to be large.

In particular for STRING BDC, it has been shown that if H (e.g. for (4 × 3) system) is of the form,

$$H = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix}, \qquad (3)$$

then the system of n MicroStressBots is independently controllable using m control primitives with a significantly largely reduced ξ_n. An illustration for the implementation of microassembly using STRING is shown in **Fig. 6**, reproduced with permission from [2].

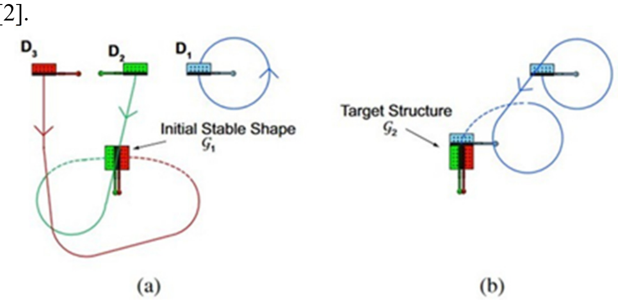

Figure 6: Three microrobots in STRING system forms assembly in two steps, (a) Step 1, the assembly of initial shape. (b) Step 2, docking of D_1 to form target shape. Reproduced with permission from [2].

TOWARDS SCALABLE BDC

Electromagnetically Saturated (Esat) BDC

In [2] we proposed to reduce theorized that a reduction of ξ_n to a sub-linear bound is possible. A n microrobotic system first sorted according to ascending values of $V_{U,i}$ and then $V_{D,i}$ forms a ***Electromagnetically Saturated (ESat) system***. **Fig. 7** shows a hypothetical system of 9 MicroStressBots R_1-R_6 with three snap-down voltages V_D and three release voltages V_U where the indexes $R_{x,y,z}$ indicate which MicroStressBots the voltages apply to (e.g. $V_{DR3,6,9}$ us the snap-down voltage applying to R_3,R_6, and R_9.)

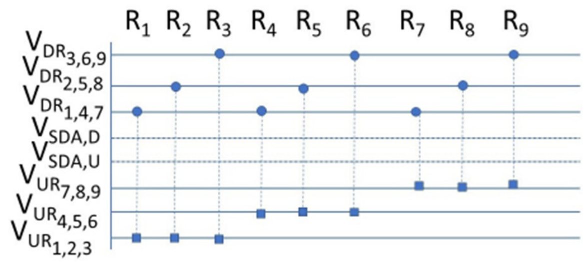

Figure 7: Nine microrobots ESat system.

Considering n-microrobot Esat, k is the number of independent snap-down voltages and l is the number of independent release voltages, $n \leq kl$. The control voltage bandwidth of such a system is given as $\xi_n = k + l$. To maximize $n = kl$ we have, $k = l = \xi_n/2$, and $\xi_n = \sqrt{2n}$ or $O(\sqrt{n})$. This is known as ***Symmetric ESat (SESat)***. The control voltage bandwidth is now ***sublinear***, and the system of n MicroStressBots can now be controlled using $O(\sqrt{n})$control voltage levels. This is an important step towards swarm control of MEMS microrobots. Unfortunately, The generation of the control pulses is recursive in nature, and the length of the control signal to address each primitive is linear, $O(n)$, substantially limiting the scalability, and correspondingly the utility, of the microrobotic system.

2-SYMMETRIC S-NESAT (2-S^{2}NESAT)

In this work, we show that it is possible to further reduce the number of pulses in the control signal to a sublinear length, in fact to achieve constant ($O(1)$) complexity. We achieve this by re-sorting the robots into subsets, where each of the subset form a Nested Hysteresis Gap (NHG). These subsets are called ***NHG subsets***. The re-sorted hypothetical system of microrobots from Fig. 6, now resorted according to 2-SNESAT is shown in **Fig. 8**.

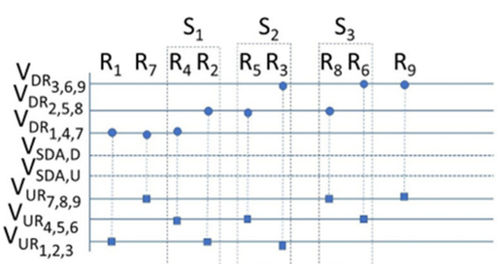

Figure 8: Nine microrobots ESat system resorted according to NHG, resulting in a 2-SNESAT.

This resorting allows us to access all the necessary hysteresis states of the steering arms with a constant number of control pulses in n. The ability to both provides a sublinear control bandwidth complexity ξ_n, and constant complexity in the length (number of pulses) of the control signal allows, theoretically, to control large number of MEMS microrobots. We summarize the scalability of the different BDC schemes in Tab. 1.

Table 1: Control bandwidth complexity and number of control pulses for each of the BDC control schemes.

	NHG	STRING	**SESat**	**2-S^{2}NESat**
Control voltage bandwidth (ξ_n)	$2n$	$n+1$	$2(\sqrt{n})$	$1+2(\sqrt{n})$
Control pulses	1	2	$O(n)$	$O(1)$

EXPERIMENTAL IMPLEMENTATION OF 2-SNESAT CONTROL

To demonstrate 2-SNESat control theory, six (6) MicroStressBots denoted as R_1 - R_6 were fabricated and stress-engineered with snap-down and release voltages programmed to form a six microrobot 2-SNESat system, as shown on **Fig. 9**.

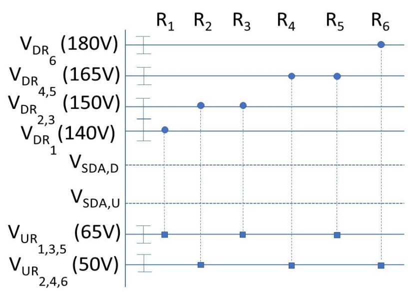

Figure 9: Experimentally measured snap-down and release voltages of six MicroStressBots in a 2-SNESat system with error bars indicating the reproducibility of each voltage level.

The experimentally obtained hysteresis matrix H (left), and the programming pulses of the control primitives for two representative hysteresis states are shown in **Fig. 10**. In total, ten control primitives were created, denoted as Primitive A – J, with the waveforms of primitives D and E shown in **Fig. 10.** Experimentally recorded sequence of micrographs, 1:(a)-1:(c) and 2:(a)-2:(c) showing progressive assembly of six MicroStressBots into two target shape using 2-SNESat are shown in **Fig. 11**. Videos of the assembly experiments are available online here: https://youtu.be/iro_zHgG1BY

CONCLUSIONS

In this paper, we have shown the theory and experimental verification of a new control scheme called 2-SNESat, which enables scalable control of large numbers of electrostatically driven MEMS microrobots (MicroStressBots). The new scheme requires sublinear $O(\sqrt{n})$ control voltage bandwidth (i.e. number of voltages needed to control n robots), and constant ($O(1)$) number of control pulses. This scheme demonstrates that by using electromechanical switching logic, in this case in the form of a steering arm, scalable control of large numbers of microrobots using a global control signal is achievable.

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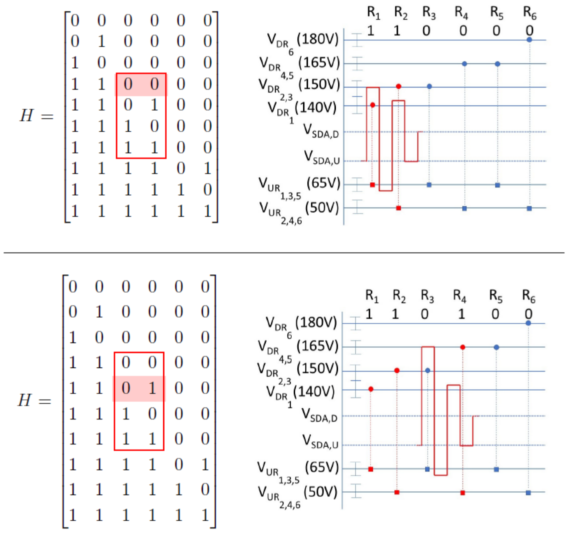

Figure 10: Hysteresis matrix (left) with representative programming pulses (right) for R_1–R_6. The programming pulses corresponding to the hysteresis states (left) are shown on right.

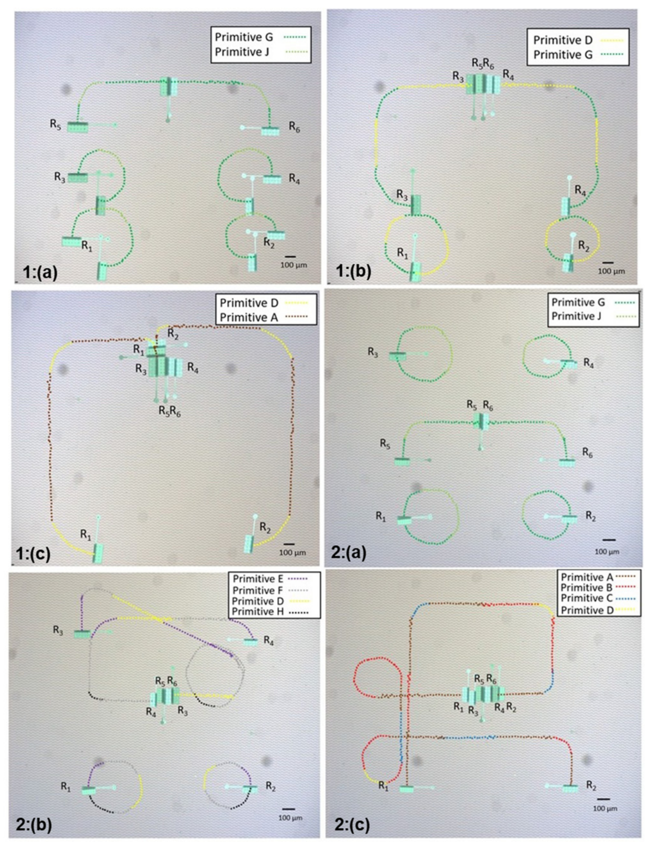

Figure 11: Experimentally recorded sequence of micrographs, 1:(a)-1:(c) and 2:(a)-2:(c) showing progressive assembly of six MicroStressBots into two target shape using 2-SNESat.

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