Scalability of Controlling Heterogenous Stress-Engineered MEMS Microrobots (MicroStressBots) through Common Control Signal using Electrostatic Hysteresis

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***Abstract*— In this paper we present control strategies for implementing reconfigurable planar microassmbly using multiple stress-engineered MEMS microrobots (MicroStressBots). A MicroStressBot is an electrostatic microrobot that consists of an untethered scratch drive actuator (USDA) that provides forward motion, and a steering-arm actuator that determines whether the robot moves in straight line or turns. The steering-arm is actuated through electrostatic pull-down to the substrate initiated by the applied global power delivery and control signal. Control of multiple MicroStressBots is achieved by varying the geometry of the steering-arm, and hence affecting its electrostatic pull-down and/or release voltages. Independent control of many MicroStressBots is achieved by fabricating the arms of the individual microrobots in such a way that the robots move differently from one another during portions of the global control signal. In this paper we analyze the scalability of control in an obstacle free configuration space. Based on robust control strategies, we derive the control signals that command some of the robots to make progress toward the goal, while the others stay in small orbits, for several classes of steering-arm geometries. We also present a comprehensive analysis and comparison between the numbers of required independent pull-down and release voltages, demonstrating significant improvement in terms of the efficiency as well as the size of the control signal presented in past work. Our analysis presents an important step for developing multi-microrobots control of MicroStressBots.**

Keywords: multi-microrobot systems control, MEMS, underactuated system.

I. Introduction

Microscale robotic systems have many applications in areas such as biomedicine [1], surveillance [2], or microassembly [3]. In [4, 5, 6] a globally controllable 240 μm × 60 μm × 10 μm mobile stress-engineered microelectromechanical systems (MEMS) microrobot (MicroStressBot) is presented. A MicroStressBot contains an untethered scratch drive actuator (USDA) [7] which provides forward propulsion, and a steering-arm actuator which controls when the robot moves in straight line or turns.

All these envisioned microrobotic applications rely on the combined actions of large number microrobots. The high level of underactuation presents in such systems (all robots are controlled by a *single* global control signal), makes the simultaneous control of several microrobots significantly more challenging than control of single microrobot.

Controlling a distributed system of many devices that differ in behavior falls under the concept of Ensemble Control (EC) [8, 9] and Global Control Selective Response (GCSR) [6]. In Ensemble Control (EC) the robots are modeled as nonholonomic unicycles with inhomogeneity in turning and linear velocity. By using state feedback control policy, globally asymptotically stable ensemble of unicycles controlled by uniform control inputs, is achieved. It has been shown in [9] that the ensemble of nonholonomic unicycles is asymptotically stable by using a suitable Lyapunov function. Although EC provides promising control policy to any number of robots in theory but in practice it is not successful for more than ten of robots due to the control error (system noise), which cancels the inhomogeneity effect. Also EC needs perfect state estimation and the controllers required at worst a matrix inversion and at best a summation over all robot states which is not practical for large number of robots. In [9], the control policy is based on the robots local coordinate and the trajectory of each robot is independent and disregards collision, which is impractical for any microrobotic system due to Stiction effects.

However, in this paper, we present the theory and proof of a novel control voltage methods for multiple heterogeneous stress-engineered Microrobots (MicroStressBots) that provide highly underactuated, reconfigurable, time-efficient and multi-shapes microassembly system. Furthermore, this is the first technique relying on inhomogeneity that the control primitives can always be achieved with a constant number of control primitives and, unlike the previous techniques, do not increase with size of the system, enabling the implementation of the control strategy presented in [6].

The paper is structured as follows: in Sec. II, we introduce the stress-engineered Microrobot (MicroStressBot). The general approach to controlling multiple MicroStressBots is discussed in Sec. III. Sec. IV describes the theory, proof, and scalability analysis for String-Cluster System and ESATC systems. Concluding discussion regarding the scalability of these different systems is described in Sec. V.

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II. STRESS-ENGINEERED MICROROBOT

The stress-engineered MEMS microrobot, MicroStressBot for short, consists of an untethered scratch drive actuator (USDA) [7] that provides forward motion and a curved steering-arm actuator that determines whether the robot moves straight or turns. Fig. 1 shows the schematic of the MicroStressBot. The USDA is composed of a 120 μm × 60 μm backplate and a 1.5-μm-tall bushing. The steering-arm actuator consists of a 120 to 160 μm long cantilever beam with a circular pad and a 0.75 μm-deep dimple.

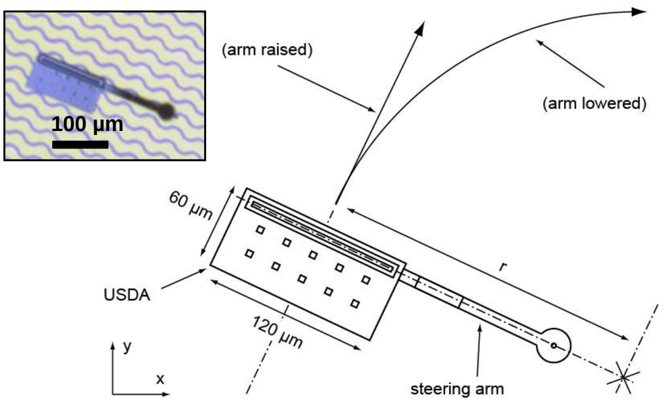

Fig. 1: The schematic of the MicroStressBots.

The MicroStressBots are fabricated using surface micromachining PolyMUMPS foundry process [10]. The initially planar steering arms is curved out-of-plane (upwards) using a stress engineering process [11]. This process adds a patterned layer of a stressor material (Chromium, Cr) with high compressive stress to provide an upward curvature. The thickness of the deposited material and the area covered by the stressor layer must be precisely defined, such that the steering arm is deflected at the preset actuation voltage.

The microrobot operates on a grid of insulated interdigitated electrodes. When voltage is applied between sets of electrodes, the electrodes and the conductive chassis of the microrobot form a capacitive circuit, and an electric potential is induced on the microrobot. This potential causes the microrobot body to be bent to the substrate, and the scratch-drive converts this vertical motion into a forward step. This voltage (waveform) changes over time to provide power to the USDA and to control the state of the steering arm. This waveform is called the *control waveform*. The waveform is divided into two parts:

a) Control cycle: containing control pulses, that sets the state of the steering-arm actuator, and *b) power-delivery cycle:* that provides power to the USDA. The power-delivery cycle consisting of stepping pulses, changing between a maximum (V_{high}) and a minimum (V_{low}). In order for the USDA to actuate, V_{high} must be greater than the minimum voltage (V_{flx}) at which the backplate of the USDA obtains enough curvature to produce

b) a forward step, while V_{low} must be less than the maximum voltage (V_{rel}) at which that curvature is sufficiently relieved to generate forward motion. V_{flx} and V_{rel} are described in more detail in [12, 13].

Similar to an electrostatic cantilever beam [14], the steering arm of each microrobot has two distinct voltage levels at which the arm suddenly changes states. This is the snap-down voltage at which the arm is pulled in contact with the substrate as the robot is turning and the release voltage at which the arm is released and the robot is commanded to move straight. We call these voltage levels the transition voltages of the steering arm. The transition voltages are determined by the steering-arm designs. The steering arm can be either raised to cause the robot to move in a straight line, or lowered to cause the robot to turn. We call the position of the steering-arm actuator the *hysteresis state* of the microrobot (arm raised, hysteresis state = 0; arm lowered, hysteresis state = 1). A system of n MicroStressBots contains 2^npossible hysteresis states (all 2^n combinations of n steering arms being raised or lowered).

III. GCSR: A STRATEGY FOR MULTI-MICROROBOT CONTROL AND ASSEMBLY

As mentioned in [6], GCSR is a strategy to control and maneuver robots to complete the microassembly. GCSR uses design-induced heterogeneity of MicroStressBots and resulting differences between their trajectories to maneuver the robots from an initial to a target goal configuration. As stated in [6], GCSR uses the control matrix to control the single robot sequentially while the other robots confined to the circular trajectories. A mapping between the control primitives (waveforms that program the hysteresis states of the system) and the motion of the individual robots is defined using a control matrix, where each entry contains the hysteresis state of one of the microrobot during the applied control primitive. The resulting sequence of control primitives is called the *control sequence*, usually denoted by S . Fig. 2 shows the trajectory of a microrobot D_1 from initial (i) to target (ii) configuration (docking with a seed-shape (iii)), during the application of control sequence S={P_0,P_2,P_1,P_2,P_1,P_2,P_1,P_2,P_1}. During this partial assembly robot D_2 orbits without advancing to goal. This type of STRING (STRIcly Non-nested hysteresis Gap) GCSR is designed to be sequential (i.e. one robot at a time is maneuvered towards the goal) to increase the number of controllable microrobot and enable robust colision avoidance. The control matrix denoting the correspopndens between control primitives in a STRING microaseembly is called a STRING control matrix. It has been shown in [6] that microassembly can be implemented on a group of MicroStressBots if a STRING matrix can be generated for such system.

IV. BEYOND STRING CONTROL: ENABELING GCSR THROUGH CONTROL VOLTAGE DIFFERENTIATION

Successful implementation of GCSR control relies on a set of control primitives that couple the motion of the microrobots in a specific way (later called *STRING control primitives*). For a given system of n microrobots, let V_{di} and V_{ui} denote the snap-down and release voltages of microrobot i. We define the *control voltage bandwidth* (ξ) of a MicroStressBot system as the number of independent electromechanically addressable *transition voltage levels* (pull-down and release voltages) of the global control signal. In general, a microrobotic system with fewer accessible hysteresis states has a lower control voltage bandwidth requirement. More specifically, the accessibility of the hysteresis states depends on the relation between the hysteresis gaps of the individual robots. Let δ_v be the maximum deviation of the transition voltage manifested during the microrobot operation. We define two transition voltages to be *significantly independent* if they are separated by at least $2\delta_v$.

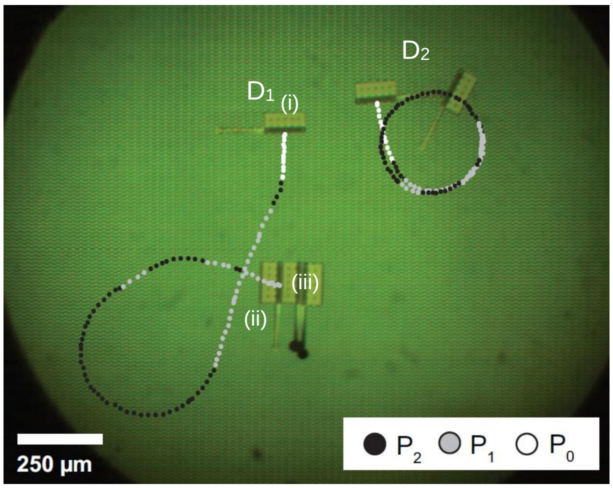

Fig. 2: Trajectories of MicroStressBots D_1 and D_2 during partial microassembly. *Reproduced with permission from [6].*

Several steering-arm design configurations (*NHG*, *STRING*, and *SESat*) have been proposed in [6] to achieve GCSR. The objective of all these designs is to reduce the control bandwidth size with respect to the number of robots, i.e. maximize the number of independently controllable microrobots for a given microrobotic system. Per [15], *Nested Hystersis Gaps* (*NHG*) is the system of n steering arms, sorted according to ascending V_{di}, when ($V_{di}+2\delta_v<V_{dj}$) and ($V_{ui} - 2\delta_v>V_{uj}$), for all $i<j$. *NHG* systems can access all 2^n hysteresis states. However each device requires two unique control voltage levels, and so the control voltage bandwidth requirement of this system is $\xi_n = 2n$. However, *NHG* is sufficient but not necessary to achieve GCSR. *Strictly non-nested hysteresis gaps* (*STRING*) [6] is an n - microrobotic system, primarily sorted according to ascending values of V_d, and secondarily sorted according to ascending values of V_u, has non-nested hysteresis gaps if ($V_{di} \leq V_{dj}$) and ($V_{ui} \leq V_{uj}$), for all $i<j$. It has been shown in [6] that *STRING* system can access $n+1$ hysteresis states and the control bandwidth requirement for a *STRING* system is $\xi_n = n+1$. Although *STRING* system cannot not access all the 2^n states, as sequential mircoassembly algorithm makes the system controllable when implementing microassembly. *STRING* reduces the control bandwidth requirements from $\xi_n = 2n$ (*NHG*) to $\xi_n = n+1$. Further, sublinear reduction ξ_n has been done under the *SESat* control strategy [6]. It has been shown in [6] that *SESat* needs $\xi_n = \lceil 2\sqrt{n} \rceil$ while it can access at least $n+1$hysteresis states which are essential for sequential microassembly algorithm.

Although *SESat* could reduce the control bandwidth requirements to $O\,(2\sqrt{n})$, only 3 out of the 4 hysteresis states for the first two robots forming the seed-shape are accessible, making their independent control challenging. In this paper we present new set of control strategies (***String-cluster System* and *Electromechanically SATurated Cluster system (ESATC)***) that not only has the control voltage bandwidth $\xi_n = O(n)$ and $\xi_n = O\,(2\sqrt{n})$ but also are capable of controlling two microrobots simultaneously.

A. *String-Cluster System*

In this section we introduce a control strategy that is capable to control two microrobots simultaneously at each iteration of assembly process. We start with the following definitions:

Definition. I: *Nested-Group-Microrbots (NGM) set:*

Set of all groups of two Microrobots that forms a *Nested-Hysteresis-Gaps* (*NHGs*) structure is *Nested-Group-Microrbots (NGM)*. M is the set of all microrobots in the system. $M = \{D_1, D_2, \dots, D_n\}$; where D_i is ith Micorobot in the system.

$$NGM = \{(D_i, D_j)\,|(D_i, D_j \in M,\ \ V_{dj} > V_{di},\ V_{ui} > V_{uj})\ i,j \in N\} \quad (1)$$

where V_d and V_u are snap-down and release voltages.

Definition. II: *Nested-Group-Microrbots Cluster (Cluster):* Each member of *NGM* is called *Cluster*.

$$Cluster = (D_i, D_j) \in NGM;\ i,j \in N \quad (2)$$

In each *Cluster*, we define $V_{dl} = Min\,(V_{di}, V_{dj})$, $V_{dh} = Max\,(V_{di}, V_{dj})$, $V_{ul} = Min\,(V_{ui}, V_{uj})$ and $V_{uh} = Max\,(V_{ui}, V_{uj})$, respectively. Fig. 3. Shows the relation between the transition voltages in a *Cluster*, the snap-down and release voltages are shown as circles and rectangles, respectively.

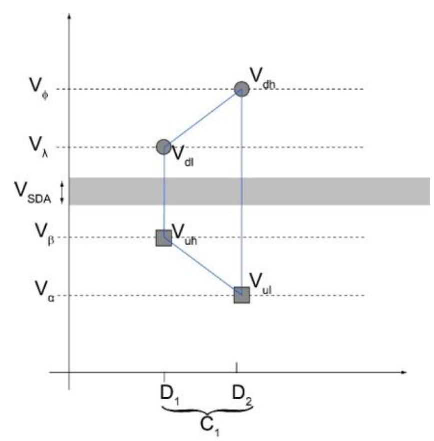

Fig.3. Cluster Structure

$$String - Cluster = \{Cluster \in NGM \mid \forall Cluster_k, Cluster_m\ (k < m), (V_{dh,k} \leq V_{dl,m};\ V_{uh,k} \leq V_{ul,m});\ m,k \in N\} \quad (3)$$

Definition. III: *STRIctly Non-nested hysteresis-Gaps (String)-Cluster (**String-Cluster**)* system:

This system consists of *Clusters* where each two microrobots in two different *Clusters* form a *String* system. This system is formed by Equation. 3.

It is convenient for us to define a lexicographic sorting of the robots, using two keys. In general, an *M- Clusters* microrobotic system, primarily sorted according to ascending values of V_{dl}, V_{dh} and secondarily sorted according to ascending values of V_{ul}, V_{uh} has non-nested hysteresis gaps between each two microrbots belong to different *Clusters*. However, in the case when $V_{dl,j} - V_{dl,i} < 2\delta_v$, $V_{dh,j} - V_{dh,i} < 2\delta_v$ and $V_{ul,j} - V_{ul,i} < 2\delta v$, $V_{uh,j} - V_{uh,i} < 2\delta_v$, the behavior of robots of *Cluster$_i$* and *Cluster$_j$* is indistinguishable, and four such microrobots in *Cluster$_i$* and *Cluster$_j$* cannot be controlled independently. We call such two *Cluster*s a *degenerate Cluster pair*. Fig. 4 shows ***String-Cluster*** system.

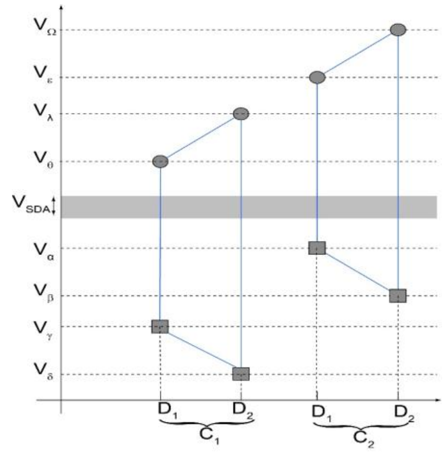

Fig. 4. String-Cluster system

Lemma. 1: *An **M- String-Cluster** system has exactly "**n+3=2M+3**" accessible hysteresis states, where **M**= no. Clusters, **n** = no. Microrobots and **M=n/2**.*

Proof: By Induction:

Base condition: *An **String-Cluster** system with **M=2** has seven accessible states*.

In each *Cluster* we have two microrobots sorted in an *NHG* system format. Each of the microrobots got 2 states: (0=arm up) and (1= arm down). Hence we have $2^2 = 4$ states (00= arm up, arm up), (01= arm up, arm down), (10= arm down, arm up) and (11= arm down, arm down). Let ***M=2*** *Clusters* microrobtic system, C_1 and C_2, where each *Cluster* C_i consists of two microrobots $\{D_1, D_2\}$. Without loss of generality, $V_{dh,1} \leq V_{dl,2}$ and $V_{uh,1} \leq V_{dl,2}$. Fig. 5 shows the ranges for transition voltages of *Cluster (C_2)*, such that the M=***2*** *Clusters* microrobtic system becomes ***String-Cluster***.

Let $V_\delta, \ldots, V_\Psi$ be significantly independent transition voltage levels, ordered such that $V_\delta < V_\gamma < V_\beta < V_\alpha < V_\zeta < V_\theta < V_\lambda < V_\varepsilon < V_\varphi < V_\Omega < V_\Psi$ with $\left|V_\Omega - V_\varphi\right| = 2\delta v$ and $\left|V_\zeta - V_\alpha\right| = 2\delta v$. Let $V_{dl,1} = V_\varepsilon$, $V_{dh,1} = V_\varphi$ and $V_{ul,1} = V_\beta$, $V_{uh,1} = V_\alpha$. It follows that the snap-down voltage $V_{dl,2}$ can have value $V_1 \in (V_\varphi, V_\Omega]$, or voltage $V_2 = V_\varphi$ and the snap-down voltage $V_{dh,2}$ can have value $V_3 \in (V_\Omega, V_\Psi]$, or voltage $V_4 = V_\Omega$ and $\left|V_{dh,2} - V_{dl,2}\right| \geq 2\delta v$. Similarly, the release voltage, $V_{uh,2}$ can have the value $V_5 \in (V_\zeta, V_{rel} - 2\delta v]$ or voltage $V_6 = V_\zeta$, and the release voltage $V_{ul,3}$ can have the value $V_7 \in (V_\alpha, V_\zeta]$ or voltage $V_8 = V_\alpha$ and $\left|V_{uh,2} - V_{ul,2}\right| \geq 2\delta v$. Consequently, for the ***M+1*** *Clusters* microrobtic system to remain ***String-Cluster***, one of the following combinations of the snap-down and release voltages for C_2 must hold: (V_1, V_5, V_3, V_7), (V_1, V_5, V_3, V_8), (V_1, V_6, V_3, V_8), (V_2, V_5, V_3, V_7), (V_2, V_5, V_3, V_8), (V_2, V_6, V_3, V_8), (V_2, V_5, V_4, V_7), (V_2, V_5, V_4, V_8) and (V_2, V_6, V_4, V_8).

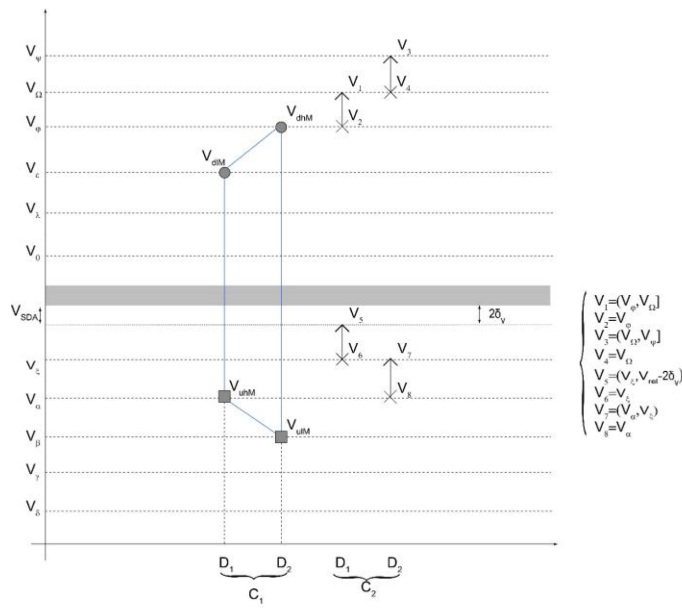

Fig. 5. Illustration of the proof of Lemma. 1

We examine each case separately:

(V_1, V_5, V_3, V_7): because of $V_{dl,2}$, $V_{dh,2}$ are greater than the snap-down voltages of *C_1*, ($V_{dl,2} > V_{dl,1}$, $V_{dl,2} > V_{dh,1}$), and ($V_{dh,2} > V_{dl,1}$, $V_{dh,2} > V_{dh,1}$), we can only snap down the arms of *D_1* and *D_2* in *C_2* after we snap down the arms of *C_1*. Since $V_{ul,2}$, $V_{uh,2}$ is greater than the release voltages of *C_1*, ($V_{ul,2} > V_{ul,1}$, $V_{ul,2} > V_{uh,1}$), and ($V_{uh,2} > V_{ul,1}$ and $V_{uh,2} > V_{uh,1}$), we can only release the arms of *C_1* after we have released the arms of *D_1* and *D_2* in *C_2*. Because the ($V_{dh,2} > V_{dl,2} > V_{dh,1}, V_{dl,1}$), we can snap down *$C_1$* and *$D_1$* of *$C_2$* while

D_2 of C_2 is released. Since the $V_{uh,2} > V_{ul,2} > V_{ul,1}, V_{uh,1}$), we can release D_1 of C_2 while D_2 and all other clusters are snapped down. Consequently, we can change the states of C_2 to "01", "10" or "11" when C_1 are in state "11". During all other states of the system the state of C_2 must remain "00". Consequently, the number of accessible hysteresis states increase by exactly 3.

(V_1,V_5, V_3, V_8): This case is similar to (V_1, V_5, V_3, V_7), except that the arm of D_1 of *Cluster* C_1 is released at the same time as the arm of D_2 of *Cluster* C_2. As long as $V_{dh,2} > V_{dl,1}$, we can snap down the arm of D_2 of C_2 only after all other clusters are in state "11". As a consequence the number of accessible hysteresis states increase by exactly 3.

(V_2, V_5, V_3, V_7): The snap-down voltage D_1 of C_2 is equal to the snap-down voltage of D_2 of C_1, ($V_{dl,2}$=$V_{dh,1}$). In this case, the arm of D_1 of C_2 is snapped down at the same time as the arm of D_2 of C_1. Because the release voltage of D_1 of C_2 is greater than the release voltages of C_1, ($V_{uh,2} > V_{ul,1}$, $V_{uh,2}$), we can only release the arm D_2 of C_1 after we release the arm D_1 of C_2. As in the (V_1, V_5, V_3, V_7) case, the state of C_2 must be "00" except when C_1, is snapped down, then D_1 of C_2 can be either "00", "01", "10" or "11" by varying the release voltages. Consequently, the number of accessible hysteresis states increases by exactly 3.

(V_1, V_6, V_3, V_8): This case is similar to (V_1, V_5, V_3, V_8).
(V_2, V_6, V_3, V_8): This case is similar to (V_2, V_5, V_3, V_8).
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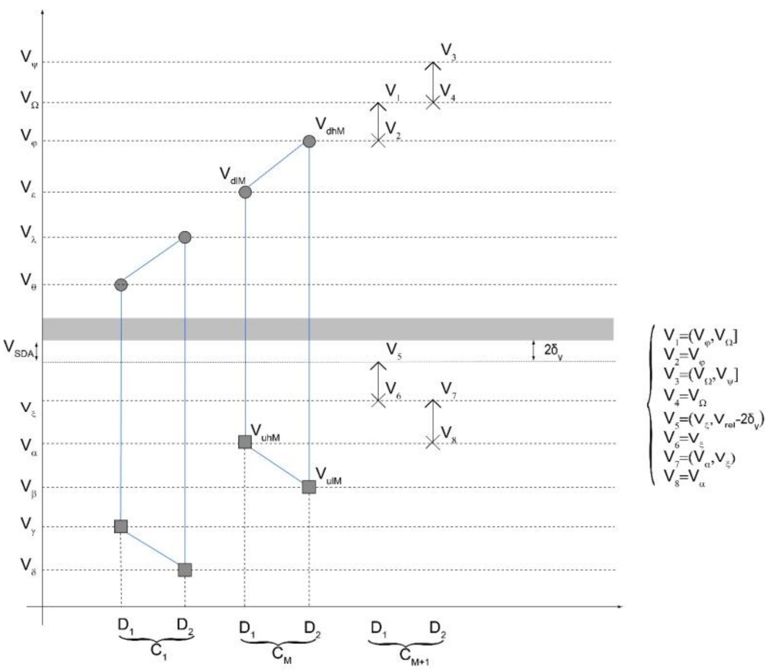

Fig. 6. Illustration of the proof of Lemma. 1

Inductive step: adding a *Cluster* (changing the size of the system from ***M*** to ***M+1*** *Clusters*) extends the number of accessible control states by exactly 3, provided that both ***M*** and ***M+1*** *Clusters* microrobtic system remain ***String-Cluster***. Let ***M*** *Clusters* microrobtic system, C_1,..., C_M, where each *Cluster* C_i consist of two microrobots { D_1, D_2}, be a ***String-Cluster*** system sorted according to $V_{dl,i}$, $V_{dh,i}$ and $V_{ul,i}$, $V_{uh,i}$. Without loss of generality, $V_{dh,M} \leq V_{dl,M+1}$ and $V_{uh,M} \leq V_{ul,M+1}$. Fig. 6 shows the ranges for transition voltages of *Cluster*$_{M+1}$ (C_{M+1}), such that the new ***M+1*** *Clusters* microrobtic system remain ***String-Cluster***.

Let V_δ, ... , V_Ψ be significantly independent transition voltage levels, ordered such that $V_\delta < V_\gamma < V_\beta < V_\alpha < V_\zeta < V_\theta < V_\lambda < V_\varepsilon < V_\varphi < V_\Omega < V_\Psi$ with $\left|V_\Omega - V_\varphi\right| = 2\delta v$ and $\left|V_\zeta - V_\alpha\right| = 2\delta v$. Let $V_{dl,M} = V_\varepsilon$, $V_{dh,M} = V_\varphi$ and $V_{ul,M} = V_\beta$, $V_{uh,M} = V_\alpha$. It follows that the snap-down voltage $V_{dl,M+1}$ can have value $V_1 \in (V_\varphi, V_\Omega]$, or voltage $V_2 = V_\varphi$ and the snap-down voltage $V_{dh,M+1}$ can have value $V_3 \in (V_\Omega, V_\Psi]$, or voltage $V_4 = V_\Omega$ and $\left|V_{dh,M+1} - V_{dl,M+1}\right| \geq 2\delta v$. Similarly, the release voltage, $V_{uh,M+1}$ can have the value $V_5 \in (V_\zeta, V_{rel} - 2\delta v]$ or voltage $V_6 = V_\zeta$, and the release voltage $V_{ul,M+1}$ can have the $V_7 \in (V_\alpha, V_\zeta]$ or voltage $V_8 = V_\alpha$ and $\left|V_{uh,M+1} - V_{ul,M+1}\right| \geq 2\delta v$. Consequently, for the ***M+1*** *Clusters* microrobtic system to remain ***String-Cluster***, one of the following combinations of the snap-down and release voltages for C_{M+1} must hold: : (V_1, V_5, V_3, V_7), (V_1, V_5, V_3, V_8), (V_1, V_6, V_3, V_8), (V_2, V_5, V_3, V_7), (V_2, V_5, V_3, V_8), (V_2, V_6, V_3, V_8), (V_2, V_5, V_4, V_7), (V_2, V_5, V_4, V_8) and (V_2, V_6, V_4, V_8). We examine each case separately:

(V_1, V_5, V_3, V_7): because of $V_{dl,M+1}$, $V_{dh,M+1}$ are greater than the snap-down voltages of C_1, ... , C_M, ($V_{dl,M+1} > V_{dl,i}$, $V_{dh,i}$) and ($V_{dh,M+1} > V_{dl,i}$, $V_{dh,i}$), $i \in Z_M$ where $Z_M = \{1, ..., M\}$, we can only snap down the arm of D_1 and D_2 in C_{M+1} after we snap down the arms of all other clusters.
Since $V_{ul,M+1}$, $V_{uh,M+1}$ is greater than the release voltages of C_1, ... , C_M, ($V_{ul,M+1} > V_{ul,i}$, $V_{uh,i}$) , and ($V_{uh,M+1} > V_{ul,i}$, $V_{uh,i}$), $i \in Z_M$ where $Z_M = \{1, ..., M\}$, we can only release the arms of all C_1, ... , C_M after we have released the arm of D_1 and D_2 in C_{M+1}. Because the $V_{dh,M+1} > V_{dl,M+1} > V_{dl,i}$, $V_{dh,i}$, $i \in Z_M$ where $Z_M = \{1, ..., M\}$, we can snap down all other clusters and D_1 of C_{M+1} while D_2 of C_{M+1} is released. Since the ($V_{uh,M+1} > V_{ul,M+1} > V_{ul,i}$, $V_{uh,i}$), $i \in Z_M$ where $Z_M = \{1, ..., M\}$, we can release D_1 of C_{M+1} while D_2 and all other clusters are snapped down. Consequently, we can change the states of C_{M+1} to "01", "10" or "11" when $C_1, ..., C_M$ are in state "11". During all other states of the system the state of C_{M+1} must remain "00". Consequently, the number of accessible hysteresis states increase by exactly 3.

(V_1,V_5, V_3, V_8): This case is similar to (V_1, V_5, V_3, V_7), except that the arm of D_1 of *Cluster* C_M is released at the same time as the arm of D_2 of *Cluster* C_{M+1}. As long as $V_{dh,M+1} > V_{dl,M}$, we can snap down the arm of D_2 of C_{M+1} only after all other clusters are in state "11". As a consequence the number of accessible hysteresis states increase by exactly 3.

(V_2, V_5, V_3, V_7): The snap-down voltage D_1 of C_{M+1} is equal to the snap-down voltage of D_2 of C_M, $V_{dl,M+1}$=$V_{dh,M}$. In this case, the arm of D_1 of C_{M+1} is snapped down at the same time as the arm of D_2 of C_M. Because the release voltage of D_1 of C_{M+1} is greater than the release voltages of $C_1, \ldots, C_M$, $V_{uh,M+1} > V_{ul,i}, V_{uh,i}$, $i \in Z_M$ where $Z_M = \{1,\ldots, M\}$, we can only release the arm D_2 of C_M after we release the arm D_1 of C_{M+1}. As in the (V_1, V_5, V_3, V_7) case, the state of C_{M+1} must be "00" except when $C_1, \ldots, C_M$ are all snapped down, then of D_1 of C_{M+1} can be either "00", "01", "10" or "11" by varying the release voltages. Consequently, the number of accessible hysteresis states increases by exactly 3.

(V_2, V_5, V_3, V_8): This case is similar to (V_1, V_5, V_3, V_7), except that The snap-down voltage D_1 of C_{M+1} is equal to the snap-down voltage of D_2 of C_M, $V_{dl,M+1}$=$V_{dh,M}$. In this case, the arm of D_1 of C_{M+1} is snapped down at the same time as the arm of D_2 of C_M. Because the release voltage of D_1 of C_{M+1} is greater than the release voltages of $C_1, \ldots, C_M$, $V_{uh,M+1} > V_{ul,i}, V_{uh,i}$, $i \in Z_M$ where $Z_M = \{1,\ldots, M\}$, we can only release the arm D_2 of C_M after we release the arm D1 of C_{M+1}. As in the (V_1, V_5, V_3, V_7) case, the state of C_{M+1} must be "00" except when $C_1, \ldots, C_M$ are all snapped down, then C_{M+1} can be either "00", "01", "10" or "11" by varying the release voltages. Consequently, the number of accessible hysteresis states increase by exactly 3.

(V_2, V_6, V_3, V_8): This case is similar to (V_2, V_5, V_3, V_8).
(V_1, V_6, V_3, V_8): This case is similar to (V_1, V_5, V_3, V_8).
(V_2, V_5, V_4, V_7): This case is similar to (V_2, V_5, V_3, V_7).
(V_2, V_5, V_4, V_8): This case is similar to (V_2, V_5, V_3, V_8).
(V_2, V_6, V_4, V_8): This case is similar to (V_2, V_5, V_3, V_8).

We have shown that adding a Cluster to a ***String-Cluster***, such that the resulting system remains a ***String-Cluster***, increases the number of accessible hysteresis states by exactly 3. Combined with the base case (n = 1, four hysteresis states), it follows by induction that every ***M- String-Cluster*** system has exactly ***"n+3=2M+3"*** accessible hysteresis states, where ***M****= number of Clusters,* ***n*** *number of Microrobots* and ***M=n/2***.

We now construct the control primitives and corresponding control matrix that can access the $n + 3$ hysteresis states of an ***M- String-Cluster*** system. The ordering of the clusters is determined by the transition voltages of the steering arms. We construct the control primitive $P_j(S)$ such that it assigns the state "11" to all clusters C_i for $i < j$, and "00" to all cluster C_i for $i > j$, and base on the value of (S), it can assign the states "01", "10" or"11" to C_j. P_j is defined by a control cycle containing two control pulses, $P_j(S)$ = ($V_{a,1}$, $V_{a,2}$) with a decision variable (S). Consider the ***String-Cluster*** system shown in Fig. 7, where $V_\delta, \ldots, V_\Omega$ represent significantly independent control voltage levels. (S) selects the Hysteresis state of C_j:

$$C_j\text{ -Hysteresis-States} = \begin{cases} '00' & when\ S = 0 \\ '01' & when\ S = 1 \\ '10' & when\ S = 2 \\ '11' & when\ S = 3 \end{cases} \quad (4)$$

We define $P_j(S)$ as

$$P_j(S) = \begin{cases} (V_{dl,j}, V^+_{ul,j}) & if\ j \in Z_M,\ S = 0 \\ (V_{dh,j}, V^+_{ul,j}) & if\ j \in Z_M,\ S = 1 \\ (V_{dl,j}, V^+_{uh,j}) & if\ j \in Z_M,\ S = 2 \\ (V_{dh,j}, V^+_{uh,j}) & if\ j \in Z_M,\ S = 3 \end{cases} \quad (5)$$

where $V^+_{ul,j} = V_{ul,j} + \delta v$ and $V^+_{uh,j} = V_{uh,j} + \delta v$.

When $S = 0$, the first control pulse ($V_{a,1}$) snaps down the steering arms of all the *Clusters* C_i, $i \in Z_{j-1}$, where $Z_{j-1} = \{1,\ldots, j-1\}$, and D_1 of cluster C_j. The second control pulse ($V_{a,2}$) keeps all the *Clusters* C_i, $i \in Z_{j-1}$ snapped down while all other clusters are released.
The first control pulse ($V_{a,1}$) snaps down the steering arms of all the *Clusters Ci*, $i \in Z_j$ where $Z_j = \{1,\ldots, j\}$, as well as any devices D_1 *of* C_k, $k > j$ with $V_{dl,k} = V_{dh,j}$ and the second control pulse ($V_{a,2}$) releases all the *cluster* C_k, $k > j$ and the device D_1 of C_j that were snapped down by the first control pulse when $S = 1$, because in the case when $V_{dl,k} = V_{dh,j}$, it must hold that $V_{ul,j} < V^+_{ul,j} \leqslant V_{ul,k} < V_{uh,k}$.

For $S = 2$, the first control pulse ($V_{a,1}$) snaps down the steering arms of all the *Clusters* C_i, $i \in Z_{j-1}$, where $Z_{j-1} = \{1,\ldots, j-1\}$, and D_1 of cluster C_j. The second control pulse ($V_{a,2}$) keeps all the *Clusters* C_i, $i \in Z_{j-1}$ and D_1 of *cluster* C_j snapped down while all other clusters are released.

Similarly, The first control pulse ($V_{a,1}$) snaps down the steering arms of all the *Clusters* C_i, $i \in Zj$, as well as any devices D_1 *of* C_k, $k > j$ with $V_{dl,k} = V_{dh,j}$ and the second control pulse ($V_{a,2}$) releases all the *cluster* C_k, $k > j$ that were snapped down by the first control pulse when $S = 3$, because in the case when $V_{dl,k}$= $V_{dh,j}$, it must hold that $V_{ul,j} < V^+_{ul,j} \leqslant V_{ul,k}$.

The $n + 3$ control primitives generated by $P_j(S)$ form a $(n + 3) \times (n)$ control matrix (A). An example of such a control matrix for two clusters (Four Devices) is:

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 \end{bmatrix} \quad (6)$$

We refer to A as the *String-Cluster control matrix*, the $n+3$control primitives contained in M as the ***String-Cluster** control primitives*, and the $n+3$ hysteresis states accessible using these control primitives as the ***String-Cluster** hysteresis states*. Note that because adding three new control states to a ***String-Cluster*** system requires the addition of two independent voltage level (per Lemma. 1), the control bandwidth requirement for a ***String-Cluster*** system is $\xi_n = n+2$.

As it can be seen, String-Cluster system needs a control voltage bandwidth of order n but as compared to [6] String (which could control one robot at a time), it can control and maneuver two robots simultaneously which results in time efficient and also reconfigurable system because the first two robots that create the assembly point need not to be in a specific configuration.

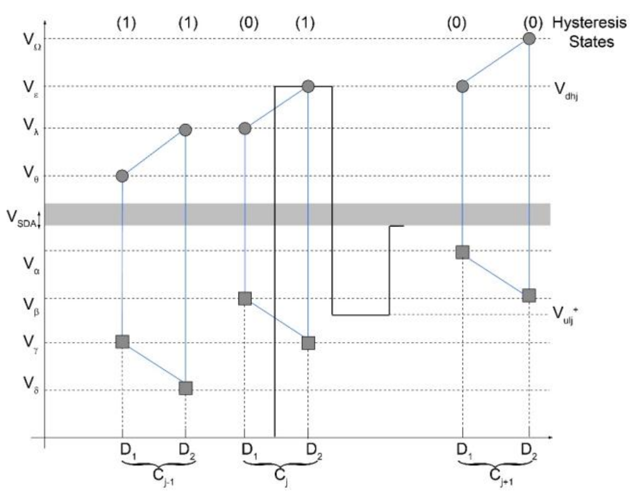

Fig. 7. Illustration of control cycle in String-Cluster System

B. *Electromechanically SATurated Cluster system (ESATC)*

Lemma. 2: *Any **M- Cluster** system with no degenerate pairs of clusters can be sorted such that all "**n+3=2M+3**" **String-Cluster** hysteresis states are accessible, where **M**= number of Clusters, **n** = number of Microrobots and **M=n/2**.*

Proof: By Construction:

Consider an ***M- Cluster*** system with(K) independent snap-down voltages, and (L) independent release voltages. Assuming no degenerate pairs of clusters, it follows that n = *2M* $\leq KL$*, where **M**= no. Clusters, **n** = no. Microrobots and **M=n/2***. Consider a system, sorted primarily according to snap-down voltages $V_{dl,i}$, $V_{dh,i}$ and secondarily sorted according to increasing release voltages $V_{ul,i}$ and $V_{uh,i}$. Fig. 8 shows such a system when k = 4 and l = 4. Note that sorting ensures a monotonic increase of $V_{ul,i}$ and $V_{uh,i}$ with increasing index *i*. We call such a system *Electromechanically SATurated Cluster system (ESATC)*. In this system $n = 2\,(K-1)(\frac{L}{2})$ or $n = 2\,(L-1)(\frac{K}{2})$.

For such an order, there exists a formula$P_j(S)$, shown in equation (8), which generates all $(n+3)$ ***String-Cluster*** control primitives. $P_j(S)$ is defined by a control cycle containing six control pulses, $P_j(S)$= $(V_{a,1}, V_{a,2}, V_{a,3}, V_{a,4}, V_{a,5}, V_{a,6})$ with a decision variable S. Unlike the previous techniques, the new control primitives do not increase with population size, enabling the implementation of the control presented in [6]. The control cycle for each control primitive defined by equation (8) contains a sequence exactly 6 control pulses. Again (S) selects the Hysteresis state of C_j in Equation. 7. We construct the control primitive $P_j(S)$ in Equation. 8, Where $V_{max} = MAX\{V_{dh,j}\}$, $1 \leq j \leq n$; $V^{+}_{ul,j} = V_{ul,j} + \delta v$, $V^{+}_{uh,j} = V_{uh,j} + \delta v$, $V^{-}_{ul,j} = V_{ul,j} - \delta v$ and $V^{-}_{dl,j} = V_{dl,j} - \delta v$.

$P_j(S)$ generates $n+3$ control primitives that form a ***String-Cluster*** matrix, by causing all clusters C_i (i< j) to be in the state "11", and all cluster C_i (i > j) to be in the state "00", while based on the value of (S) it assigns the states "01", "10" or"11" to C_j. Consider the base case, where all C_j, ($j \in Z_M$) are in state "00".

Proof:

We define *Group* (G_i), ($i \in \mu = \{1, \ldots, {}^{M}/_{K-1}\}$, Where M is the number of clusters and k is the number of independent snap-down voltages) to be the set of all clusters C_j, ($j \in Z_M$) with equal $V_{ul,j}$ and $V_{uh,j}$.

$$G_i = \left\{ \begin{matrix} Cluster \\ \in NGM \end{matrix} \middle| \begin{matrix} \forall Cluster_k, Cluster_m \in G_i, \\ (V_{ul,j} = V_{ul,k};\ V_{uh,j} = V_{ul,k});\ m,k \in Z_M \end{matrix} \right\} \quad (7)$$

We make the inductive argument:

Base condition: Base case keeps all cluster C_j, ($j \in Z_M$) in state"00".

Inductive step: after applying of the first two control pulses $(Vmax,\ Vul,j^{-})$, all *Groups* (G_1, …, G_{j-1}) are in state "11" and all cluster G_i, (i > j-1) are in state "00". We will show that by applying the sequence of four primitive control voltages shown in Eq. (9), the system will be in one of the three states of ***String-Cluster*** system, where *Cluster* (C_j) will be in state "01", "10"or "11" based on the value of (S) while all *clusters* (C_1, …, C_{j-1}) are in state "11" and all cluster C_i, (i

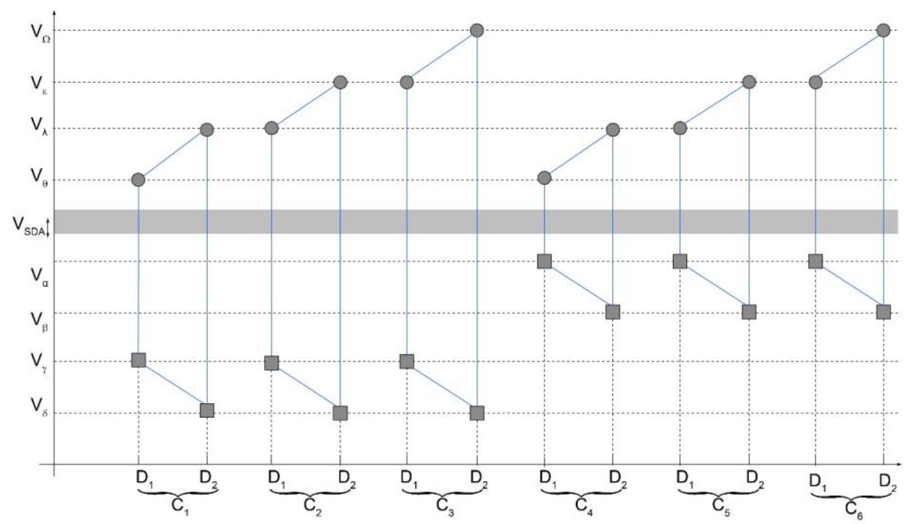

Fig. 8. Example of an *ESATC* system with $k = 4$ and $l = 4$.

$> j$) are in state "00". The $V_{ul,i}$, $V_{uh,i}$ and $V_{dl,i}$, $V_{dh,i}$, $i \in Z_M$ sorting implies that, for a cluster C_k , $k > j$, only six cases are possible with respect to its transition voltages:

(a) $V_{dl,j} < V_{dh,j} < V_{dl,k} < V_{dh,k}$ and $V_{ul,j} = V_{ul,k} < V_{uh,j} = V_{dh,k}$ (e.g., $j = 1$ and $k = 3$ in Fig. 8)

(b) $V_{dl,j} < V_{dh,j} < V_{dl,k} < V_{dh,k}$ and $V_{ul,j} < V_{uh,j} < V_{ul,k} < V_{uh,k}$ (e.g., $j = 1$ and $k = 6$ in Fig. 8)

(c) $V_{dl,j} < V_{dh,j} = V_{dl,k} < V_{dh,k}$ and $V_{ul,j} = V_{ul,k} < V_{uh,j} = V_{uh,k}$ (e.g., $j = 2$ and $k = 3$ in Fig. 8)

$$C_j\text{-Hysteresis-States} = \begin{cases} '00' & when\ S = \\ '01' & when\ S = \\ '10' & when\ S = 2 \\ '11' & when\ S = 3 \end{cases} \quad (8)$$

(d) $V_{dl,j} < V_{dh,j} = V_{dl,k} < V_{dh,k}$ and $V_{ul,j} < V_{uh,j} < V_{ul,k} < V_{uh,k}$ (e.g., $j = 2$ and $k = 6$ in Fig. 8)

(e) $V_{dl,k} < V_{dh,k} \leq V_{dl,j} < V_{dh,j}$ and $V_{ul,j} < V_{uh,j} < V_{ul,k} < V_{uh,k}$ (e.g., $j = 2$ and $k = 4$ in Fig. 8)

(f) $V_{dl,j} = V_{dl,k} = < V_{dh,j} = V_{dh,k}$ and $V_{ul,j} < V_{uh,j} < V_{ul,k} < V_{uh,k}$ (e.g., $j = 1$ and $k = 4$ in Fig. 8).

$$P_j(S) = \begin{cases} \left(Vmax,\ Vul,j^-,\ Vdl,j,\ Vul,j^+,\ Vdl,\ j^-,\ Vuh,\ j^+\right) \\ \quad if\ j \in Z_M,\ S = 0 \\ (Vmax,\ Vul,j^-,\ Vdh,j,\ Vul,j^+,\ Vdl,j^-,\ Vuh,j^+) \\ \quad if\ j \in Z_M,\ S = 1 \\ (Vmax,\ Vul,j^-,\ Vdl,j,\ Vuh,j^+,\ Vuh,j^+,\ Vuh,j^+) \\ \quad if\ j \in Z_M,\ S = 2 \\ (Vmax,\ Vul,j^-,\ Vdh,j,\ Vul,j^+,\ Vdl,j^+,\ Vuh,j^+) \\ \quad if\ j \in Z_M,\ S = 3 \end{cases} \quad (9)$$

set C_j to state "01" and C_k ="00" and will release D_1 of all clusters $C_i = (i \leq j)$ with $Vuh,i = Vuh,j$. Finally, Vdl,j^+ and Vuh,j^+ will set C_j to state "11" again while keeping C_k in state $if\ S = 0$ then
$P_j(S) =$
$(Vmax,\ Vul,j^-,\ Vdl,j,\ Vul,j^+,\ Vdl,\ j^-,\ Vuh,\ j^+)$:

Case (a), (b): Vdl,j sets *cluster* C_j to state "10", while C_k, $k > j$ is in state "00". Vul,j^+ will set C_j to state "00" and will release D_1 of all *clusters* C_i $(i \leq j)$ with $Vuh,i = Vuh,j$. By applying the remaining control primitives Vdl,j^-, Vuh,j^+, all D_1 of all clusters Ci $(i \leq j)$ with $Vuh,i = Vuh,j$ will snapped down while keeping the state of C_j in "00".

$if\ S = 1$ then
$Pj\ (S) =$
$(Vmax,\ Vul,j^-, Vdh,j, Vul,j^+, Vdl,j^-, Vuh,j^+)$:

It is clear that in case (a) and (b): Vdh,j sets *cluster* C_j to state "11", while $C_k sd$, $k > j$ is in state "00". Consequently, Vul,j^+ will set C_j to state "01" and will release D_1 of all *clusters* C_i *(i ≤ j)* with $Vuh,i = Vuh,j$. By applying the remaining control primitives Vdl,j^-, Vuh,j^+, all D_1 of all *clusters* C_i *(i ≤ j)* with $Vuh,i = Vuh,j$ will snapped down while keeping the state of C_j in "01". Case (c), (d): Vdh,j sets *cluster* C_j to state "11" and C_k, $k > j$ to "10". Consequently, Vul,j^+

Table 1: Comparison of the control voltage bandwith requirements, ξn , the number of control pulses of *n*-robot NHG, Reconfigurability and Multi-shape-Assembly of STRING, SESat systems, String-Cluster and SESATC.

	NHG	STRING	SESat	String-Cluster	SESATC
ξn	*2n*	*n+1*	$\lceil 2\sqrt{n} \rceil$	*n+2*	$\lceil 1+ 2\sqrt{n} \rceil$.
No. control pulses	*1*	*2*	*O(n)*	*2*	*6*
Number of robots with ξn=20	*10*	*19*	*100*	*18*	*90*
Reconfigurable	*YES*	*NO*	*NO*	*YES*	*YES*
Multi-shapes-Assembly	*YES*	*NO*	*NO*	*YES*	*YES*

will set C_j to state "01" and C_k ="00" and will release D_1 of all clusters C_i *(i ≤ j)* with $Vuh,i = Vuh,j$. By applying the remaining control primitives Vdl,j^-, Vuh,j^+, all D_1 of all clusters *Ci (i ≤ j)* with $Vuh,i = Vuh,j$ will snapped down while keeping the state of C_j in "01". Case (e), (f): Vdh,j sets *clusters* C_j and C_k , $k > j$ to state "11". Consequently, Vul,j^+ will set C_j to state "01" and C_k ="00" and will release D_1 of all clusters C_i *(i ≤ j)* with $Vuh,i = Vuh,j$. By applying the remaining control primitives Vdl,j^-, Vuh,j^+, all D_1 of all clusters C_i *(i ≤ j)* $Vuh,i = Vuh,j$ will snapped down while keeping the state of C_j in "01".

$if\ S = 2$ then
$Pj\ (S) = (Vmax, Vul,j^-, Vdl,j, Vuh,j^+, Vuh,j^+, Vuh,j^+)$:

Case (a), (b): Vdl,j sets *cluster* C_j to state "10", while C_k, $k > j$ is in state "00". Consequently, Vuh,j^+ will keep C_j in state "01". Case (c), (d): Vdl,j sets *cluster* C_j to state "10", while C_k, $k > j$ is in state "00". Consequently, Vuh,j^+ will keep C_j in state "01". Case (e), (f): Vdl,j sets *cluster* C_j to state "10", while C_k, $k > j$ is in state "11". Consequently, Vuh,j^+ will keep C_j in state "01" and release *cluster* C_k.
$if\ S = 3$ then

$Pj\ (S) = (Vmax\ ,\ Vul,j^-,\ Vdh,j, Vul,j^+, Vdl,j^+, Vuh,j^+)$:

Case (a), (b): Vdh,j sets *cluster* C_j to state "11", while C_k, $k > j$ is in state "00". Consequently, Vul,j^+ will set C_j to state "01" and will release D_1 of all clusters Ci = *(i ≤ j)* with $Vuh,i = Vuh,j$. Finally, by applying Vdl,j^+, Vuh,j^+, C_j will be in state "11" and all clusters C_i = *(i ≤ j)* will be snapped down.

Case (c), (d): Vdh,j sets *cluster* C_j to state "11" and C_k, $k > j$ to "10". Consequently, Vul,j^+ will "00".
Case (e), (f): Vdh,j sets *cluster* C_j to state "11" and C_k, $k > j$ to "11". By applying $Vul,j^+, Vdl,j^+, Vuh,j^+$ C_j will be in "11" while C_k is released.

Theorem : An algorithm that can plan the motion (i.e., finds the control sequence) for a String-Cluster system can be applied to plan the motion for any (ESATC) system of stress-engineered microrobots.

Proof: A consequence of Lemma 2; a ***string-cluster*** control matrix can be constructed for any *M-**(ESATC)*** microrobotic system.

Theorem 1 allows us to further reduce the control bandwidth requirements ξ_n. The control voltage bandwidth requirement for a microrobot system with K independent snap-down voltage levels and L *independent* release voltage levels is $\xi_n = K + L$. In an ***Electromechanically SATurated Cluster system (ESATC),*** the number of non-degenerate microrobots, is $n = (K-1)(L)$ or $n = (K)(L-1)$. It follows that n is maximized when $L = K = \xi_n/2$, and $n = \lceil 1 + \sqrt{1+4n} \rceil \approx \lceil 1+ \sqrt{4n} \rceil = \lceil 1+ 2\sqrt{n} \rceil$. We call such a system *symmetric* ***Electromechanically SATurated Cluster system (SESATC)***. Table. 1 compares the control voltage bandwidth requirements, the number of control pulses in the control cycle, Reconfigurability and Multi-shapes-Assembly of the five classes of microrobotic systems: a) *NHG*, b) *STRING*, c) *SESat*, d) *String-Cluster* and e) *SESATC*.

V. Conclusion

In this paper, we presented a comprehensive analysis of the scalability of different methods for differentiating the behavior of MicroStressBots using electrostatic hysteresis. We have shown that by the two new control strategies not only we can have a highly underactuated system but also we will have robust controllable system which could complete any microassembly process started from any configuration. These control methods are sufficient to implement a reconfigurable system. These results lay the theoretical foundation for developing new methods to control of large number of MEMS microrobots.

References

[1] P. Dario, R. Valeggi, M.C. Carozza, M.C. Montesi and M. Cocco,"Microactuators for microrobots:a critical survey,"*Journal of* Micromechanics and Microengineering 2,pp. 141-157,1992

[2] J.M. Kahn,R.H. Katz and K.S.J. Pister, "Mobile networking for small dust,"ACM/IEEE international conference on mobile computing and *networking(MobiCom'99)*,Seattle, USA, pp. 17-19,August 15-19,1999.

[3] D. Popa and H.E. Stephanou,"Micro and meso scale robotic assembly,"SME Journal of Manufacturing Process, vol. 6, issue 1,pp. 52-71,2004.

[4] B.R. Donald,C.G. Levey,C. McGray,I. Paprotny and D. Rus, "An untethered,electrostatic,globally-controllable MEMS microrobot," Journal of Microelectromechanical Systems,vol. 15,issue 1,pp.1-26,2006.

[5] I. Paprotny, C. Levey, P. Wright, and B. Donald, "Turning-rate selective control: A new method for independent control of stress-engineered MEMS microrobots," in Robotics: Science and Systems VIII, 2012.

[6] B. R. Donald, C. Levey, I. Paprotny, and D. Rus, "Planning and control for microassembly using stress-engineered," International Journal of Robotics Research, vol. 32, pp. 218–246, January 2013.

[7] B.R. Donald,C.G. Levey,C. McGray,D. Rus and M. Sinclair, "Power delivery and locomotion of untethered microactuators," *Journal of Microelectromechanical Systems*,vol. 10 issue 6,pp. 947-959, 2003.

[8] A. T. Becker, Ensemble Control of Robotic Systems. PhD thesis, University of Illinois at Urbana-Champaign, 2012

[9] A. Becker, C. Onyuksel, and T. Bretl, "Feedback control of many differential-drive robots with uniform control inputs," in Proceedings of IEEE International Conference on Intelligent Robots and Systems (IROS), 2012.

[10] D. Koester, A. Cowen, R. Mahadevan, M. Stonefield, and B. Hardy, PolyMUMPs Design Handbook, A MUMPs Process, 10th ed. Grenoble, France: MEMSCAP, 2003.

[11] R. Majumdar, V. Foroutan, and I. Paprotny, "Post-release stress-engineering of surface-micromachined MEMS structures using evaporated Chromium and in-situ fabricated reconfigurable shadow masks." *Micro Electro Mechanical Systems (MEMS), 2015 28th IEEE International Conference on*. IEEE, 2015.

[12] T. Akiyama and K. Shono, "Controlled stepwise motion in polysilicon microstructures". *Journal of Microelectromechanical Systems* 2(3): 106–110, 1993

[13] R.J. Linderman and V.M. Bright, "Optimized scratch drive actuator for tethered nanometer positioning of chip-sized components." In: *Solid-state sensors, actuators and microsystems workshop*, pp. 214–217. June 1–5, 2008, Hilton Head Island, SC, San Deigo: TRF.

[14] H. C. Nathanson, W. E. Newell, R. A. Wickestrom, J. R. Davis, " The resonant gate transistor," *IEEE Transactions on Electron Devices* vol. 14, issue 3, pp. 117–133, 1967.

[15] B. R. Donald, C. G. Levey, and I. Paprotny, "Planar microassembly by parallel actuation of MEMS microrobots," Journal of Microelectromechanical Systems, vol. 17, pp. 789–808, August 2008.