NON-CONTACT BATCH MICRO-ASSEMBLY BY CENTRIFUGAL FORCE

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ABSTRACT

Due to the minute scale of MEMS, inertia forces are often neglected. However, we have proven that these forces can be significant even if a microstructure's mass is <1µg (a 250µmx100µm mass with MUMPs poly1, poly2, and Au layers). We have demonstrated that at this scale, mass inertia force can overcome surface forces and be used for non-contact self-assembly of MEMS structures. Centrifugal force was applied to hinged MUMPs#31 structures, causing these structures to self-assemble by rotating themselves 90° out of substrate plane and automatically locked themselves to designed latches. This batch-assembly technique is very fast, low-cost, non-contact, and non-destructive. Moreover, we have successfully characterized the centrifugal forces needed to assemble these microstructures by integrating sensors on the same MUMPs chips to provide wireless signal that relate to the dynamic behavior of the microstructures. This is a very important result in terms of making feasible quantitative analyses of surface forces acting on surface micromachined MEMS devices.

I. INTRODUCTION

New designs in surface-micromachining that requires micro-assembly to form 3D devices have now focus on the ease of assembly. An example of a simple technique was reported as a single-step assembly system in [1], where movement of a single plate or structure assembles the entire structure constrained by hinges. Automatic latches have also been used to engage and lock these structures into position. Numerous techniques to move this plate or assemble other hinged structures are available and have been summarized in [2]. These methods include using on-substrate actuators, manual probing, or tensile films to assemble. Other techniques include magnetic actuation and triboelectricity. These methods all have inherent disadvantages such as yield, cost, and difficulty in implementation. We propose a fast, reliable, and low-cost batch assembly technique using centrifugal force to lift MEMS structures.

It is generally accepted that, for MEMS devices, surface forces are dominate over volume forces since, by isometric scaling argument, surface area reduction is proportional to only 2/3 power of the reduction in volume. Consequently, it is often assumed that inertia force is negligible in the presence of other forces such as friction or surface forces. However, our research proved that mass does matter to a certain scale in MEMS. Our work demonstrated that for many MEMS structures, their inertia force could overcome friction and surface forces. From this, we present a novel non-contact method of batch auto-assembly of surface-micromachined devices that has many advantages over conventional micro-assembling methods.

II. MICRO-ASSEMBLY BY CENTRIFUGAL FORCE

Theoretically, gravitational force can become significant compared to other micro-scale related forces if the sizes of objects fall within a certain dimensional range. By replacing the gravitational force with centrifugal force, the surface forces, e.g., stiction, friction, electrostatic…etc., may be overcome, thus allowing microstructures to be lifted. However, some engineering considerations must be given, such as a hinge that undergo significant stress from a pulling mass may break.

As the suitable force to manipulate microstructures should be in the range of micro-Newtons to avoid damaging the microstructures under manipulation, centrifugal force is appropriate to perform the task because the force can be applied to the structures uniformly, and the force can be made in the order of micro-Newtons. As an example of application, micro-mirrors can be rotated from horizontal to a desired position (see illustration in Figure 1), where the final position of the mirror can be decided by the geometry of a pre-designed locking system. The applied centrifugal force should be large enough to overcome the surface forces, otherwise, the microstructures would not be released from the substrate. On the other hand, the upper limit for applied force should not cause the a stress greater than the allowable stress on the hinge structure.

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The centrifugal force acting on a microstructure depends on the its mass and angular velocity as,

$$F = mr\omega^2 \qquad (1)$$

where m is the mass of a structure to be assembled, r is the radius of a spinning disc which holds the substrate containing the structure, and ω is the rotational speed of the disc. Hence, the rotational speed and size of a spinning disc can be used to assemble a microstructure with a give mass. Based on MUMPs fabrication data, the thickness of the various structural layers are known, thus, along with given material density data, the mass of a MUMPs structure can be estimated. In general, the mass of poly1 and poly2 layers can be neglected if gold layer is used to build a structure, due to their significant difference in density [3]. Hence, the centrifugal force acting on a MUMPs mass can be related to the rotation speed by:

$$F = \frac{V\rho r R^2 \pi^2}{900} \qquad (2)$$

where V is the volume of the gold layer, ρ is the density of gold, r is the distance for the rotation and R is the angular velocity in rpm.

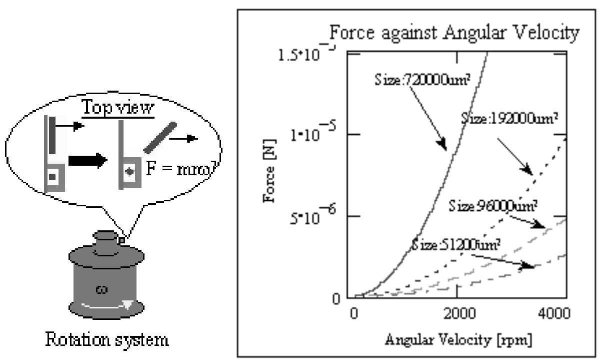


Figure 1. Conceptual drawing for centrifugal force applied on micro mirrors. Theoretically, centrifugal force can be generated on different sizes of MUMPs structures (poly1, poly2, and gold) by changing the angular velocity of a spinning disc.

III. Stress on Polysilicon Hinges

In order not to destroy the hinges used to clamp the microstructures during the centrifugal assembly process, stress on the polysilicon should be estimated. For a typical Pister Hinge (shown in Figure 2) 3 areas on the hinges are the weakest part in the whole structures.

The tensile stress acting on these 3 areas can be estimated by the following equation,

$$\sigma = \frac{F_{applied}}{A_{total}} \qquad (2)$$

where $F_{applied}$ is the minimum centrifugal force to overcome the surface force, A_{total} is the total area on the specific region. We have estimated that if we applied 1 μN centrifugal force to one hinge, the stress on it would be 3.629×10^4Pa, which does not exceed the maximum tensile strength of polysilicon, given by Sharpe et al. [4] for MUMPs polysilicon as 1.20±0.15GPa. In general, sufficient number of hinges should be used to hold the microstructures to be assembled to ensure that the structures will not *fly* off the substrate during the centrifugal assembly process.

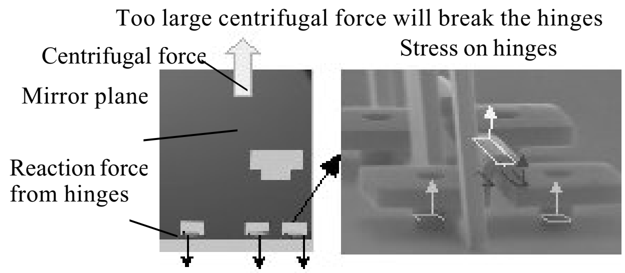


Figure 2. Stress acting on the polysilicon.

IV. Centrifugally Assembled Structures

We have assembled various MUMPs structures using centrifugal force. Some detailed experiments were performed on applying centrifugal force on micro mass (mirror) structures. A rotation system was setup to realize our non-contact batch micro-assembly process, which is able to provide steady angular velocity up to 6250rpm. In order to reduce airflow from the surrounding during high speed rotation, a cover is used to cover the chip. (MUMPs structures have been observed to break and fly off the substrate by small amount of air flow.)

Arrays of "poly_tower" (300 μmx400μm floor) structures and "Tsing-ma Bridge" (Figure 3) were self-assembled successfully.

(a) (b)

Figure 3. (a)Tri-level "poly_tower" assembled by centrifugal force. The floors are connected by polySi columns that are latched in position with polySi beams to make a ladder (designed by Scott Goodwin-Johansson of MCNC). (b)An array "Tsing-ma Bridge" (a famous bridge in Hong Kong) structures released by centrifugal force.

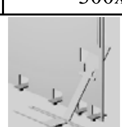
A number of MUMPs micro masses mirrors have been fabricated for centrifugal assembly tests. The masses are classified into four different groups based on their size and locker system. The different mass designs are give in Table 1.

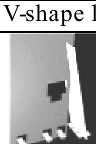
The batch micro-assembly process was tested to investigate the performance and repeatability. Two identical MUMPs chips were tested and the results are very consistent. By increasing the angular velocity, different sizes of mirrors rotated up from horizontal to vertical position. When the rotation system reaches the maximum angular velocity about 6250rpm (a limitation of our current rotation system), most 600x300μm^2 micro-mirrors have locked successfully into vertical position. Applied centrifugal forces are greater for larger mass size at the same angular velocity. So, Type I mirrors can be assembled at a smaller angular velocity than Type II and III mirrors. When the angular velocity is at 6250rpm, the centrifugal forces applied on Type I, Type II, and Type III mirrors are $2.23x10^{-5}N$, $7.45x10^{-6}N$, and $3.10x10^{-6}N$, respectively.

In Figure 4, arrays of assembled mirrors are shown after a MUMPs chip is rotated under a certain angular velocity. A plot of the number of mirrors assembled versus rotational speed is given in Figure 5. An SEM picture showing an array of assembled mass platforms is shown in Figure 6.

Table 1. Sizes of mirrors tested.

Type	Size of mass	Locker system
I	600x300um^2	Traditional latches
II	300x200um^2	Traditional latches
III	250x100um^2	Traditional latches
IV	300x200um^2	V-shape latches


Traditional Latch


V-shape Latch

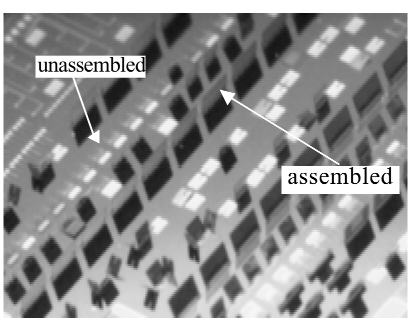


Figure 4. Different sizes of mass assembled by centrifugal force. The white structures in the picture represent the unassembled structures (reflection from gold layer), and the gray structures are the assembled structures with black shadows.

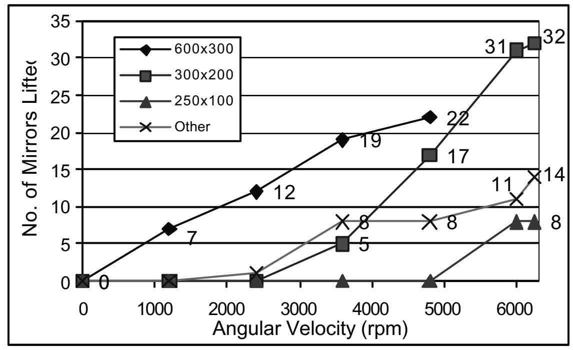


Figure 5. Number of micro mirrors assembled versus angular velocity, with mirror size as a parameter.

This self-assembly process has been verified to be very successful. None of the micro mirrors were destroyed during the assembling process because the applied centrifugal force was small and did not exceed the maximum tensile strength of polysilicon.

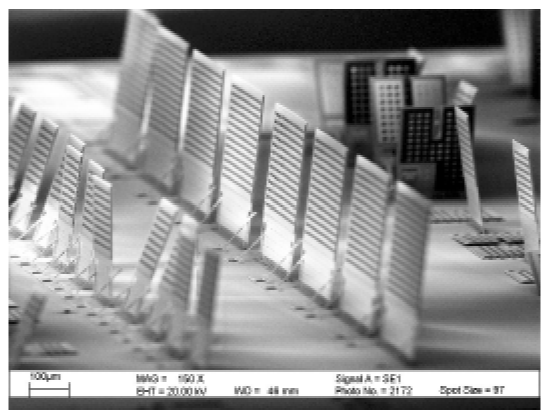


Figure 6. The batch micro-assembled mirror arrays.

V. SURFACE FORCE MEASUREMENT

To determine the limitations of the centrifugal-force-assisted assembling method, we have performed systematic experiments to ascertain the multi-force interactions of structures that consist of a simple mass platform supported by 2 cantilevers. These platform-cantilever structures were designed as piezoresistive sensors capable of wirelessly transmitting motion information under rotation up to 6250rpm (similar to our prior work reported in [5]). These MUMPs surface-micromachined non-contact high-speed rotation sensors will convert the mechanical deflection or elongation of the polysilicon cantilevers into change of electrical resistance, which can be converted into a measurable change of voltage by connecting the sensors in a Wheatstone-bridge configuration. The voltage output form the bridge is then transmitted by a wireless transceiver after voltage to frequency conversion. This allows finding of the appropriate centrifugal force needed to *free* a particular structure that is initially adhered to the substrate by surface forces. At least 2 structures of each design of different mass size were tested. Typical dynamic motion of such a structure as a function of the angular velocity of a spinning disc is shown in Figure 7. The structures consistently will be freed when sufficient centrifugal force (spin speed) is applied on the mass platform. However, when the speed is decreased, the platform will *snap down* to the substrate at a lower angular speed than the *freed-state*. This hysteresis characteristic is repeatable and may be attributed to surface-force effects. The force value measuring the freed-state rpm would be the force required to overcome the surface force for particular mass size.

The relationship between the *freed-state* and the *snap-down-state* of the platform was also analyzed for various platform geometries. In general, larger mass platforms will need lower rpm to free them. Although platforms as small as 320μm x160μm were all freed successfully, the range of required spin speed to free them is more sporadic than the large platforms (greater experimental error bars as shown in Figure 8). This may be an indication of surface forces, which depends on many factors, including humidity and temperature, becoming more dominate as a mass becomes smaller.

VI. CONCLUSION

Batch micro-assembly of MUMPs microstructures using centrifugal force was demonstrated. Various complex MUMPs structures were rotated about micro hinges autonomously by centrifugal force and vertically locked by latches. To quantify the centrifugal force and surface force interaction, a wireless force sensing system using MUMPs piezoresistive sensors was used to monitor the dynamics of micro mass platforms during the centrifugal-assembling process. Results indicate that a consistent hysteresis exists between the freed-state and snap-down-state of microstructures during assembly. This effect should be studied further to understand surface force interactions for surface micromachined structures. The non-contact, batch-assembling process reported in this paper is very low-cost and non-destructive, thus it will provide MEMS engineers a quick and convenient way to make 3-dimensional MEMS devices. Ultimately, this process can be used to batch assemble very complex micro devices not possible today using conventional manipulator-based assembling process.

VII. ACKNOWLEDGMENTS

We would like to thank Dr. Winston Sun for his help in setting up the wireless sensing data acquisition system for analyzing the micro-structural dynamics during rotation assembly.

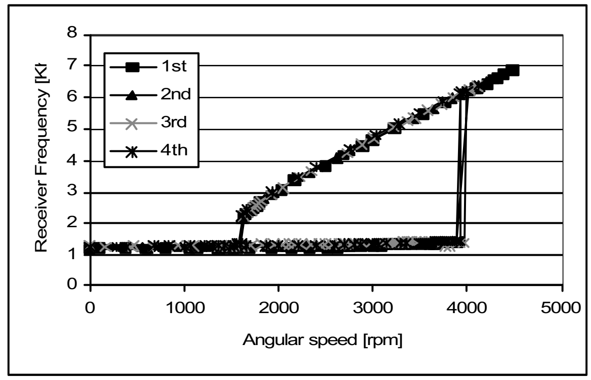


Figure 7. Typical motion of a platform suspended by two cantilevers beams under rotation (frequency is the wireless signal received and is proportional to the position of a platforms).

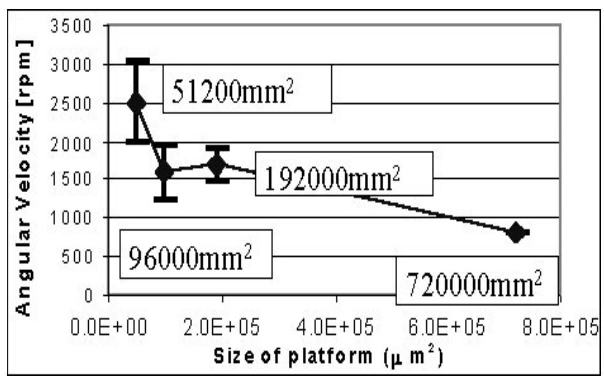


Figure 8. The "freed-state" for 4 different sizes of MUMPs mass platforms. The angular velocity at which each platform type is freed from the substrate can be related to the centrifugal force acting on the micro platforms.

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