MicroRobot Conveyance and Propulsion System Using Comb Drive and Parallel Plate Actuators: The ScuttleBot

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Abstract

A new type of one-dimensional locomotive device has been designed using the coupled actuation of two well-understood electrostatic actuators: a comb-drive resonator and a parallel-plate capacitor. The device is termed the ScuttleBot, and the design considerations leading up to it are reported. Theoretical analyses of the device performance are presented to support the parameter choices that were made. The proposed fabrication method for the ScuttleBot is discussed with particular attention to the advantages it provides. Additionally, potential applications are discussed along with considerations for future research of this means of locomotion.

Introduction

Several groups have described their efforts to generate micro-conveyor systems for positioning, manufacturing, and inspecting micro-scale objects [1-3]. Many different actuation methods have been used including: thermal (the most popular), pneumatic, magnetic, and electrostatic (See Table 1 of [3] for a summary). Some excellent techniques for coordinating actuators to produce motion on a larger scale have arisen from this work. While several of these have been successful as conveyors, none of these devices have been able to propel themselves, and reliable manufacturing remains a major challenge.

A self-propelled micro-robot has obvious appeal and several possible applications including: surveillance vehicles, transport of raw materials for micro manufacture, and tight quarters inspection. Several propulsion systems have been developed for micro-flight, swimming, and ground propulsion, but reliability and manufacturability remain a challenge. The simplest approach to the problem seemed to offer the best chance of success, so we decided to construct our device from well-understood components. We call our device a "Scuttlebot."

Our research aims to produce a functional prototype of a Scuttlebot capable of one-dimensional motion. This motion could be used either to move the Scuttlebot itself or to serve as a conveyer-line system if placed on its backside with the actuators facing up. The actuation of the Scuttlebot comes from a comb drive resonator coupled with a parallel plate capacitance actuator. Fundamentally, the concept is to use the comb drive resonator to produce large displacements and velocities in the direction of desired motion. The parallel plate capacitor will then be actuated, causing the moving paddle leg to strike the surface of the work piece (either the ground, or the object being conveyed). The paddle will then be held against the work piece by the parallel plate actuator, while the energetic suspension springs of the comb drive pull it in the desired direction of motion.

Device Concept and Fabrication

An isometric view from a solid model of a Scuttlebot leg is shown in Figure 1. At first glance, it looks like a standard comb drive resonator with a folded flexure suspension of the type described by Tang, et.all [5]. Closer inspection reveals that the suspension has been slightly modified to allow the legs to be chained electrically, and that the central shuttle has been modified from a standard plate.

This modification separates the plate into an outer frame and an inner paddle. The paddle is attached to the frame by two square torsion joints in the middle of the frame, which allow the paddle to rotate. Actuation occurs when a voltage difference is applied between the paddle and the backside plane. Since this plane only runs under half of the paddle the actuation creates a torque, causing the paddle to twist out of the plane and contact the work piece.

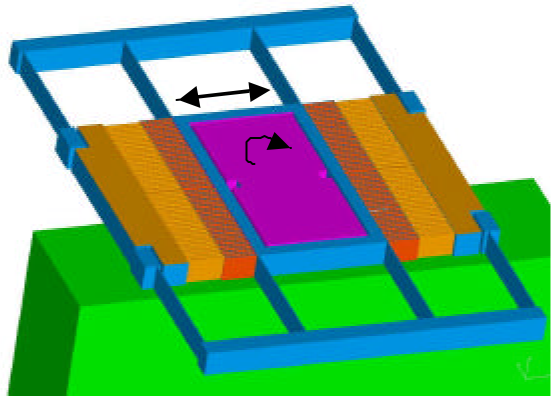

Figure 1: Isometric View of ScuttleBot Leg Solid Model

One of the strengths of the comb drive actuator is its ability to resonate, which allows relatively high displacements for correspondingly small inputs (when the input signal is the proper frequency). This large displacement will be used to generate the forward motion required for the Scuttlebot to take a single step.

Similarly, the advantage of the parallel plate capacitor actuator is that it is able to generate relatively large forces as its gap gets very small. Typically, this is a problem as the actuator "pulls in," which causes an electrical connection, potentially destroying the function of the actuator by welding the two plates together. In our case, however, the work piece (or ground), will act as a stop, preventing the actuator from pulling in. Therefore, large forces can be generated without ruining the actuator, while work piece contact is maintained.

Our device will be fabricated using the advanced SOI-MEMS process developed at the UC Berkeley Microlab by Veljko Milanovic and Matt Last. Details are available at www-bsac.EECS.Berkeley.EDU/~pister/245/2000F/handouts/process3mask.PDF.

This process offers us several advantages. The first is that it allows us to use high aspect ratio structures, resulting in a comb finger thickness twenty times that used in the original Tang paper. Second, all of our structures will be made from single crystal silicon, which has superior material properties relative to the poly-silicon commonly used in surface micro-machining processes. Third, it is a two-mask process, which allows us to create a relatively thin (~5µm) layer that makes our torsion joint compliant. Finally, the backside etch step allows for the creation of the second half of the parallel plate actuator on the underside of the chip.

There are two possible input schemes to cause the chip to scuttle. The first is to have symmetric parallel plate actuators on the backside of each leg. Both could be activated to pull the whole leg structure down slightly (so it would not be in contact with the work piece). The comb drive would then be resonated, and at the proper moment, one of the parallel plate actuators would be turned off. This would cause the paddle to flip and contact the work piece.

The more realistic input is to use every other leg for motion, and the remaining legs to support the chip. To do this, every other parallel plate actuator in the array of legs would be activated, lifting the whole chip slightly off of the work piece. The remaining legs would no longer contact the work piece, and be free to resonate. Once they were resonating at the proper displacement, the parallel plate actuators would reverse, causing the support legs to retract, and the motion legs to extend. The legs in motion would each take a single step, and the process would repeat.

Test Structures

Several test structures have been included in the layout for this chip. These are important as they identify the differences between the ideal design, and the reality of fabrication. They also allow sub-components of a device to be tested individually. If variances are detected, these structures will yield more accurate values, which will be used for our system model. The proper inputs can then be calculated, and our analyses will be more accurate.

Our first test structure is simply an array of beams 50 microns long and varying in width from one to four microns in tenth-micron increments. This structure tests whether the minimum line width is actually two microns, as specified for this process. This test is important as all of our comb fingers and cantilever springs are designed to the minimum two-micron width. Variations in spring width will affect the stiffness of our suspension as a power of three. This will have to be accounted for in the input voltage.

Our second test structure tests for the opposite property of the first, i.e. the space limit of the masks used. An array of beam pairs 40 microns long with 30 microns of overlap are laid out with the gap between varying from 0.5 to 3.4 microns in tenth-micron increments. If the space limit is reached, electrical contact will be established betweend the anchors at the ends of the beams. This test verifies that the minimum space is the process specified two microns. Our comb finger gaps are designed to the process minimum, and variations will affect the forces our comb drive is able to generate.

Similar line and space test structures have been incorporated for the backside etch step, which has a nominal limit of 15 microns for both. The line structure has 50-micron beams laid out from 10 to 20 microns thick. The space structure has 50-micron gaps laid out from 10 to 20 microns wide.

One of the more variable parameters of the advanced SOI-MEMS process is the thickness of the low single crystal silicon layer. We have nominally designed our paddle torsion spring for a 5µm thickness, but as it is formed by a timed etch, it may vary from 5µm to 10µm. This variation will greatly affect the stiffness of our torsion spring, and so we must determine the actual thickness. To do this, we have designed the test structure shown in Figure 2. The spring is designed so this variation will not cause it to fail, but the input voltages will have to be adjusted to accommodate the increased stiffness.

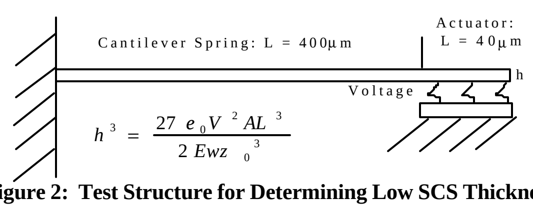

Figure 2: Test Structure for Determining Low SCS Thickness

Figure 3 shows the relationship between pull-in voltage of this test structure and the thickness of the Low SCS layer. Since the beam is ten times longer than the actuator, it was assumed that the actuator applies a pure force (i.e. no moment) to the beam. Comparing the increasing force applied by the actuator with the stiffness of the cantilever spring generated the equation for this figure.

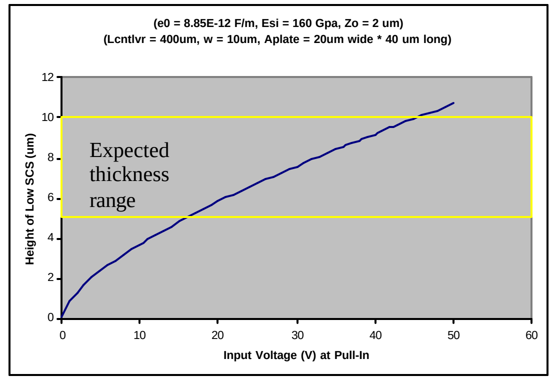

Figure 3: Test Structure Pull in Voltage vs. Low SCS Thickness

Additionally, decoupled sub-components of the leg with varying design parameters have been included in order to examine a larger portion of the available design space. Specifically included are torsion paddles de-coupled from the comb drive frame, and comb drives with the paddles permanently fixed to the frame (it is necessary to include the fixed paddle to maintain the proper area and mass of the comb drive). The paddle length, width, and torsion spring length and location have been varied on the isolated paddles, and the folded flexure length has been varied on the isolated resonators, so that we can study resulting changes in performance.

Theoretical Performance and Design Parameter Selection

The first sub-component that was designed was the torsion paddle. This is important because the required size of the paddle determines the size of the comb drive shuttle. To design this, we first derived an equation for a parallel plate actuator in pure torsion. For this derivation, we ignored all fringe-field effects. The derivation began with the equation for the derivative of capacitance.

$$\partial C = \frac{e_0 \partial A}{z} = \frac{e_0 \partial A}{g - xq}$$

Integrating from zero to L (the length of the arm) yields:

$$C = -\frac{e_0 w}{q} \ln\left(\frac{g - Lq}{g}\right)$$

Knowing that energy, U = (C*V^2)/2, leads to the moment generated by the actuator.

$$M = \frac{\partial U}{\partial q} = -\frac{e_0 w V^2}{2}\left(\frac{-\ln\left(\frac{g - Lq}{g}\right)}{q^2} - \frac{L}{q(g - Lq)}\right)$$

This moment was then compared with the equations for a square beam under a twisting load, borrowed from Hibbeler's "Mechanics of Materials" [6].

$$t_{max} = \frac{4.81\ M}{a^3}, q = \frac{7.10\ ML}{a^4 G}$$

Design parameters were selected based on these equations, and the results are plotted in Figure 4. .

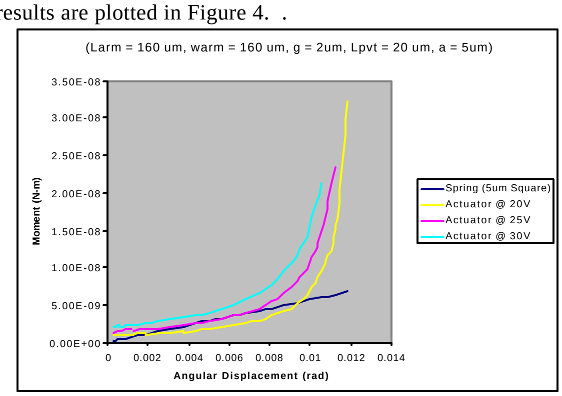

Figure 4: Torsion Paddle Performance (Moment vs. Angle)

Once the torsion paddle design was completed, some of the basic parameters were set for the design of the comb drive resonator. As the paddle needed to be about 400µm x 200µm, the size of the shuttle was set, which in turn set the number of comb fingers since we wished to use minimum line and space for them. The major remaining design parameter was the length of the suspension springs. Several papers were referenced for this design [5, 7-9], and the relevant equations can be found in this literature. Figure 5 is a graph of the comb drive displacement as a function of the folded flexure suspension length

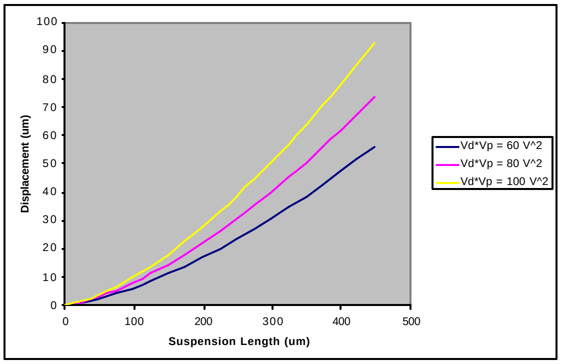

Figure 5: Comb Drive Displacement vs. Suspension Length

While a long suspension yields a large displacement, it also reduces the quality factor of the resonator, reduces the suspension stiffness in non-desirable directions, and takes up a lot of space on the chip. To balance these effects, a suspension length of 200µm was selected.

Figure 6 is a plot of the comb drive displacement at resonance as function of the DC offset voltage times the driving input voltage. It is important to note that the advanced SOI-MEMS process assists in generating large displacements for a given input. It does this by yielding structures that are 40 µm thick (compared with a 2 µm thickness of the original comb drives) that provide much larger forces, and a large mass to area ratio, resulting in a large quality factor. Note that all theoretically calculated quality factors in this paper have been divided by two to give a closer approximation to the real system. Resonance for this comb drive was calculated to occur at 6.7 kHz using Rayleigh's method as described in [5].

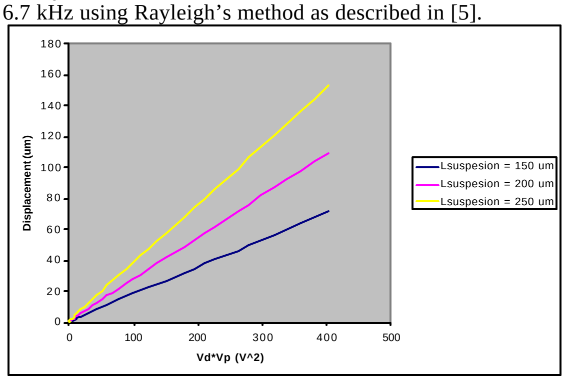

Figure 6: Comb Drive Displacement vs. Input Voltage Squared

If the Scuttlebot is to propel itself, it must be able to lift its own weight. To accomplish this, the applied voltage must exceed the pull-in voltage for each leg, as it must now overcome the force of the spring, and a portion of the weight of the chip. Figure 7 is a graph of the number of legs that will be required to lift a 1cm^2 x 342 µm chip at 30 Volts as a function of the angular displacement the leg must travel through to contact the ground. The maximum number of legs required is about 110, and this value occurs at an angular displacement of about .004 radians. Of course, the actual chip must have at least twice this number of legs to be able to walk. (i.e. at least half of the legs must be in contact with the ground to take advantage of the locomotion method described above in "Design Concept.") Therefore, an actual scuttling chip of 1cm^2 x 342 µm must have at least 220 legs when driven at 30 Volts, not including any additional wiring or external connections that will be required. To accommodate this many legs on a single chip, the design will have to be refined so that either they take less space, or the torsion paddle is capable of generating a larger force. Of course, using a higher input voltage is also a solution.

Once the paddles generate enough force to lift itself or the work piece, pull-in once again becomes a problem. To prevent against this, either a mechanical stop will have to be designed into the Scuttlebot, or a feedback system between the weight of the work piece and the input voltage must be implemented.

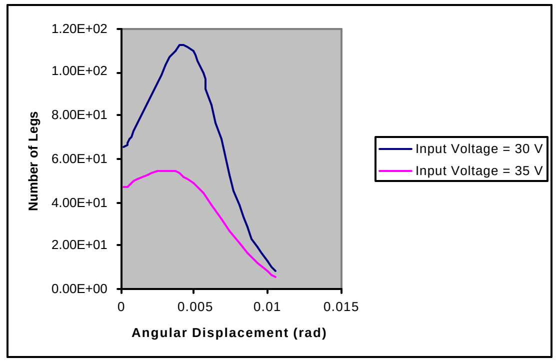

Figure 7: Number of Legs to Lift a 1 cm^2 Scuttlebot

To verify that none of the legs would break, stresses were calculated for each of the springs. The folded flexure suspension springs were examined for the bending load they would incur, and they were found to have a safety factor of 7 against failure. Similarly, the torsion spring was examined for a twisting shear failure for which a safety factor of 12 was found. Other possible failure modes, such as bending and shear, had even higher factors of safety, due to the extremely high yield strength of single crystal silicon (7 GPa).

Discussion and Future Work

One of the anticipated difficulties in making the Scuttlebot function properly is determining the proper input signals. Specifically, coordinating all of the legs so that they step at the same time could prove troublesome. We have laid out two chains of legs on our chip for testing the required inputs to a single chain of legs. These are designed so that all of the comb drive shuttles are electrically connected, as are the comb fingers. Further, we have alternated the electrical connectivity of the backside of the chip so that when one signal is sent, every other torsion paddle is actuated. This design will greatly facilitate the required wiring of the chip, but will cause an RC delay of the input signal across the leg array. As electrical delays such as this typically are much shorter than the response time of the mechanical system, we anticipate that it will not significantly affect the performance of our system. However, we must be aware that this delay could cause our legs to move out of phase for a long leg array.

This layout should require only four separate input signals to power it. First a DC offset voltage will be applied to the shuttles of the comb drive array. This can easily be applied at the end of the array, where a large bonding pad will be located. Next, the driving signal (at the comb drive resonant frequency of about 6.7 kHz) will be applied to the fingers of the comb drive array to drive the shuttles. One of the backside ground planes must have an applied voltage that precisely matches that of the comb drive shuttle DC offset, to prevent premature actuation of the paddle drive. The other backside plane will have an applied voltage to actuate the legs that will support the chip. At the proper moment, the signals will switch, initiating one step of the chip. Since every other leg will be in contact with the ground, the comb drive actuation these legs receive will be very small (as they will not be able to operate at resonance).

Of course, determining the precise moment of when to initiate the step is a difficult task itself. We have included two sets of comb fingers on each drive so that one set may be used to measure the displacement of the shuttle. We believe that the best time to initiate the step is when the shuttle is at its maximum displacement, because at this point the folded flexure suspension has stored the most potential energy. However, there are some significant unknowns that must be addressed before a prototype can function. First, it must be determined how far the actuators must travel before they engage the ground. To ensure that all legs contact at the same time, a highly polished surface will have to be used. Second, the mechanical dynamics of the system must be examined, as there will be a lag time between the times when the paddle is actuated, and when it actually touches the ground.

Even though only four input signals will be required for this Scuttlebot, wiring will still be challenging. This is because two of the signals must be applied to the top of the chip, and two to the back. We have designed cut-outs into the top of the chip so that the backside will be accessible for wiring from the top, but this approach will only work for conveyance mode, and not for chip self-propulsion. A separate wiring scheme will have to be conceived to allow the wires to be attached from the backside. Specifically, pass-throughs will have to be etched into the backside so that electrical contact may be established with the top plane from the back.

At a comb shuttle displacement of 60μm the folded flexure suspension will generate a force of 768 μN that can be applied to the work piece. However, the friction between the paddle and the work piece (or ground) will not be able to support that much force. If we assume the work piece is to be made of a Si or SiO_2 wafer, the coefficient of static friction is .38 [10]. If we exceed the static friction coefficient, the force transfer between the two pieces will drop significantly. Figure 8 shows a graph of the friction between the leg and the work piece as a function of the input voltage into the paddle, as well as the angular position of the paddle. The friction is assisted by the weight of the chip, and this analysis is performed for a 1 cm^2 chip with 110 legs supporting it. As Figure 8 shows, the friction of the leg will only be able to provide 10 – 20 μN of force. However, the force generated by the large displacement of the comb drive will not be entirely lost as this displacement will allow the spring to do a great deal of work on the system as it returns to its unloaded state. Better force transfer (and less slipping) would be attained it the torsion paddle could generate a larger force normal to the surface of the work piece.

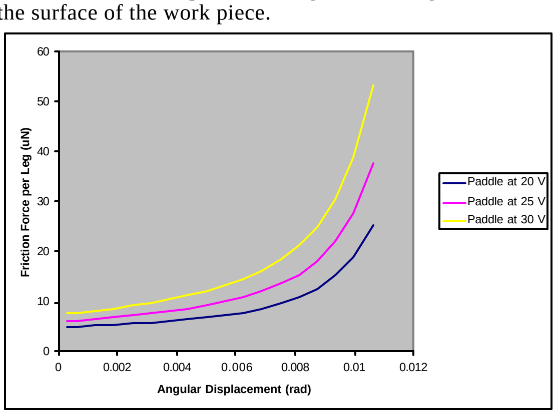

Figure 8: Friction Force Generated by Each Leg

Other future work includes the possibility of including Scuttlebot legs that are oriented to provide for two-dimensional motion.

Conclusions

Comb drive resonators and parallel plate actuators have been combined with a torsion joint to create a leg design which provides conveyance or propulsion.

The advanced SOI-MEMS process offers many advantages to MEMS device design. Specifically, it can provide very thick structures with high aspect ratios and thin, compliant structures useful for torsion actuators.

Test structures have been designed on the chip to provide information about the manufacturing process. This will allow the system models to be updated with more correct information to help in design of inputs, and system analysis.

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