THERMO-BIMORPH MICROCILIA ARRAYS FOR SMALL SPACECRAFT DOCKING

Joel Reiter, Mason Terry, Karl F. Böhringer
Center for Applied Microtechnology
Department of Electrical Engineering
University of Washington, Seattle, WA

John W. Suh
Systems & Practices Laboratory
Xerox Palo Alto Research Center
Palo Alto, CA

Gregory T. A. Kovacs
Center for Integrated Systems
Department of Electrical Engineering
Stanford University, Stanford, CA

ABSTRACT

Microelectromechanical system (MEMS) technology promises to improve performance of future spacecraft components while reducing mass, cost, and manufacture time. Arrays of microcilia actuators offer a lightweight alternative to conventional docking systems for miniature satellites. Instead of mechanical guiding structures, such a system uses a surface tiled with MEMS actuators to guide the satellite to its docking site.

This paper describes an experimental setup for precision docking of a "picosatellite" with the help of MEMS cilia arrays. Microgravity is simulated with an aluminum puck on an airtable. A series of experiments is performed to characterize the cilia, with the goal to understand the influence of normal force, picosat mass, docking velocity, cilia frequency, interface material, and actuation strategy ("gait") on the performance of the MEMS docking system.

We demonstrate a 4 cm^2 cilia array capable of docking a 45 gram picosat with a 2 mm^2 contact area at micrometer precision. It is concluded that current MEMS cilia arrays are useful to position and align miniature satellites with up to several kg of mass.

INTRODUCTION

A number of MEMS cilia systems have been developed with the common goal of moving and positioning small objects, so far always under the force of gravity [1-3]. Similar to biological cilia, all of these systems rely on many actuators working in concert to accomplish a common goal. Recent techniques range from single crystal silicon arrays [4,5] actuated using electrostatic force to arrays constructed with polyimide [6,7], and relying on the wide range of coefficients of thermal expansion (CTE) inherent in these materials.

The goal of this project is to investigate the feasibility of a MEMS-based space docking system. For such a system, the docking approach is divided into two phases: (1) free flight and rendezvous, with the goal to achieve physical contact between the two satellites, and (2) precision docking with the goal to reach accurate alignment between the satellites (e.g., to align electrical or optical interconnects). Phase 1 constitutes unconstrained motion with 6 degrees of freedom and lower accuracy; phase 2 constitutes planar motion with 3 degrees of freedom and high accuracy. This paper focuses on phase 2 and investigates MEMS cilia as a means to achieve precise alignment between two satellites.

During this project thermally actuated polyimide based microcilia, as seen in Figure 1 and identical to those published in [6], are extensively characterized to ascertain their practicality for docking miniature spacecraft. To this end, experiments were performed using an airtable, seen in Figure 2, which was designed to support the microcilia in a vertical configuration. The airtable can be tilted towards the microcilia producing a known normal force against the faces of the chips. This force can then be adjusted independently from the mass of the picosatellite puck. To increase the realism of the experiment and to ease data collection, position sensing and position feedback are incorporated and computer controlled. Two position sensing systems are used: an array of Hall effect sensors and a video capture based system. These are strictly non-contact techniques compatible with a space environment.

The purpose of this paper is to describe the experiments that were performed with the microcilia and to evaluate the appropriateness of microcilia to spacecraft docking applications. Through the course of this study microcilia are able to provide the speed, robustness, reliability and strength for use in miniature spacecraft applications. The microcilia successfully moved blocks of aluminum in excess of 40g of mass and calculations indicate that a patch 25cm in radius is sufficient to position a 40kg satellite.

MICROSATELLITE DOCKING

Figure 3 describes a large, broad purpose satellite, surrounded by a constellation of smaller, mission specific satellites. The miniature satellites provide inspection, maintenance, assembly and communication services for their larger brethren. One important future task for the microsatellites is inspecting the larger satellite for damage. Cameras mounted on the microsatellite provide imagery of the primary platform that is otherwise unobtainable. From these pictures, damage could be assessed and the mission of the main satellite adapted. Due to their simplicity, small size, weight and limited interaction with ground controllers these specialized satellites are expected to be indispensable during future missions [8].

As the size of a satellite shrinks their ability to carry fuel and power is reduced. It is expected that this will force microsatellites to dock frequently to replenish their resources. Since the time spent docking subtracts from the microsatellites' mission time, this procedure should be as simple and quick as possible. When docking microspacecraft there are two primary tasks: attaching the microsatellite to the larger craft, and orientating the satellite to connect fuel, data and electrical services. The first of these tasks is largely the domain of the microsatellite and is dependent on how quickly velocity adjustments can be made, and on the specific attachment mechanism. The second task is made simpler and faster by the microcilia surface. Using microcilia to perform the delicate final orientation and positioning of the satellite will greatly speed up the docking operation because the entire satellite, with its fixed connections, could be mated to fixed connections on the main satellite. This alleviates the use of flexible and cumbersome umbilical cords and attendant positioning systems.

A further benefit of using microcilia as a docking surface is a reduction in mass compared to other docking and alignment techniques. On the host satellite only a surface of microcilia is required along with minimal control electronics and sensors. The microcilia docking system could simply replace one of the satellite's body panels for maximum weight savings. On the microsatellite side, the additional mass to incorporate docking functionality could be as low as zero. The optimal microcilia interface is a flat plane, which may already be part of the microsatellite chassis, thus requiring minimal integration.

The microcilia themselves have inherent advantages for this application. Foremost among these advantages is their ability to arbitrarily position the satellite anywhere on the surface and in any orientation. The microcilia can also act as sensors, however, it has already been demonstrated that they can position objects open loop with little loss of accuracy [9]. By using thousands of microcilia on a single docking patch, it is possible to build systems that incorporate massive redundancy. Thus, if there is some kind of docking mishap the entire mission need not be effected. Finally, thermal microcilia have been shown to perform better in vacuum then air [10]. This is largely due to a lack of convective cooling which slows the heating cycle.

The scalability of microcilia also enables the construction of widely varied systems. While the primary task envisioned for microcilia is manipulating picosatellites (mass <1kg) much greater masses are feasible. By using additional cilia and a greater contact area, larger microsatellites can be handled. The current generation of microcilia is capable of moving a 41.2g puck with an interface area of $2cm^2$. This indicates that a patch only 25cm in radius (100,000 times as large as the area in the experiment) would be sufficient to position satellites with more than 40kg mass under microgravity conditions.

EXPERIMENTAL SETUP

The measurements in this paper were performed using the thermal actuator based microcilia originally described in [6]. A cross section of microcilia arms is shown in Figure 4. The arrayed actuators are deformable microstructures that curl out of the substrate plane. The curling of the actuators is due to the different CTE of the polyimide layers that make up the bimorph structures. For these devices the top layer CTE is greater than the bottom CTE. The thermal stress from this interface causes the actuator to curl away from the substrate at low temperatures and towards it when heated. This stress also aids in releasing the microcilia arms because they automatically rise out of the plane when the sacrificial layer is etched.

The microcilia arm is placed into motion using a heating resistor, sandwiched between the two polyimide layers. When an electric current is passed through this loop, the temperature of the actuator increases, and the structure deflects downward. This produces both horizontal and vertical displacements at the tip of the microcilia. The motion of the microcilia arm has been shown to be approximately 30µm vertically, starting from a maximum height of approximately 120µm [6].

Objects in contact with the surface of the array are made to move by coordinating the deflections of many actuators. For this study the motions for the microcilia arms correspond to those shown in Figure 5. This motion gait has four steps during which two transitions produce forward motion. Other gaits, such as a three phase gait (in which the phase in top of Figure 5 is skipped), are also investigated.

To assess the applicability of microcilia to spacecraft docking this study investigates the effects of: operating frequency, normal force, interface surfaces, microcilia temperature, and, indirectly, microcilia life span. Of these variables, only frequency and life span depend directly on the thermal actuation nature of the cilia while the remaining parameters should be applicable to other types of MEMS microactuator arrays. To perform these measurements the microcilia are placed vertically, at the end of a tilted airtable as show in Figure 2 and Figure 6. The table is first leveled and then the angle adjustment is manipulated to specify a slope running towards the microcilia. By adjusting the slope of the table, the mass of the microsatellite simulator, an aluminum airtable puck, can vary while the normal force against the microcilia remains constant. Conversely, the mass can vary while a fixed normal force is retained against the microcilia. Using this parameter independence, the airtable allows for an accurate simulation of microsatellite docking in microgravity.

This experiment uses four microcilia chips attached to a copper block that both actively cools the microcilia using a Peltier junction and holds them vertical at the end of the airtable. The microcilia chips were glued into a grove machined in the copper block, forcing all four chips to lie in the same plane.

During all of the experiments the microcilia were controlled with the LabView interface seen in Figure 7 and custom circuitry. Each of the microcilia gaits were broken down into a statemachine describing the sequence of movements for each of the microcilia arms. This statemachine is then loaded into an LSI programmable gate array, one per microcilia chip. The LabView interface instructs the LSI chips which gait to use, the direction to travel and the frequency through which to cycle the cilia gait. LabView also reads the Hall effect sensor array and from that data controls the starting and ending points of the puck. The ability to automatically collect position data and independently vary the puck mass and the normal force allow a wide range of measurements.

With this setup, the microcilia can manipulate objects that would otherwise flatten the actuators if all the gravitational force were applied as the normal force. By using the tilted airtable the amount of normal force the cilia experience can be tightly controlled over a wide range of puck masses.

To make displacement measurements two separate systems are employed. The first is a high resolution video capture system. This system, equipped with a zoom lens, allows for relative measurements on the order of 5µm and for capturing expanded views of the system. The other measurement system is an array of Hall effect sensors. These sensors interact with a magnet mounted atop the puck to provide micrometer resolution. The Hall effect sensor array is integrated into the LabView controlling software allowing fully automated experiments to be performed. Using either of these systems it is possible to collect relative puck position and from this to compute the velocity and acceleration of the puck.

EXPERIMENTAL RESULTS

The goal of this research is to evaluate the applicability of microcilia arrays to microsatellite docking. Thermal microcilia arrays are parameterized for: operating frequency, normal force, puck mass, interface surfaces, cilia temperature and cilia lifespan. The results for these experiments are presented here.

Influence of normal force

Figure 8 shows the velocity of the puck at different frequencies over four different normal forces. For all of these data points the mass of the puck is 41.20g and the interface surface is polystyrene, beveled on the edges. Each data point is an average of four runs over a distance of 0.8mm. This setup contains two strong resonant frequencies between 30 and 33Hz and between 13 and 16Hz as illustrated by the graph flattening at these points. For these measurements the video system is used to record the puck velocity.

Outside of these regions the velocity of the puck follows a straight line which indicates the puck moving in accordance to the driving period. This characteristic indicates the interface between the puck and microcilia arms is experiencing a fixed slip component. At these frequencies the puck motion seems largely the result of a 'step and carry' transport as seen in Figure 5. One conclusion from this graph is that the overall velocity of the puck increases as the normal force against the cilia surface decreases. This is an expected result because as the normal force increases so does the precompression of the cilia, reducing their total vertical and horizontal motion. This would indicate that the optimal normal force is that where the puck exerts just sufficient force to maintain contact with the cilia surface.

Influence of interfacing surfaces

Differences between thermal conduction and surface roughness of the puck to microcilia interface effects step size and puck velocity. The five puck to microcilia interface materials examined are: polished ceramic, hard polystyrene plastic, aluminum, polished and unpolished silicon. Puck velocity versus frequency for the differing interface materials is shown in Figure 9 and Figure 10 for three- and four-phase gaits, respectively. Puck velocity is obtained by averaging a minimum of five trials per frequency with a normal force of 63µN/mm^2.

As summarized in Figure 11, the velocity of the puck is dependent on the material interfaced with the microcilia. The thermal conduction of the interface material is thought to be the major cause for the variation in velocity magnitude per material. Surface roughness is also observed to have some influence, but to a much lesser extent. Aluminum and silicon have the highest thermal conduction and this results in the lowest velocities. Ceramic, an excellent thermal and electrical insulator, delivers some of the highest velocities. Low thermal conduction of the ceramic interface allows the cilia to heat and cool in an optimal fashion resulting in high actuation amplitudes and high velocities.

Missing data points in the three-phase graph and the flatter areas of the other graphs are due to the puck oscillating with zero or reduced velocity for multiple trials at that frequency. This effect is distributed over the entire experimental surface. The neighborhoods of 17.5Hz and 33Hz show the most pronounced reduction in puck velocity for both gaits and all interface materials. The variation of this effect for different surface material and puck mass indicate that it is strongly dependant upon the specific geometry of the experiment. Regardless of this minor variation, it is thought that this phenomenon can be traced to the puck breaking contact with the microcilia surface during part of the motion cycle. Shown in

Figure 8, as the normal force is increased this effect becomes less pronounced, however, it is still consistently observed. Within these frequency bands the puck was observed to move away from the puck surface on the order of 100µm lending support to this theory.

Thermal effects

As the background temperature of the microcilia is allowed to increase the actuators become less effective. With rising background temperature it takes longer for the cilia to gain more heat during the actuated portion of its motion cycle. This results in a lowering of the maximum available driving frequency. In the extreme case the background temperature becomes large enough that the heater loop can not raise the temperature of the cilia higher than the background. At this background temperature, no heating period would be sufficient to allow the cilia to have a net displacement. Objects in contact with the cilia would no longer be transported at this point.

This scenario was experimentally verified. If the polarity of the Peltier junction that normally cools the microcilia is reversed, it provides active heating as opposed to active cooling. As the background temperature of the cilia increases their actuation displacement decreases. Eventually all visible movement halts. Once this point is reached the heater is turned off and the microcilia are allowed to cool. Subsequent checks of the microcilia, under standard operating conditions, could determine no mechanical or electrical faults. However, prolonged operation at elevated temperatures will eventually damage the actuators. Possible failures include charring of the poyimide and fusing of the heater wire.

Life span

Over the course of these experiments the microcilia are shown to be robust and the results reproducible. All four chips, corresponding to 4 times 256 actuators were run for approximately 150 hours at an average of 20Hz. This corresponds to 10.8 million actuations. During this time only one microcilia actuator leaf was lost due to manufacturing defect. This failure was in an individual heater loop and probably corresponded to a local thickening of the material or contaminants in that area.

CONCLUSIONS

The results from these experiments indicate that a microcilia surface can be useful for docking small spacecraft. These spacecraft, used for inspection, maintenance, assembly and communication services, will see increased use as space missions become more autonomous and far reaching [8]. During this scenario, microcilia provide a good match, allowing for simple docking procedures to be used with these simple satellites.

Results from the interface experiments indicate that a variety of materials common to spacecraft can be used as docking surfaces, including aluminum and silicon, thus avoiding the need for special materials on the mating surfaces. When studying the performance of different interface materials, thermal conduction dominates surface roughness to achieve optimal object velocity. Surface roughness does effect object velocity as seen in the polished and unpolished silicon. An interface material, such as ceramic, with low thermal conduction and little surface roughness should be selected for an optimal docking surface.

Through the course of this study the microcilia exhibited the speed, robustness, reliability and strength needed for this application. A 4cm^2 microcilia array, with a 2 cm^2 interfacing surface, successfully moved large blocks of aluminum with mass in excess of 40g and calculations indicate that a patch 25cm in radius would be sufficient to support a 40kg satellite. These results show that microcilia can be an attractive alternative to conventional docking systems for microsatellite applications.

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REFERENCES

1. Böhringer, K., Donald, B., Mihailovich, R., MacDonald, N.C., 1994, “A Theory of Manipulation and Control for Microfabricated Actuator Arrays,” *Proceedings, IEEE MEMS ’94,* pp. 102-104.
2. Takeshima, N., Fujita, H., 1991, “Polyimide Bimorph Actuators for a Ciliary Motion System,” *Proceedings, ASME WAM, Symp. Micromech. Sensors, Actuators and Systems,* vol. 32, pp. 203-209
3. Pister J., Fearing R., Howe R., “A Planar Air Levitated Electrostatic Actuator System,” *Proceedings IEEE Workshop on Micro Electro Mechanical Systems*, pp. 67-71.
4. Mita, Y., Kaiser, A., Stefanelli, B., Garda, P.; Milgram, M., Fujita, H., 1999, “A distributed microactuator conveyance system with integrated controller,” *Proceedings, IEEE SMC '99,* vol.1, pp. 18–21.
5. Böhringer, K.-F., Donald, B.R., MacDonald, N.C., 1996, “Single-crystal silicon actuator arrays for micro manipulation tasks,” *Proceedings, IEEE MEMS ’96,* pp. 7-12.
6. Suh, J., Glander, S., Darling, R., Storment, C., Kovacs, G., “Organic thermal and electrostatic ciliary microactuator array for object manipulation,” 1997, *Sensors and Actuators, A: Physical,* vol. A58, pp. 51-60.
7. Ebefors, T., Mattsson, J.U., Kalvesten, E., Stemme, G., 1999, “A robust micro conveyer realized by arrayed

polyimide joint actuators," *Proceedings, IEEE MEMS '99,* pp. 576-581.

8. Campbell, M., Böhringer, K., 1999, "Intelligent Satellite Teams for Space Systems," *Proceedings, 2nd Int. Conf. on Integrated Micro/Nanotechnology for Space Applications,* vol. 2, pp. 193-204.
9. Böhringer, K., Suh, J., Donald, B., Kovacs, G., 1997, "Vector fields for task-level distributed manipulation: experiments with organic micro actuator arrays," *Proceedings, 1997 IEEE International Conference on Robotics and Automation,* vol. 2, pp. 1779-1786.
10. Darling, R., Suh, J., Kovacs, G., 1998, "Ciliary Microactuatory Array for Scanning Electron Microscope Positioning Stage," J. Vac. Sci. Tech. A, vol. 16, no. 3, pp. 1998-2002, May/Jun.

FIGURES

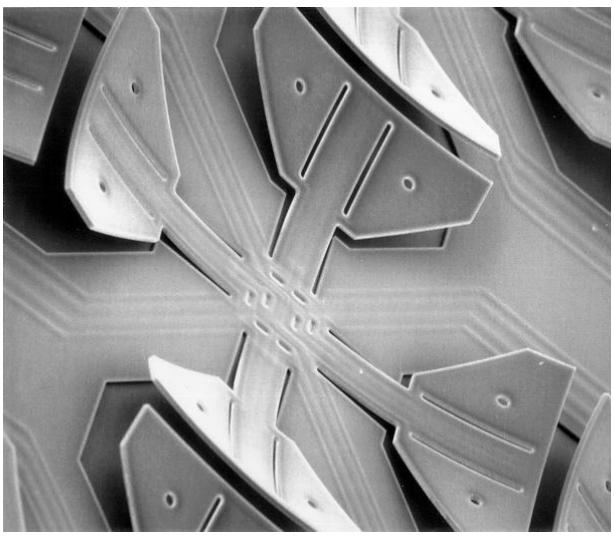

Figure 1. Scanning electron microscope (SEM) view of a single microcilia motion cell. The cell is approximately 1mm long and wide. (Image by John Suh, 1997)

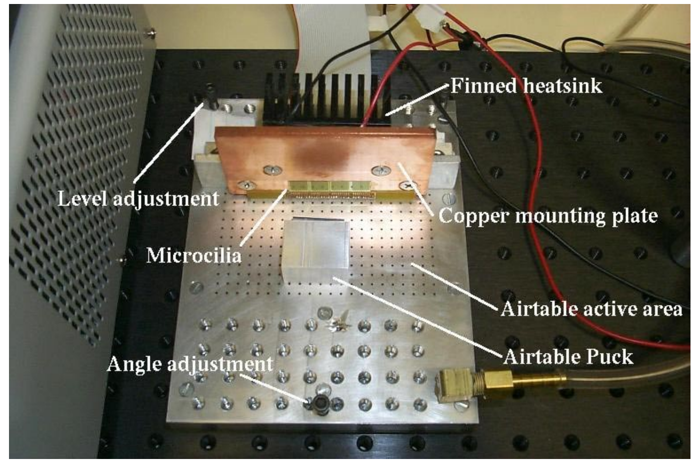

Figure 2. Airtable experimental setup to simulate microsatellite docking. A 8"x6" inch perforated aluminum plate with 3 adjustable support screws provides levitation support for an aluminum puck ("picosat"). Microcilia chips are mounted on a vertical copper plate with heat sink. The cilia are controlled by a PC and exert a lateral force on the puck during the docking procedure.

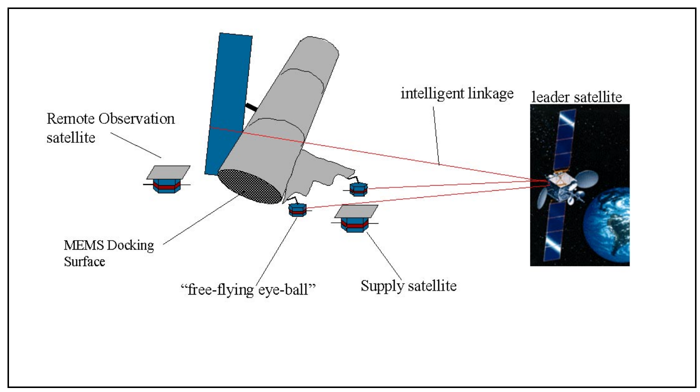

Figure 3. Envisioned microsatellite mission.

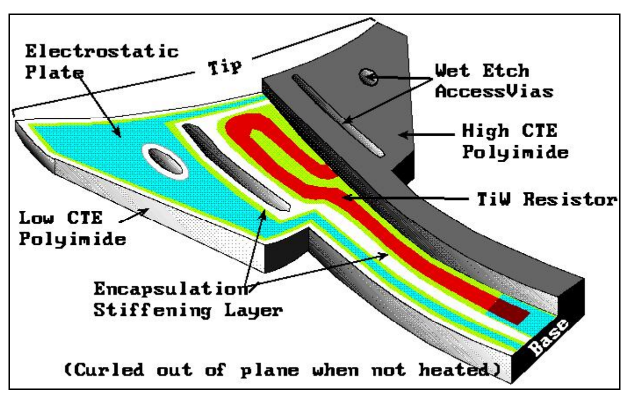

Figure 4. Cross sectional view of the microcilia with two layers of polyimide, titanium-tungsten heater loop, and aluminum electrostatic plate. (Image by John Suh, 1997).

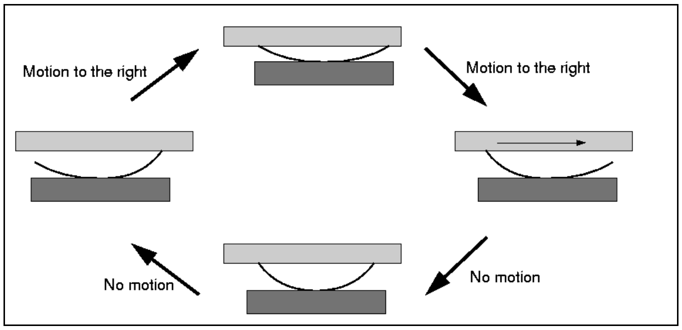

Figure 5. The four phase microcilia motion gait. A three phase gait can be achieved by omitting the top phase.

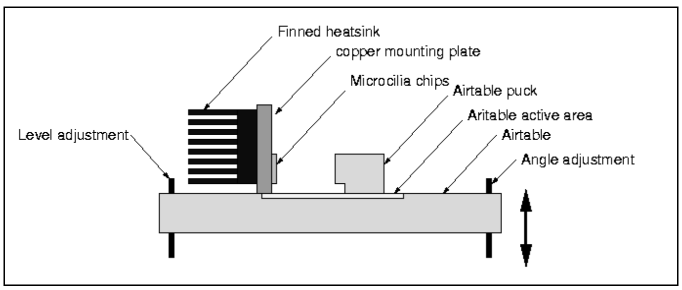

Figure 6. Side view of the airtable.

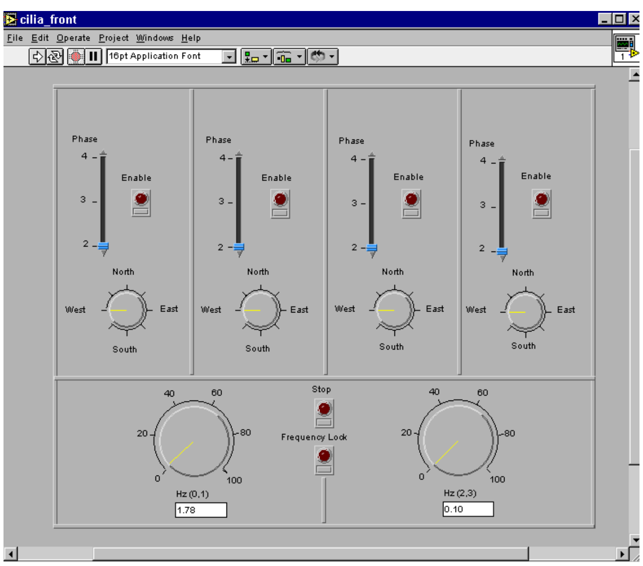

Figure 7. Labview interface for the microcilia. The four controls at the top of the screen dictate the direction and gait of the individual cilia chips. The two large controls at the bottom control the driving frequency of the two leftmost and rightmost chips.

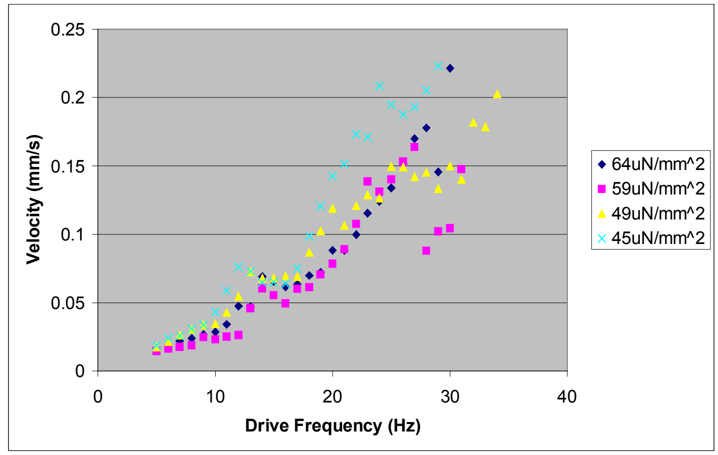

Figure 8. The velocity of the airtable puck (using the beveled plastic bumper) against different drive frequencies and normal forces.

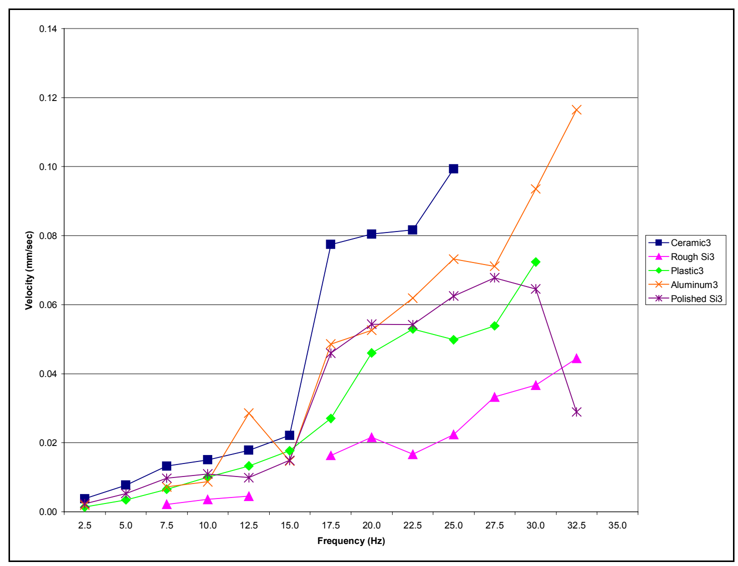

Figure 9. Influence of interface material on puck velocity (three phase gait).

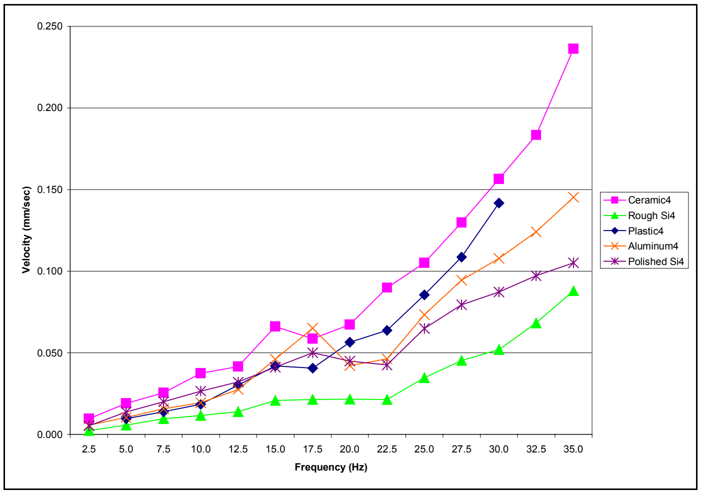

Figure 10 . Influence of interface material on puck velocity (four phase gait).

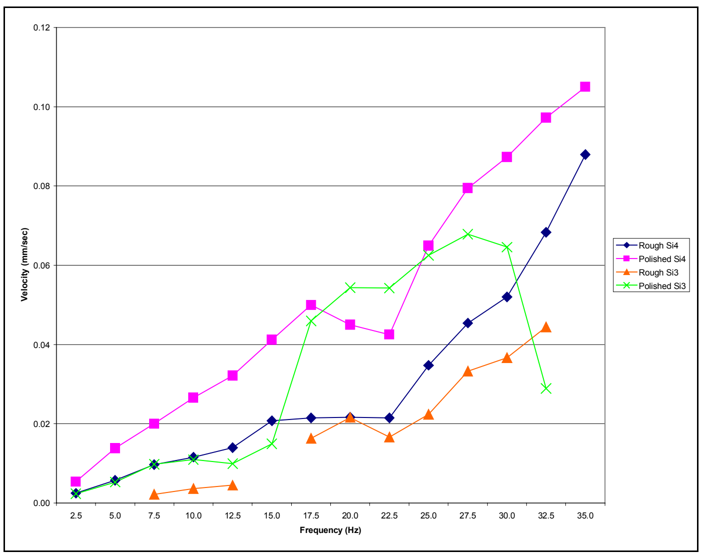

Figure 11. Comparison of all interface materials for both three- and four-phase gaits.