Rapid Contour Determination Using a Floating Pin Matrix

By

Stallion E. Yang

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

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Abstract

The exponential growth of computer and information technologies have drastically simplified the transfer of geometric information from the minds of designers to physical embodiments of design concepts. For example, it is now possible for designers to transform a complex design idea into a part or model on his desk within a few hours with the use of CAD software and CNC machining. This reduction in thought-to-part time begs the question of how the part-to-thought process can be sped up. Currently, if a designer needs to determine the geometry of a complex contour, he has to use either a phase-change material or some sort of optical scanning method. However, the use of phase-change materials can be awkward and does not permit digital manipulation of the geometric information. While optical methods do not have these short falls, it's cost is often prohibitive and it faces geometric limitations.

The objective of this thesis is to design and test an alternative method of contour determination, using a floating pin matrix which can move to conform to the shape of the contour and output the position of each pin to a computer. The pin matrix is a bed of tightly packed cylinders that can move in the axial direction independent of each other. When the pin matrix is pushed against a certain surface, each pin moves into contact with the surface, correlating the axial displacement of each pin to the height of the surface at the point of contact. Mapping the axial displacement (z-coordinate) of the pins to their known location on the matrix (x- and y- coordinates) yields a complete picture of contour.

While determining the axial displacement of a moving pin is a rather simple and trivial task, the fact that the pins need to be tightly packed in large numbers to provide a good resolution greatly complicates the task. The solution that was arrived at in this thesis involves using the moving pins as part of a "reverse potentiometer" and using two parallel plates as electrical leads that contact each and every one of the pins. The pins and the parallel plates are thus utilized both for physical function of the device and the measurement of the displacement, halving the amount of necessary components.

A prototype of the device was constructed and tested to determine the feasibility of the pin matrix system. Although the prototype only incorporated one pin, it was demonstrated that the pin matrix concept is feasible as long as issues of contact resistance between the parallel plates and the pins can be resolved.

Thesis Supervisor: Sanjay E. Sarma
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Acknowledgments

My path through and around MIT has brought me in touch of many people. And, as the Chaos Theory predicts, each little interaction has had definitive impacts on my life. Many thanks, to all of you.

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1 Introduction:

Certain industrial applications require manufacturing parts to fit existing surfaces or geometry. For example, the manufacturing of orthotic footwear requires a negative casting of the patient's foot to be made so that the footwear fits properly. In other instances, a designer may wish to adapt or modify the geometry of an existing part to use in his own design. These applications require the transfer of physical geometric information to a design medium. This transfer has generally been accomplished by using simple rulers and calipers, phase change materials, as evidenced in the orthotic footwear example, and optical scanning equipment.

The objective of this thesis is to design and test an alternative method of determining geometric information and passing the information to a design medium, using a floating pin matrix which determines the shape of a surface and outputting the position of each pin to a computer. Inspired by a common toy, the pin matrix consists of a group of tightly packed rods that are free to slide in the axial direction. This axial displacement is measured electronically and outputted to a computer, which combines information about the axial displacement with the planar location of each pin to produce a digital representation of the actual surface.

This method of contour determination holds several advantages over other established methods. Compared to the use of phase change materials, the pin matrix system has an inherent advantage in the ability to digitally output its results. The very elimination of often messy and difficult to handle phase change materials is also advantageous. On the other hand, the ability to be employed in hard to access areas—such as dental moldings—and near infinite resolution at a cheap cost still give phase change materials an edge.

On the other end of the spectrum from phase change materials, optical scanning techniques also have the capabilities to provide very high resolutions. However, the need for expensive equipment to emit, detect, and analyze the optical signals brings the cost of such equipment up considerably. Therefore, it is apparent that, in order to stay competitive with alternative methods of contour determination, cost and resolution must be the primary design considerations for the pin matrix system. The pin matrix system can only be an attractive option by providing a cheap method of contour determination without sacrificing too much resolution. The fact that most decisions on what tool to use in an industrial setting is based on budgetary constraints and functional demands, as supposed to convenience, reinforces the need to design a simple system that can have a low cost and high resolution.

2 Design of the Pin Matrix Prototype

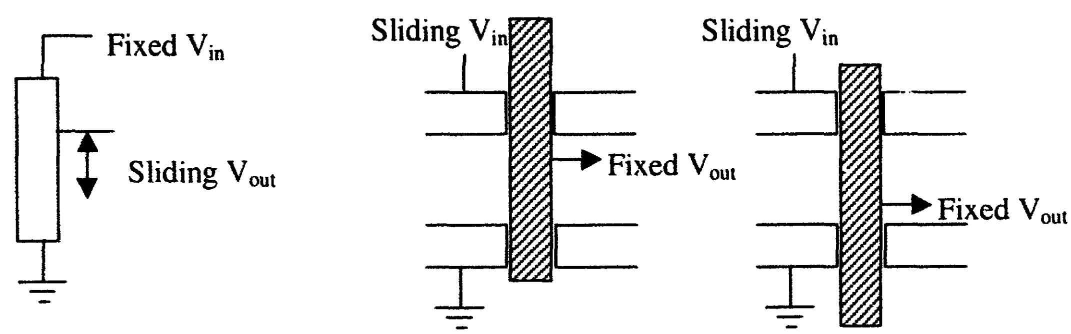
For this thesis, a prototype of the pin matrix device was designed, constructed, and tested to demonstrate the feasibility of the pin matrix concept. Since the pin matrix is essentially one identical pin design repeated a large number of times, the prototype only needed to include one pin that was cheap and simple enough to demonstrate that putting thousands of them in one device would not be impossible to assemble or cost prohibitive.

2.1 Choosing How to Measure the Displacement

Since the pins in the pin matrix system are all functionally identical to each other, the design of the entire apparatus essentially reduces to the design of one individual pin. In order to design the individual pin and its displacement measurement method, it is necessary to keep in mind how many pins are needed. Determining the contour of an object measuring 12 inches on each side with a resolution of 4 pins per inch will require more than two thousand individual pins and the accompanying displacement measurement device. Consequently, many common linear displacement measurement systems, such as optical encoding and LVDT devices, must be eliminated from consideration because it is impractical to pack these devices into the tiny spaces between the pins, which, at 4 pins per inch, is about the size of a typical word in this thesis. In fact, in order to achieve good resolutions on the reconstructed contours, the pins would necessarily have the displacement measurement systems incorporated into them in the form of resistance potentiometers. Resistance potentiometers exhibit other qualities that make them desirable for use in the pin matrix system. In addition to being compact, their cheap cost and simplicity both allow large amounts of them to be employed, making the pin matrix system very scalable.

2.2 Improving the Regular Potentiometer

Normally, a potentiometer consists of 2 fixed input leads that supply an input voltage and one output lead that moves along a material of known resistivity. The output voltage depends on the location of the contact between the output lead and the resistive material (see section 3.1). However, for the purposes of the pin matrix device, having 3 leads per pin still poses a limitation on scalability considering the daunting task of packaging, assembling, and wiring all large number of pins and the associated electrical leads. Eventually, it was realized that only two input leads need to be used in the device since all the potentiometer pins could and should have the same input voltage. Two parallel metal plates separated by a fixed distance could be used to supply the input voltage to all the pins in a giant multiple-branch parallel circuit; and the output lead was fixed to the pin so that relative motion between input and output leads still provide the basic workings of the potentiometer. Thus, the method of attachment of the input and output leads were reversed, resulting in what is referred to in this thesis as the "reverse potentiometer."



a) Regular Potentiometer b) Reverse Potentiometer

Figure 1: Schematic Differences of Regular and Reverse Potentiometers

2.3 Electrically Conductive Bearings

The use of potentiometers instead of other more sophisticated measuring techniques raises questions on whether the choice incurs a loss of precision or not. In fact, the resolution for potentiometers consisting of a continuous surface (as supposed to certain potentiometers made of wound wires), the resolution is negligibly small and the variation of slider contact-resistance is a more significant limitation [1]. The fact that, in the pin matrix device, the two sliding contacts must support the axial motion of the pins and function as bearings only complicate matters further. During early testing with the sliding pins, it was discovered that the resistance readings varied wildly, differing by as much as four orders of magnitude. The variations in resistance readings clearly came from tiny changes in the contact force—and therefore the contact resistance.

It was apparent that either an electrically conductive bearing needed to be designed or the electrical contact and the linear bearing would have to be de-coupled. However, keeping in mind that hundreds or thousands of pins would eventually be needed, there was no conceivable way of de-coupling the electrical contact and the linear bearing without introducing new components, which would greatly jeopardize the pin matrix's scalability even if only a tiny leaf string was added to each pin.

In order to establish a good electrical contact, a near constant contact force between the pin and the electrical lead must be present. However, there is a delicate balance to be struck between ensuring a good connection with a large contact force and designing a good low friction bearing with a small contact force. Unfortunately, research failed to turn up any mathematical correlations between the magnitude of the contact force to the magnitude of the contact resistance. Eventually, it was decided that since the pins don't need to withstand a large number of load cycles, ensuring good electrical contacts are more important. The final design involves adding a new plastic plate to the each of the two parallel metal plates. Pushing the metal and plastic plates in opposite directions provides the necessary contact force. Between the metal plates, which serve as the input leads, and the pins.

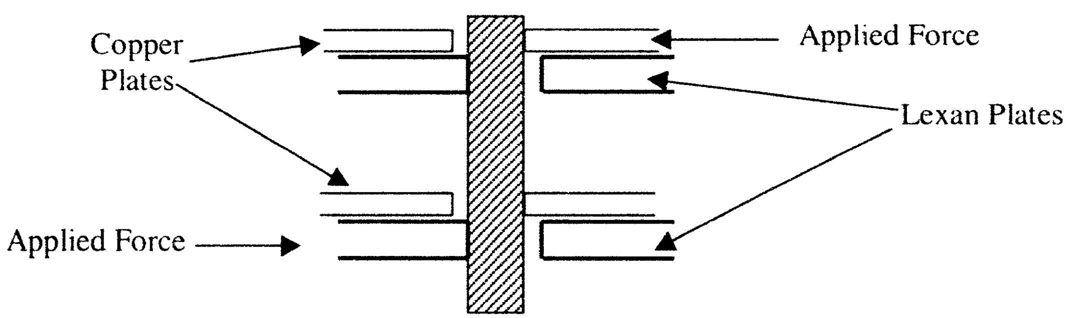


Figure 2: Side View of Parallel Plates Used as Electrically Conductive Bearings

Conveniently, this arrangement allows the same amount of contact force to be applied to each and every one of the pins at the same time. The application of the same amount of contact force to all the pins is important to ensure that the pin matrix system does not need to be calibrated for different contact forces at each pin before use. Applying the force to all of the pins at once with the addition of one component maintains the scalability of the pin matrix concept.

2.4 Choosing the Right Pin Material

Another challenge to using the pins as potentiometers is the choice of materials. Functioning both as mechanical components and electrical circuit elements left the choice of materials unclear. While commonly used engineering materials such as wood, plastics, steel, and aluminum would fill the roll of moving pins and provide contact surfaces for a sliding linear bearing, their electrical resistance were either too high or too low. Metals like steel and aluminum can be used as potentiometers since they have constant and known resistivity values. However, since they are good electrical conductors, their low resistance values can easily become masked by the contact resistance between the pins and the parallel plates. On the other hand, plastics and wood are electrical insulators and would not function as potentiometers at all. In between the two extremes lies a happy medium in the form of conductive plastics. Conductive plastics are a class of plastics which have conductive materials such as metals or graphite mixed into them to provide a pinch of conductivity.

3 Theory

3.1 How a Regular Potentiometer Works

The primary component of a potentiometer is a resistive element whose dimensions and resistivity are known. Two input leads, generally fixed to either end of the resistive element, provide a known input voltage and an output lead slides along the surface of the resistive element, between the two input leads.

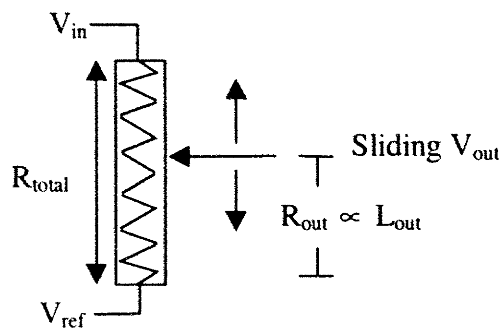


Figure 3: Circuit Diagram of a Regular Potentiometer

This arrangement constructs a voltage divider where the output voltage of the output lead depends on the resistance between the output lead and the input lead chosen as the reference.

$$\frac{V_{out}}{V_{In}} = \frac{R_{out}}{R_{total}} \qquad (1)$$

Since the resistivity of the resistive element is known and generally constant, the resistance between the output lead and the reference input lead can be related linearly to the physical distance between the output lead and the reference input lead by

$$R_{out} = \frac{L_{out}\rho}{A} \qquad (2)$$

where A is the cross-sectional area of the pin, ρ is the resistivity of the conductive plastic, and L_{out} is the physical distance between the output lead and the reference input lead. These relations cascade to link the output voltage of the output lead to the physical distance between the output lead and the reference input lead, making the potentiometer a very simple and low cost displacement measurement device.

$$\frac{V_{out}}{V_{In}} = \frac{R_{out}}{R_{total}} = \frac{\frac{L_{out}\rho}{A}}{\frac{L_{total}\rho}{A}} = \frac{L_{out}}{L_{total}} \qquad (3)$$

3.2 How a Reverse Potentiometer Works

In principle, the reverse potentiometer works the identically as the regular potentiometer. Reversing which electrical connections have sliding contacts and which ones have fixed contacts. The output voltage still varies with physical separation between the output lead and the reference input lead.

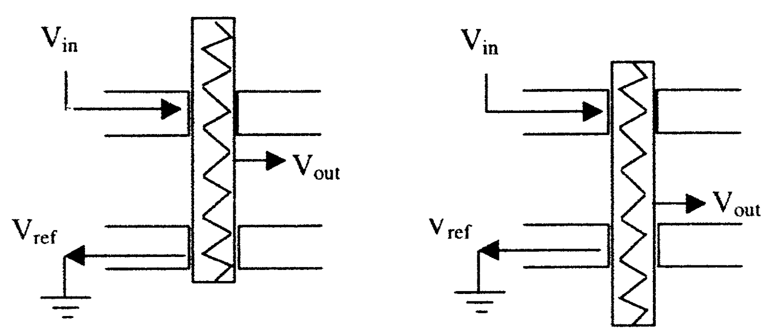


Figure 4 Circuit Diagram of a Reverse Potentiometer

The relationship between the output voltage and the position of the output lead from section 3.1

$$\frac{V_{out}}{V_{In}} = \frac{R_{out}}{R_{total}} = \frac{\frac{L_{out}\rho}{A}}{\frac{L_{total}\rho}{A}} = \frac{L_{out}}{L_{total}} \qquad (3)$$

still applies. While the physical appearance of a reverse potentiometer may look very different from that of a regular potentiometer, the fundamental principle and working mathematics remains the same as a regular potentiometer.

3.3 The Effects of Contact Resistance

The equations relating out put voltage to the axial displacement of the pins in section 3.1 and 3.2 were based on the assumption that contact resistance was negligible. However, if a significant contact resistance occurs, then the equations become

$$\frac{V_{out}}{V_{In}} = \frac{R_{out} + R_{C1}}{R_{total} + R_{C1} + R_{C2}} \neq \frac{L_{out}}{L_{total}} \qquad (4)$$

where R_{C1} and R_{C2} stand for the contact resistance at each of the sliding contacts. The introduction of contact resistance alters the ratio since the added values are not proportional to each other. Also evident is the effect of using potentiometers of low resistance. The smaller R_{out} and R_{total} are, the more easily R_{C1} and R_{C2} can dominate the ratio and skew the relationship.

While pins made of conductive plastics are much less susceptible to the effects of contact resistance compared to metal pins, it is clear that contact resistance must be avoided if possible.

4 Construction of the Pin Matrix Prototype

4.1 Construction of the Pins

The conductive plastic used to build the prototype was purchased from Hyperion Catalysis International, Inc., Cambridge, MA. The material contained 95% PBT plastic and 5% fibrils, a form of carbon. Fibrils are tiny electrically conductive particles made of graphite sheets wrapped around to form a hollow cylinder [2]. Their addition to normal PBT reduces the resistivity of the insulator material greatly.

Normally, the conductive plastic is sold in pellet form and easily injection molded. However, only a small amount of the material was purchased and used since the company charged a prohibitive per unit price for orders smaller than one ton. The small amount of available material made the use of injection molding unfeasible. As an alternative method of production, the plastic pellets were loaded inside copper tubing used for domestic plumbing, placed over a natural gas flame, and clamped from both sides with a C-clamp between ramming pistons. After approximately 10 minutes of heating the copper tubing, the plastic pellets melted and were packed into a solid cylinder. Then the assembly was quenched and the plastic pins were removed from the copper tubing. The size of the copper tubing ultimately determined the size of the prototype plastic pin, which was four inches in length and 0.550 inches in diameter.

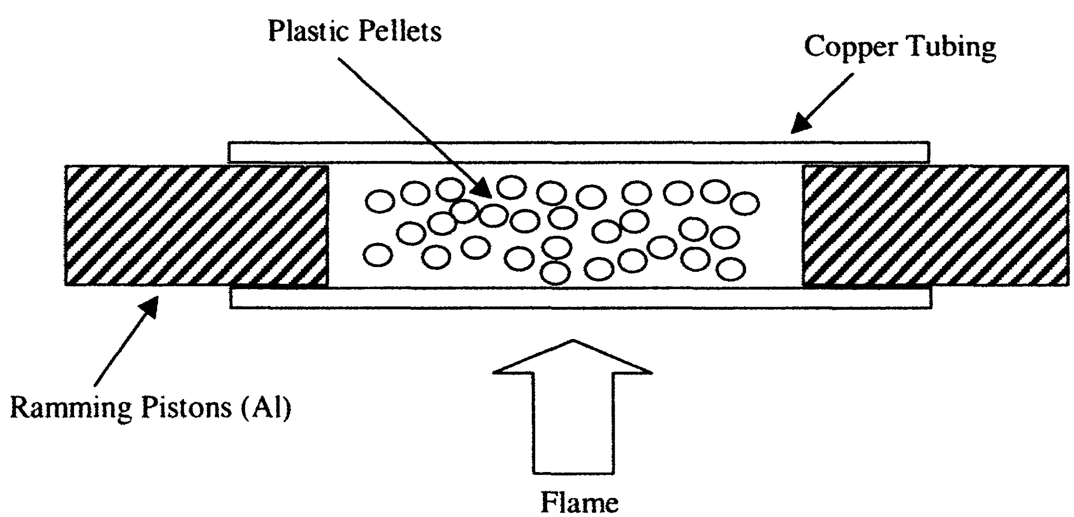


Figure 5: Production Method of Conductive Plastic Pins for Low Volumes

Due to the fact that the pins for the prototype were not injection molded, there was no embedded attachment for the output electrical lead. As a result, it was necessary to saw a slight groove at the midpoint of the pin and wrap wiring from the output lead around the pin inside the groove. The output wire was then clamped down with a hose clamp to reduce contact resistance.

4.2 Construction of the Parallel Plates

Due to availability, copper and lexan were chosen as the metal and plastic parallel plates, respectively. Support fixtures were machined out of aluminum to hold the copper plate and lexan plates together to form two plate aseemblies. Since the longest fabricated plastic pin was only four inches in length, the separation between the two plate assemblies was set to be two inches, half the length of the pin. The two plate assemblies were bolted to four two-inch pillars through the lexan plates.

Two holes were drilled at either end of each of the copper plates. The input wires were passed through the holes at one end and soldered to the copper plate to provide a good electrical connection. Two strings were passed through the holes at the other end to provide a method of applying force, either manually or by hanging a weight.

Finally, all four plates were clamped together and a hole .5785 (37/64) inch in diameter, just a tiny bit larger than the pin, was drilled through all four plates for the pin to fit through. Refer to Appendix A for machine drawings of the various parts.

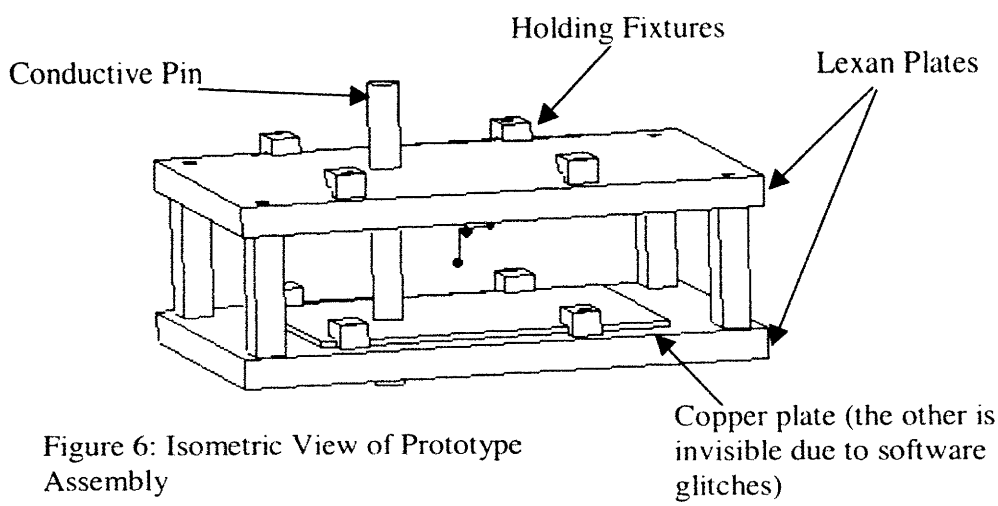


Figure 6: Isometric View of Prototype Assembly

5 Testing

5.1 Testing Procedures

After assembly of the prototype was complete, the output and ground leads were attached to a Digital Multimeter (DMM). The strings attached to the copper plates were strung over the edges of the lexan plate such that, when a heavy weight was hung from the strings, the plates would be pushed in opposite directions and provide a constant and significant contact force at the point of the sliding contacts. The plastic pin was moved through its range of travel and resistance values were taken at various points.

Then a 9V DC battery was added to the circuit, attached to the two input leads going into the copper plates. The output voltages across the DMM were taken at various points along the travel range of the plastic pin.

5.2 Testing Results

Unfortunately, the both the resistance readouts and voltage readouts of the crude tests varied widely with time, rendering the results mute. However, it was possible to distinguish that the resistance and voltage readouts did vary with the displacement of the plastic pin, generally in a linear fashion.

6 Conclusion

6.1 The Resolution of the Reverse Potentiometer

Throughout the testing phase of this thesis, it was clear that the chop-and-build approach to building a pin matrix forced by a variety of circumstances would not produce a product that had even the bare minimum resolution needed for actual contour determination. Several problems that destroyed the resolution of the reverse potentiometer existed within various parts of the prototype.

The first and probably the most dominant problem with the prototype resides within the most key component, the moving pins. The fabrication method of cooking the plastic pellets and then clamping them with the force of a C-clamp could not provide enough pressurization. In addition, the heating of the plastic pellets was often uneven; and some of the samples that were cut open showed that the interior of the plastic pins was not fully molten before cooling. The result was tiny air pockets and gaps that would affect the volume resistivity of the plastic pins.

Another potential problem affecting the plastic pins of the prototype was the intensity of the heating. The use of copper tubes and direct heating made the control of the heating difficult. Consequently parts of the plastic pins produced showed a white coating on certain parts of the surface. The origin and nature of this coating is unknown but it is likely the result of some sort of chemical reaction that occurred as the plastic was overheated. Given the importance of low contact resistance, the intrusion of an alien substance on the surface of the plastic pin may have had grave consequences.

Another factor that may have added extra contact resistance was the attachment method of the fixed output lead. While wrapping the output wire tightly around a groove on the pin and then clamping the wire with a hose clamp was the best method of attachment available at the time of prototype construction, having a built in metal electrical lead inside the pin and then soldering the output wire to the lead would be preferable.

While all these flaws in the prototype conspired to render the displacement readings taken from the DMM untrustworthy, the overall concept of using a reverse potentiometer to measure the axial displacement of the pin matrix was validated by the generally linear dependence between the DMM readouts and the axial displacement of the pin. As long as the technical issues, almost all related to the reduction of contact resistance, can be overcome, producing reverse potentiometers to be used as part of a pin matrix with resolutions on the order of 1 millimeter should be possible and plausible.

6.2 The Cost of the Pin Matrix

The cost of the raw materials for the pin matrix prototype was roughly $40, the bulk of which consisted of the cost of the copper plates. The fact that no sophisticated linear displacement measurement devices were used and that the pin matrix did not need to be actuated provided significant reduction in costs. It is premature to predict the final costs of a fully developed pin matrix contour determination device with only the cost of a primitive prototype available; however, it is safe to say that the costs of the pin matrix device should be much less than that of an optical scanning device, since the cost of the pin matrix device scales mostly with the amount of material use while the cost of an optical scanning device would scale with the cost of optical detection equipment.

7 Future Improvements

Many lessons were learned from the construction and testing of the prototype single pin device. Given the terrible resolution of the readouts on the DMM, there is much room for improvement.

The first and most obvious improvement to be made in the future is the use of injection molded pins. While the use of injection molding to manufacture the pins is almost required by the large volume of pins utilized in each pin matrix device, the use of injection molding should also provide a great improvement in the material consistency of the fabricated pins, ensuring that the resistivity of the conductive plastic is uniform throughout the pin. The control systems in an injection molding would also be a superior method of controlling the melting process of the plastic pellets compared to manual roasting over an open flame, eliminating the coating of white unknown substances on the outer surface of the pins. Finally, electrical leads can be pre-placed into the mold prior to the injection of plastic, resulting in a pin that has a built in electrical lead which provides a better electrical connection than bare wiring clamped down with a hose clamp.

Another possibility for future improvement is the use of copper sheets with flextures stamped into them as the metal plate that provides electrical contact. While the use of a heavy hung weight may be convenient for a prototype, it would be ungainly in a real-world device. Also, it was realized during the prototyping process that different pins would have different amounts of interference with the current bearing metal plate due to slight variations in the manufacturing process. This translates to a varying amounts of contact force for each pin, which again translates to a varying amount of contact resistance at the two contact points for each pin. This will undoubtedly adversely affect the accuracy of the contour determination. The solution lies in the form of flextures. The use of small flexible features stamped into the copper sheets would ensure that the contact force for each pin is within a reasonable tolerance of each other since the flextures would flex and compensate for small manufacturing imperfections. This copper sheet with flextures stamped into it can then, in turn, be pushed into the pins by a constant force actuator. This combination provides a good method to provide a constant contact force to all the pins and a good way to evenly distribute the applied force to all the pins individually.

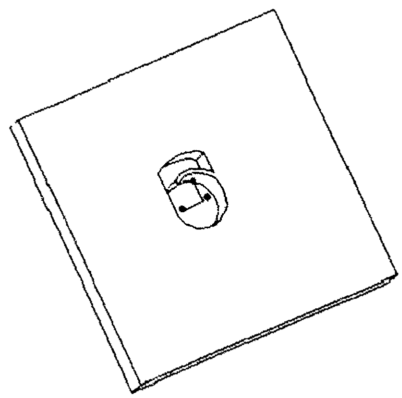


Figure 7: Close Up View of Possible Flexture Design

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2 Hyperion Catalysis International, Inc. (2000) *Hyperion Graphite Fibrils™.* Retrieved April 13th, 2000, from the World Wide Web: www.hyperioncatalysis.com/grafibs.htm