A New Approach to the Electronic Pen Idea

by

Adrian N. Bischoff

Submitted to the Department of Mechanical
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ABSTRACT

The pen is a very useful, comfortable, quick and portable output device. Even in a world with Personal Digital Assistants (PDAs) and laptops in abundance, many people still prefer pens for situations like taking notes in a lecture or a business meeting or for sketching an idea.

A pen product has been developed that takes writing and produces voltages related to the direction vectors of the writing. The idea to use direction vectors to produce ASCII characters through handwriting recognition is unique. Though it seems like a complex problem, there are few ambiguities in the direction vectors used to write letters. Additionally many of the ambiguities of similar-looking letters would not exist because the strokes used to write them are different. Tests show that the X- and Y- coordinates of the outputs are uncoupled when forces are applied while the pen is held vertical and stationary but somewhat coupled while one is writing. Preliminary tests also show that the voltage plots can distinguish between the lines in a box, a horizontal line and a diagonal line, the two lines in an X, and the letters U and V.

Thesis Supervisor: Gang Chen
Title: Associate Professor of Mechanical Engineering

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Acknowledgements

I would like to acknowledge Chris Dames for help and support throughout the project and without whom this work would not have been possible. I would also like to acknowledge Prof. Gang Chen, who originated the idea of using the deflection of the ink-cartridge to sense pen movement.

1. Background

The pen is a convenient output device that dates back to the use of a pointed stick in clay. Even with the advent of computers, most people still takes notes in classes and meetings with a pen and the easiest way to visually display an idea is using pen and paper. They are convenient to carry around as they easily fit in a pocket or a bag. They are discreet; one can take notes in a meeting quietly as opposed to using a laptop in the same situation. Finally pens are able to quickly produce visual representations of ideas.

The original idea behind this project was created by Prof. Gang Chen. He saw his CrossPad which, as described below, digitizes writing on paper but uses a bulky tablet placed underneath the pad of paper to track the pen and saw the possibility of a pen that did the same thing as a stand-alone device. The major goal of this project is to make a pen that can write on paper with ink while digitizing the writing at the same time.

2. Specifications

From this broad goal, many criteria were considered as goals for this pen design and the following specifications were set out:

- This pen should be a stand-alone device. There should be no wire tether and preferably no base station. A person should be able to pull this out of his pocket or bag and write with it and put it away.
- It should be able to write on any paper. It should be able to write on the back-of-the-envelope or a napkin as well as a notepad or a lab notebook. The goal is to have this product be inconspicuous as possible.

- It should have hand writing recognition for text and some type of graphical output (eg JPEG or TIFF) for sketches. By scanning and typing in a page of text from my notebook, I found that the same page was 1.3 kB in ASCII format, 41 kB as a 50 dpi JPEG and 86 kB as a 425x585 8 bit bitmap. In order to keep the storage space to a maximum and to minimize the size of the pen, the writing should be in ASCII format. Additionally having the writing in an editable format allows one to change it and put it in any form of writing or communication quickly.
- It should be able to store 336 pages of notes. This number was arrived at by assuming this pen should be able to store the information that a person would write on two week business trip, writing four hours a day at a rate of six pages per hour. The memory needed for 336 pages would then be 400 kB for ASCII, 13 MB for JPEG and 28 MB for bitmap.
- Naturally, the battery life should meet or outlast the previous requirement, so a battery of 56 hours is needed.

These were the goals of this project. Under the scope of this project, achieving all of this is not possible, but either they could be accomplished in the next steps of the project or compromises were made.

3. What's out there now?

In developing this pen, I did a search to find out what was out there that was similar to this idea. The basic criteria used to narrow down all the pen-related products to products that would be competitors to this pen were that the pen had to write on paper with ink and had to digitize the writing. This narrowed out Personal Digital Assistants (PDAs) and the like. The devices that I found could be placed into four separate categories: (i) regular paper on top of a special tablet, (ii) a device that clipped to the top of a regular pad, (iii) a camera pen with proprietary paper and, (iv) a Doppler-based motion sensing pen. All of these are available for somewhere between $100 and $300.

3.1 Tablets

The general concept of the tablet is that the pen has a radio frequency (RF) transmitter and the tablet has RF receivers. By triangulation the pad can determine the position of the pen tip. There is also a sensor in the pen so that it can tell whether the pen is being pressed down or not. With the RF triangulation and the ability to tell if the pen is writing or not, these tablets can generate an image of what is written at 72-254 dpi.

Examples of these tablets are the Sieko SmartPad, pictured below in Figure 1; the CrossPad and IBM Thinkpad TransNote, which has one of these tablets built into a laptop. Some come with Optical Character Recognition (OCR) software. Many reviews for these pads mention that the OCR is poor. Another disadvantage is the thick and bulky tablet.

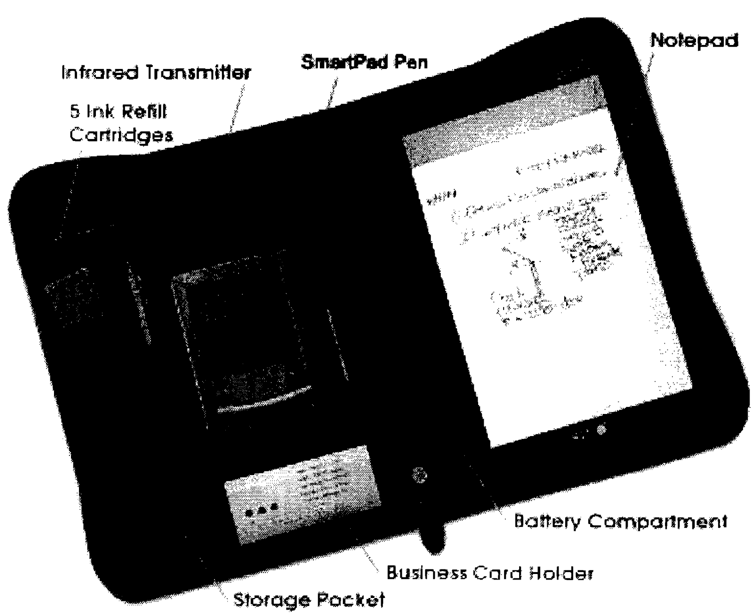

Figure 1: The Sieko SmartPad Tablet [1]

3.2 Clip Products

Clip products use triangulation, much like the tablet products, but the similarities stop there. Instead of RF, these products use infrared or ultrasound. The receivers for the signals are in a base that clips to the top of one's paper rather than in a bulky pad underneath. The information is stored in vector format, so it is scalable. This image can also be converted to jpg or other image formats using proprietary software.

DigitalInk's N-Scribe (now defunct), shown below in Figure 2 and the InMotion/ Casio E-Pen are the two products with this set-up. There is third-party handwriting-recognition software available that works with the E-Pen.

Figure 2: N-Scribe's Digital Ink clip-and-pen product [2]

3.3 Camera Pen and Proprietary Paper

Anoto developed a pen that used a camera and proprietary paper to make a digital image of the writing. The paper had a pattern of small dots on it—it simply looks gray from arm's length—that does not repeat over 60,000,000 sq. km. With the pen, the camera sampling at 50 Hz and an on-board processor, the pen then could sense its absolute position on the paper. Communication via any Bluetooth-enabled device is possible.

The obvious advantage is that the pen does not use a bulky tablet or clip. The disadvantage is that this special paper is required, so back-of-the-envelope notes cannot be digitized.

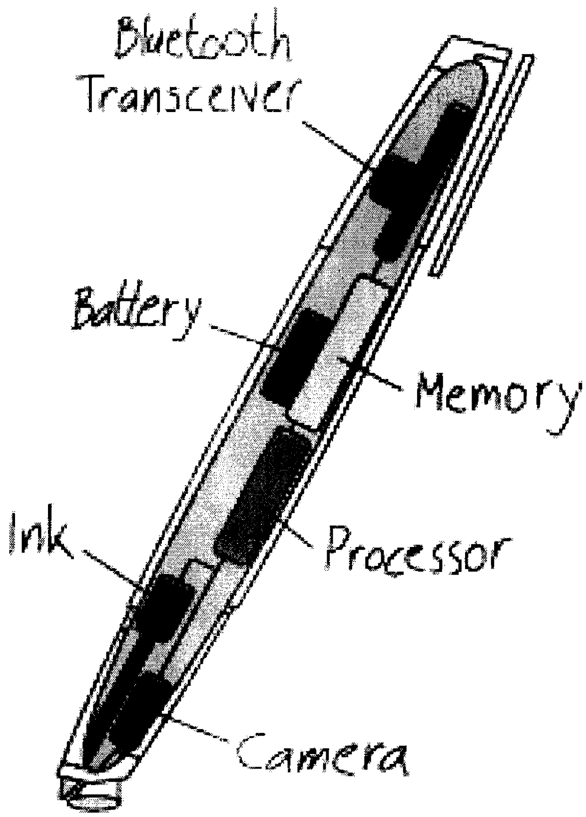

Figure 3: Anoto's camera-based pen [3]

3.4 Doppler-based Sensing

OTMtech's V-Pen, shown in Figure 4, uses what they call Optical Translation Measurement (OTM) to sense the movement of the pen over the paper. OTM is Doppler-based sensing; it shines a laser onto the paper and by using a grating and a focusing lens, the detector can sense, from where the light is hitting the detector, what direction the pen is moving.

The V-Pen has on-board in-line character processing, so that what is stored on board, or sent out using the on-board Bluetooth, is ASCII characters rather than an image file or vector data; ASCII data is much smaller. One disadvantage is that, as you can see below, the tip of the pen has a stylus rather than a pen tip. Writing on paper could be possible if the V-Pen is modified, but not in its current state.

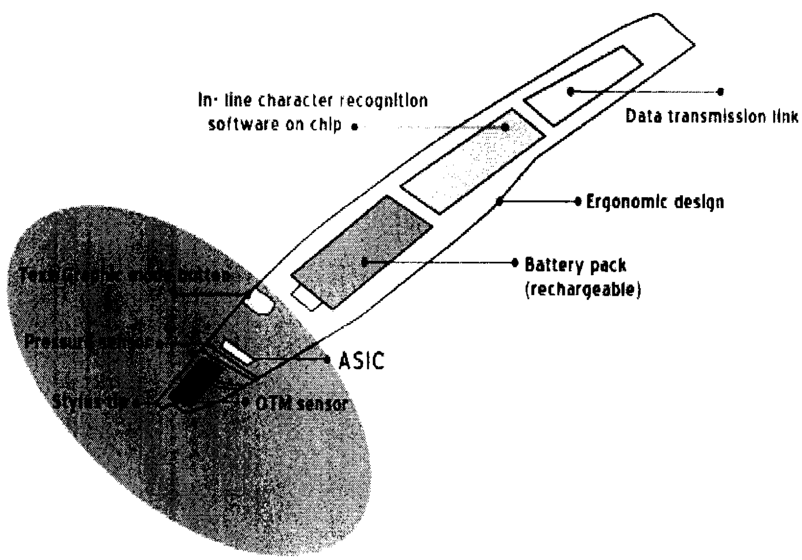

Figure 4: The V-Pen Doppler-based sensing pen [4]

4. Possible Pen Models

From the initial discussions with Gang Chen and the research of what is presently out there for pen devices that encode the writing, several possible ways of encoding with stand-alone pen were considered.

4.1 Camera

I thought it might be possible to use a camera mounted near the writing surface to capture the writing at a sampling rate around 20 to 50 Hz and then use software to splice all of these images together into one large picture of the writing. From the large picture, most commercial Optical Character Recognition (OCR) software would be at least partially effective. The software to go from the many small pictures to the larger picture would be very complicated.

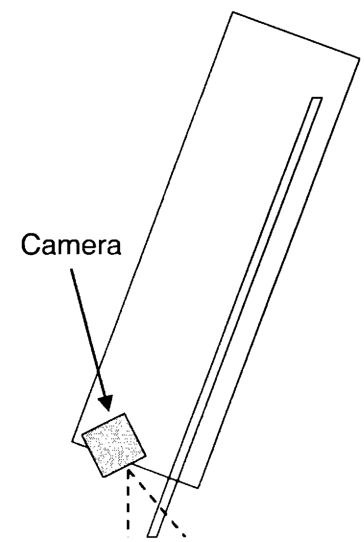

Figure 5: Schematic of a camera pen

4.2 Accelerometer

Integrating the output of a MEMS accelerometer twice is an established technology, so using this idea in a pen to get the position of the writing was obvious. Upon further investigation, I found that Patent #6,188,392 "Electronic Pen Device," [5] uses accelerometers on a pen in a similar method as I had been planning on using.

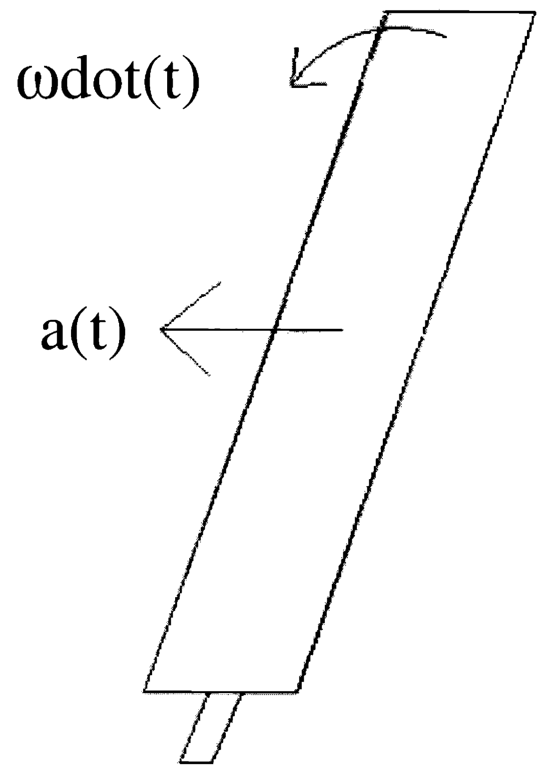

Figure 6: Schematic of an accelerometer-based pen

4.3 Ink Cartridge-End Deflection

When one puts a force by writing on the ball-end of the ink cartridge, the other end moves in the opposite direction. By sensing the movement of the opposite end of the ink cartridge with respect to the body of the pen, the direction of the writing vector (but not the magnitude) can be recorded. The ability to convert just the direction vectors without the accompanying magnitude vectors to ASCII characters through handwriting recognition will be discussed later.

Two ways of sensing the cartridge movements were considered: capacitance and optical. The ink cartridge and the body would have conductive metal pieces placed at 4 principle directions such that there would be a total of four capacitors formed. By comparing the capacitance of the pairs in the X-coordinate and the pairs in the Y-coordinate one could get a voltage proportional to the deflection of the ink-cartridge. There are many optical methods to sense the deflections of the pen-end, but one obvious one to me, considering that I had worked with them before, was Position Sensing Detectors (PSDs). By attaching an Infrared Light Emitting Diode (IR LED) to the end of the ink cartridge and attaching the PSD to the body of the pen, one can get a current—and using a normalizing circuit, voltage—proportional to the deflection of the ink cartridge.

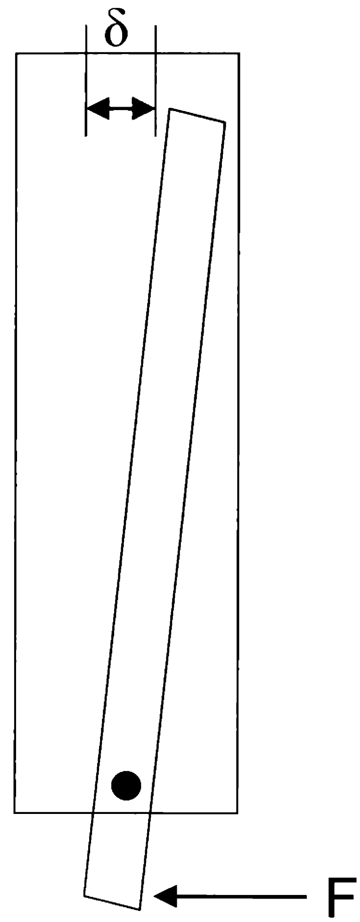

Figure 7: Schematic for a deflection-based pen

4.4 Choice

For the most part, the three ideas that were generated for this thesis fulfilled the specifications fairly well. The choice in the end came down to the academic interest each of them had. The camera idea and the accelerometer idea had both been done previously in some form. The pen-end deflection had two interesting points which had not, as far as I am aware, been tackled before: the sensing of the ink-cartridge deflection and the idea that one could go from direction vectors to ASCII characters without the magnitude vectors.

To choose between the two methods of sensing the ink-cartridge movement, it was decided that in the end, the capacitance model would be cheaper and probably more compact for the final product but that because I had more experience with PSDs, I could likely get further along in the project by using that sensor for the prototype.

The movements of the ink cartridge end were limited by the allowable movements of the tip; while writing, people expect the tip of the pen to move a negligible amount and because the ink cartridge acts a stiff beam, the cartridge end movements are proportional to the tip movements. Therefore it was reasoned that a PSD should be purchased to be big enough to capture movements within this range but not beyond, since the price of PSDs increases with size. Allowable movements at the tip end may be estimated as 0.2mm—a written letter may be 2mm wide, so this is allowing for 10% give—or about 0.008". Assuming the current ink cartridge acts as a rigid lever, the mechanical advantage is approximately 13, so the movement at the LED end would be about 2.6mm or 0.1" so it was decided that a 4x4 mm PSD would cover the required area plus an extra buffer area. After researching the various PSD options from Hamamatsu, UDT, and On-Trak, the On-

Trak DL-4, a duolateral 4mm x 4mm PSD was purchased, along with the OM-301 normalizing circuit.

5. The Design Process

By putting a force at the tip of a clear pen, it was obvious that the other end of the ink cartridge deflected. Figures 8 and 9 show a pen without any force on the tip and a pen with force on the tip, respectively. How could one model this behavior? Two possibilities seemed to be the most obvious: the ink cartridge bends or it acts as a stiff member and the deflection is caused by the body of the pen, at the point where it holds the ink cartridge, acting as a fulcrum and a torsional spring. Studying the movement of a pen while putting a force on the tip shows that while the ink cartridge body does bend somewhat, the movement can be adequately modeled by a torsional spring close to the tip of the pen where the cartridge is held.

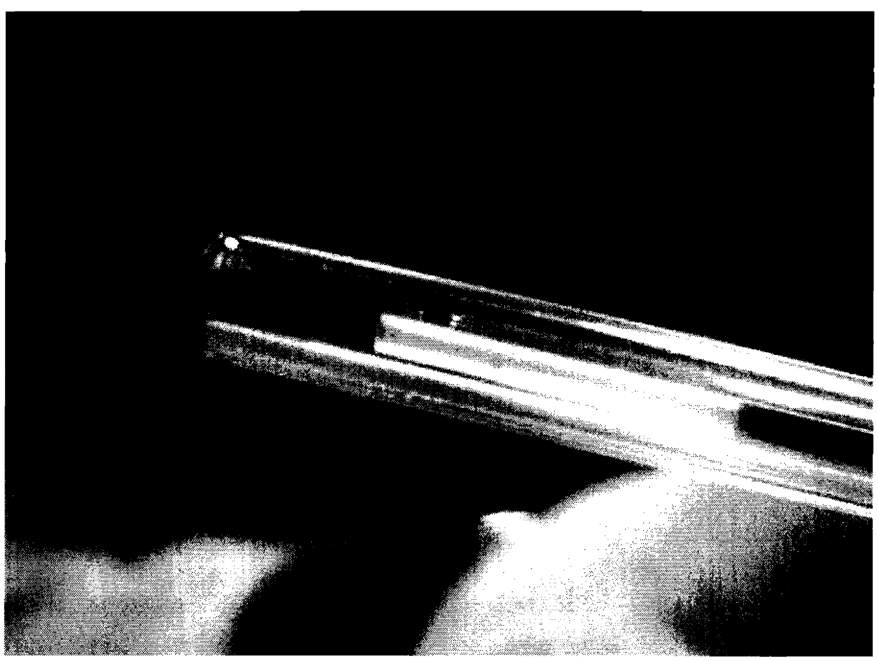

Figure 8: Ink cartridge with tip under no load

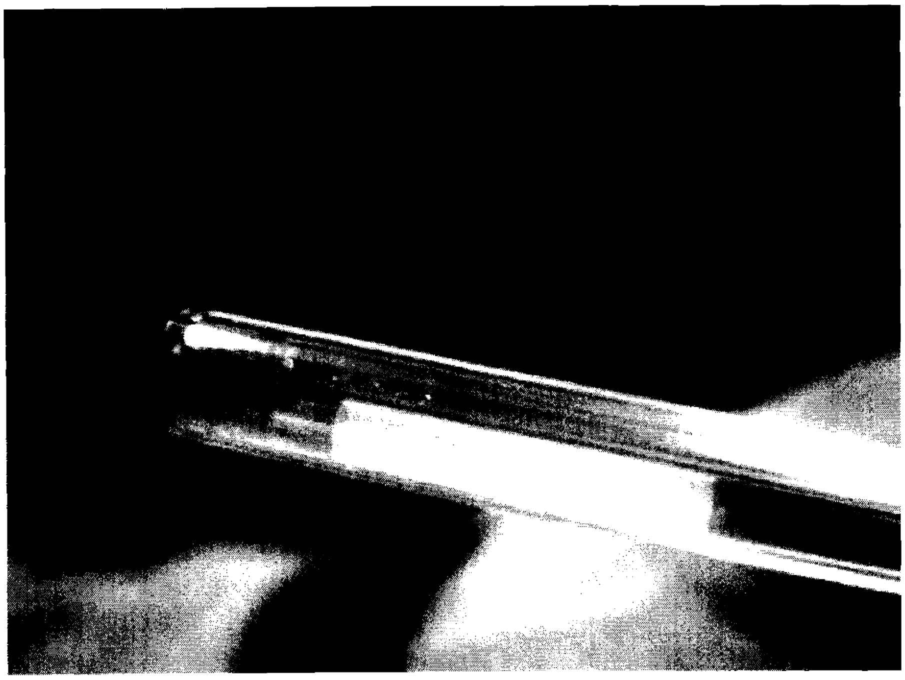

Figure 9: Ink cartridge with tip under load

There were many bench-top experiments and iterations in this design process toward a final pen that could digitize the direction data. The first step was realizing that in using a PSD, it is more convenient if the deflections at the end of the ink-cartridge are greater for the given force than for a stock pen; that is, the stiffness, k, is lower. Instead of modeling how the deflections in a pen work, the pen could be designed to deflect in a particular way at a particular stiffness. The first bench-top experiment was disabling a normal Bic Crystal pen to have a lower stiffness. This was accomplished by taking the ink cartridge out and cutting four slits into the tip of the body of the pen, where the ink cartridge was held, as shown in the schematic in Figure 10. This worked well in reducing the stiffness. It was decided however, that the PSD, which has both internal threads and screw-holes on the casing, would be difficult to attach to the brittle plastic of the Bic Crystal pens.

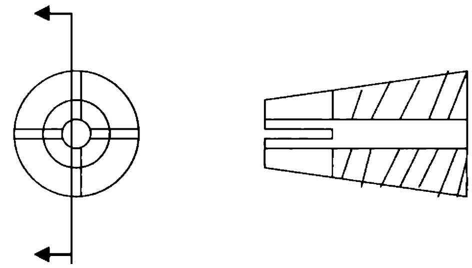

Figure 10: Pen tip with slots for compliance

I remembered a pen that had a screw-off part that held the tip of the pen; I found the PaperMate Flexgrip Ultra at the local stationary store. I reasoned that one could screw this piece into a pen body that was manufactured out of brass or aluminum, which had place for the PSD on the other end. The Flexgrip is like many pens in that the ink cartridge is constrained at both ends—the front is constrained radially and the back end is held both axially and radially. Thus using the ink cartridges from this pen with the tip that I had planned on using was not possible. The Bic pens' ink catridges that I had originally used for experimentation, however, were only constrained at the tip-end of the cartridge. By opening up the threaded part of the Flexgrip, the Bic ink catridge could fit, as shown in Figure 11.

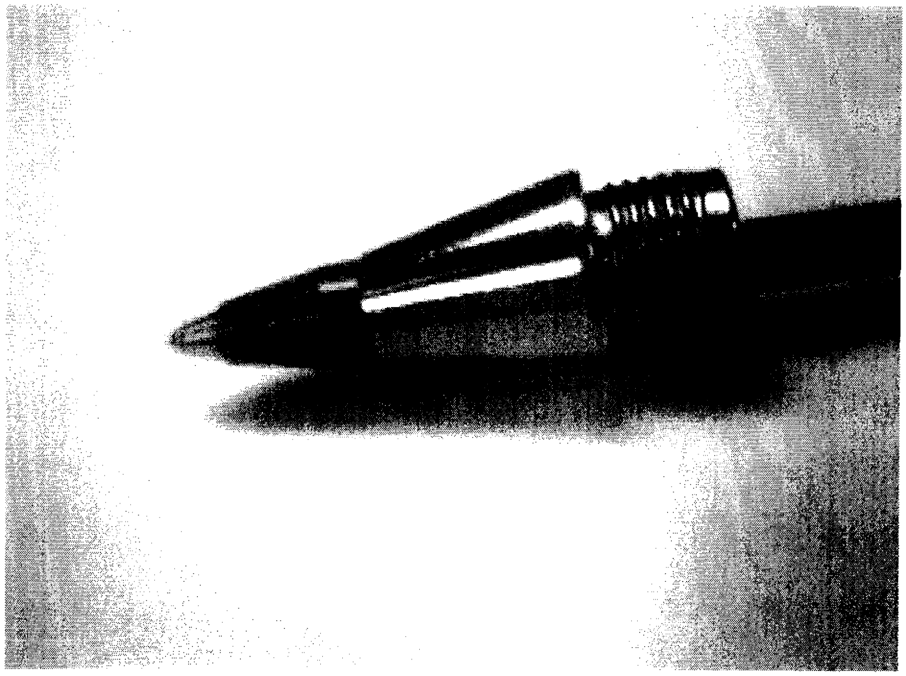

Figure 11: Bic Crystal ink catridge in a modified PaperMate Flexgrip Ultra tip

Sanding these threaded tips of the Flexgrip, I could open the end up to fit the Bic cartridge, but this operation was not precise. If the opening was just little too big the cartridge would slide axially, though this setup gave the necessary torsional compliance. If the opening was much bigger the threaded tip would act as a ball joint and if the opening was much smaller, the ink cartridge would not fit.

Reciprocal thinking produced a second option: make the tip a ball joint and put the stiffness somewhere else on the ink cartridge, as shown in the lumped element model of the final design, Figure 12. This option was more repeatable and modular in case we needed to replace the threaded metal tip than relying on sanding the threaded metal tips. Using O-rings to provide the stiffness allows for flexibility. Adjusting the number of O-rings and their distance from the tip allows for changing the stiffness.

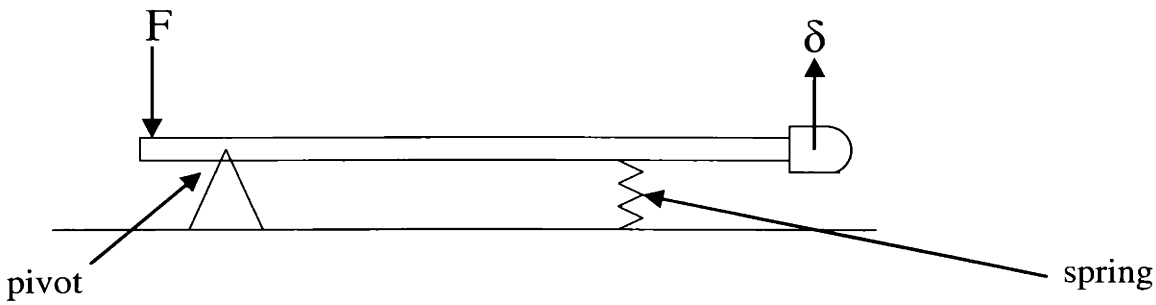

Figure 12: Lumped element model of the final pen

6. Final Design and Assembly

One concept present in the final design, a schematic of which appears in Figure 13 and the assembled version of which is shown in Figure 14, was modularity. The threaded tips, the ink cartridges and the O-rings are all cheap and replaceable. The PSD can be changed if need be. The idea was then to design the pen body to accommodate all of these modular pieces.

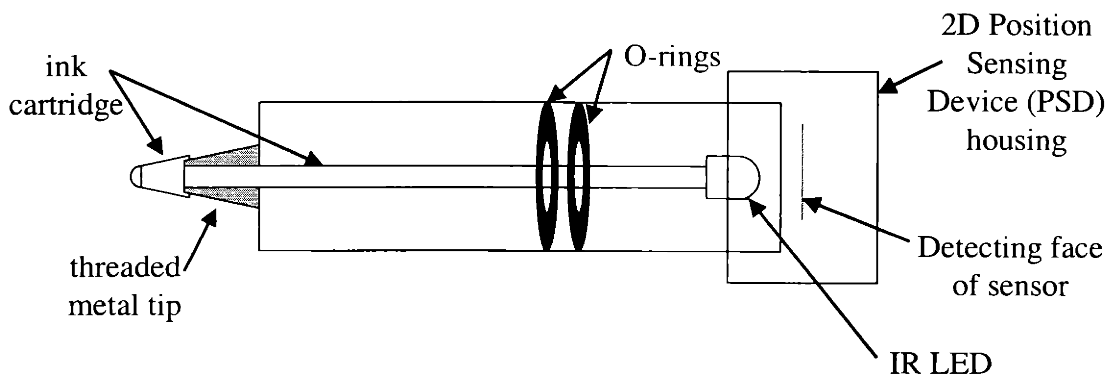

Figure 13: Schematic of the final pen design

Compare the lumped element model of the pen in Figure 12 and the schematic of the final pen in Figure 13 to see how these elements are realized in the real pen.

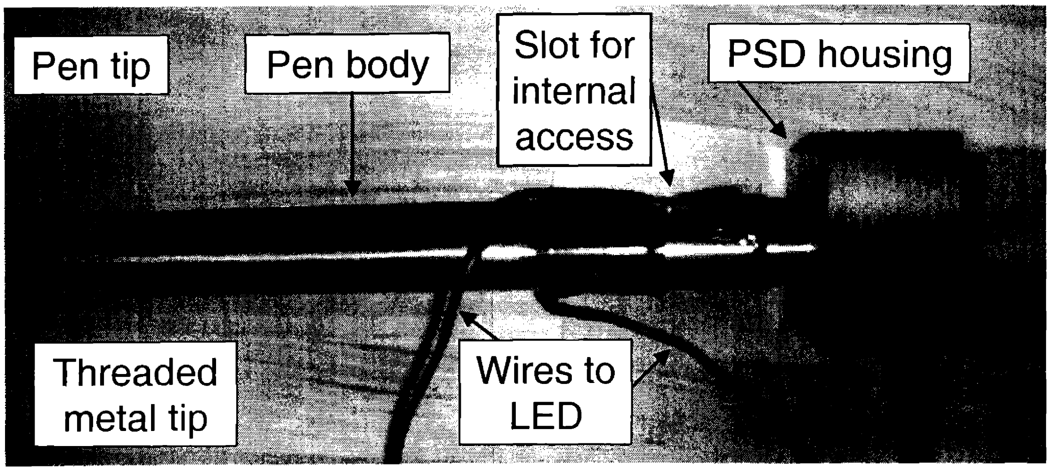

Figure 14: Final assembled pen

The PSD inner threads are .585”-40, a common microscope/ optical thread. A wide pen is uncomfortable to hold, but some larger commercial pens are around ½” in diameter so it was thought that outside diameter of the body could be .585” for the entire length with threading for the PSD at the upper end.

The Flexgrip metal pieces have a proprietary thread of 7.2 x 0.75mm according to Eddie Cambell of Papermate/ Sanford, so the inner diameter at the bottom had to be approximately .254”. The finished pen tip is shown in Figure 15 . The other constraints for the inner diameter were two-fold: the O-rings with 1/8” inner diameter—to fit the .124” outer diameter ink cartridge—and an outside diameter of 5/16” needed to be have a tight fit in part of the body and there needed to be a second part of the body where extra O-rings, to increase or decrease the stiffness, did not touch the walls. The IR LED also needed to fit inside of the body and move around freely, as shown in Figure 16 .

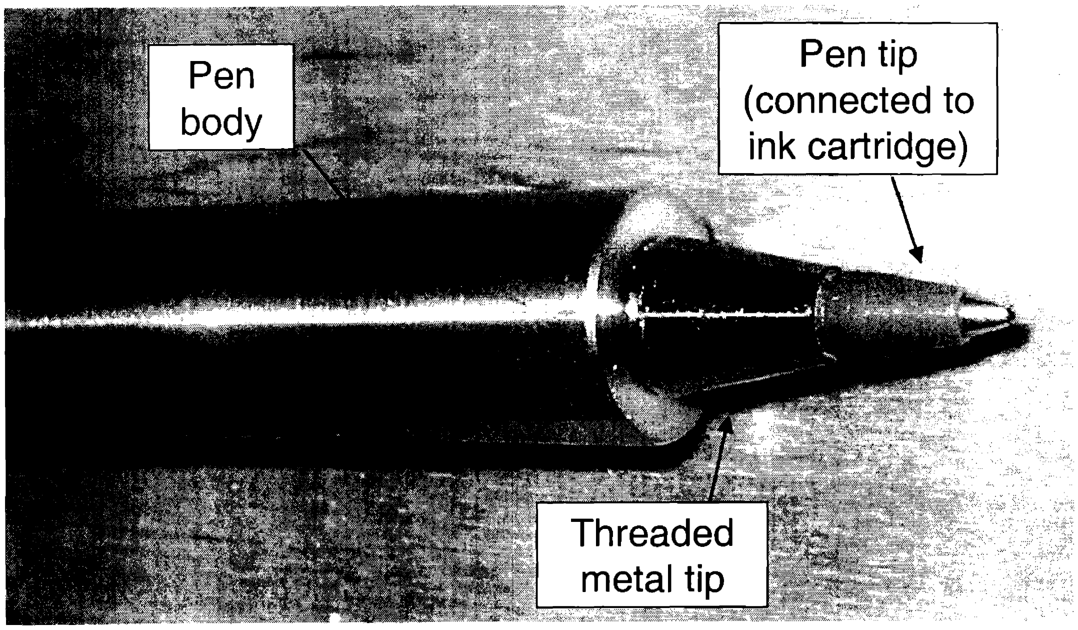

Figure 15: Pen tip on final pen

Figure 16: LED within body of final pen

Because there could not be any places inside the body where the diameter decreased and increased again—that is, there couldn't be any notches on the inside because of the difficulty machining them—and because the O-rings and the LED could not fit through the end where the threaded tip was to be attached, the pen needed to be assembled in the following order: put the ink cartridge into the threaded metal piece and screw that into the body, put the O-rings on, glue the IR LED on and solder wires onto the LED. Because of this necessary order, there needed to be places to access the O-rings to move them into place and adjust them and the ends of the LED to solder wires to them. Slots of 3/16" in width were put in the design to accomplish this, shown in Figure 17.

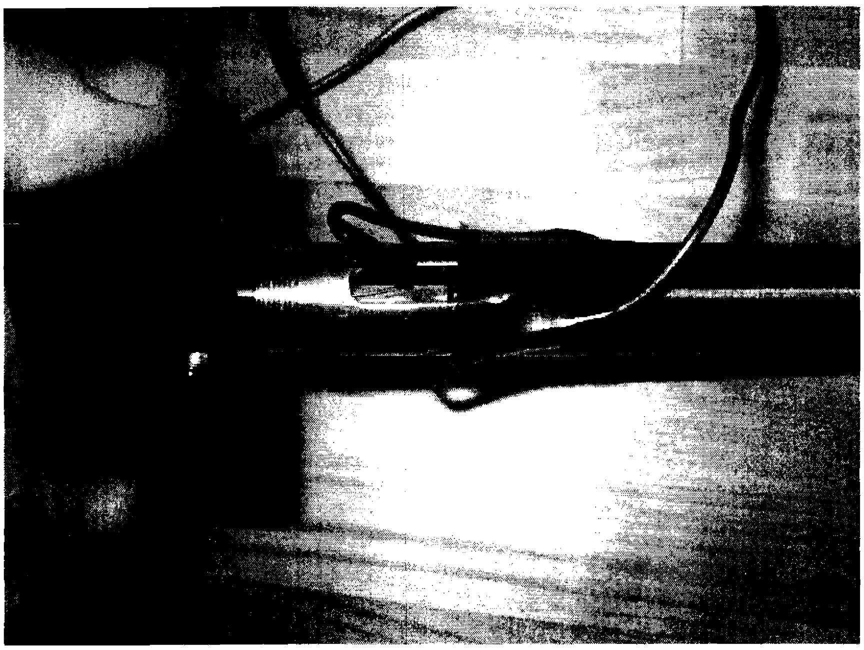

Figure 17: Slot with O-rings and wires for LED

The design was kept simple, taking into account the above constraints. Brass was chosen as the material for the body because it holds threads very well in comparison to other potential materials. A CAD generated image of the body is included below as Figure 18. A mechanical drawing is included as Appendix A.

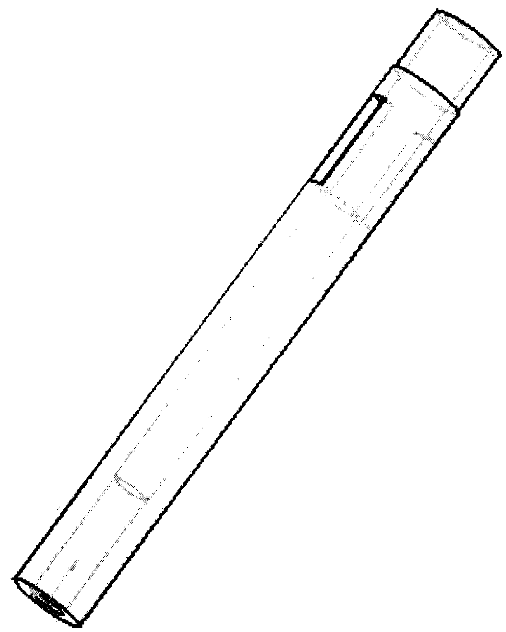

Figure 18: CAD drawing of final pen body

The body was manufactured by MIT's Central Machine Shop in early December 2002. The threaded pieces were used by the machinists to match the threads on the pen body to the necessary pieces. The current assembly uses one silicone O-ring to act as the spring. To power the LED, a DC power supply over 1.6-1.8 V is used and the LED is in series with at 200Ω current-limiting resistor. The PSD was hooked up to the On-Trak OT-301 normalizing circuit, which has BNC outputs for the X-axis, Y-axis and sum. The X- and Y-axis outputs were viewed and recorded on a computer with the National Instruments Data Acquisition (DAQ) Device SCSX-1000 and National Instruments LabView software with a sampling rate of 20 Hz. A block diagram of the setup can be seen in Figure 19. A photograph of the experimental setup can be seen below in Figure 20.

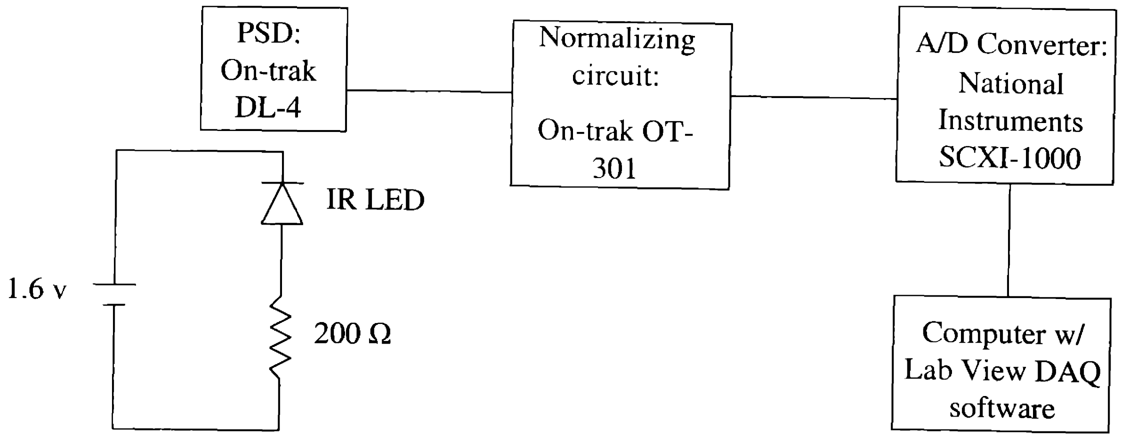

Figure 19: Block diagram of the experimental setup

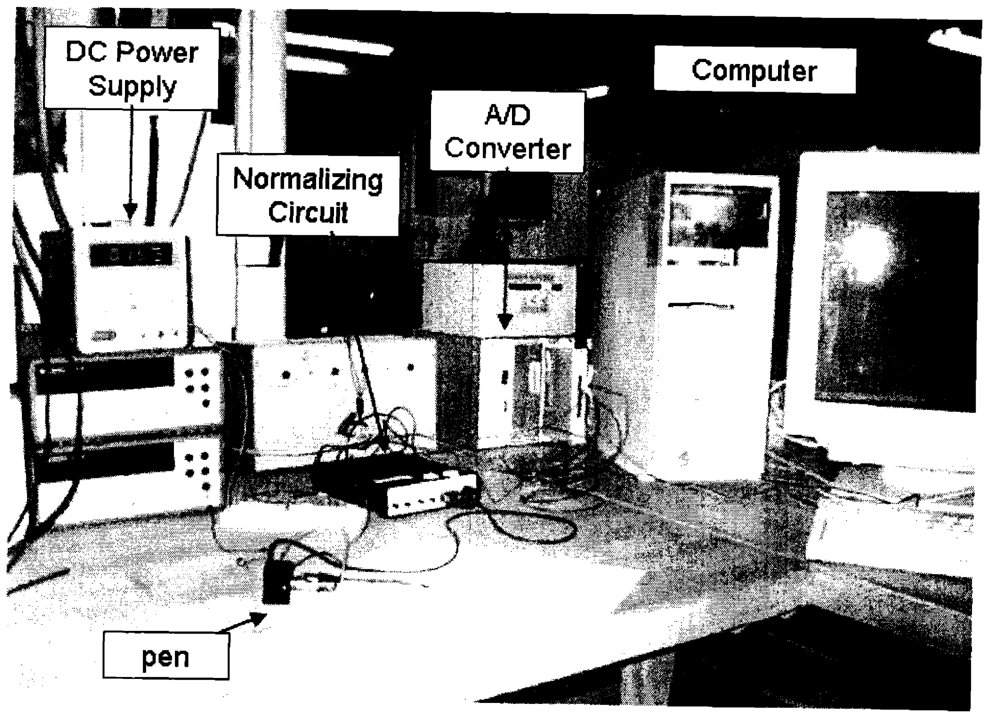

Figure 20: Experimental setup

7. Results

Hooking the sum channel to the computer with the DAQ and LabView software showed change with movement. Next I wired up the DAQ to accept two channels of input and tested the set-up with the X- and Y-channels.

An experimental spring constant was measured using a known mass and the voltage outputs. During a particular test, the full scale voltage change—that is, that is, while pushing the ink cartridge to the limit—was 4.155 V while the voltage change due to hanging a mass of 26.2g, made up of coins and tape, was 0.367 V. The farthest the LED can travel is .090" or 2.3mm. Therefore the spring constant of the system—force at the tip per deflection at the ink cartridge end—can be estimated as 1.3 N/mm.

An initial test of distinguishing the pen output was to hold the pen upright and push in the four principle directions and see if the output was coupled or uncoupled. The resulting data is plotted in Figure 21.

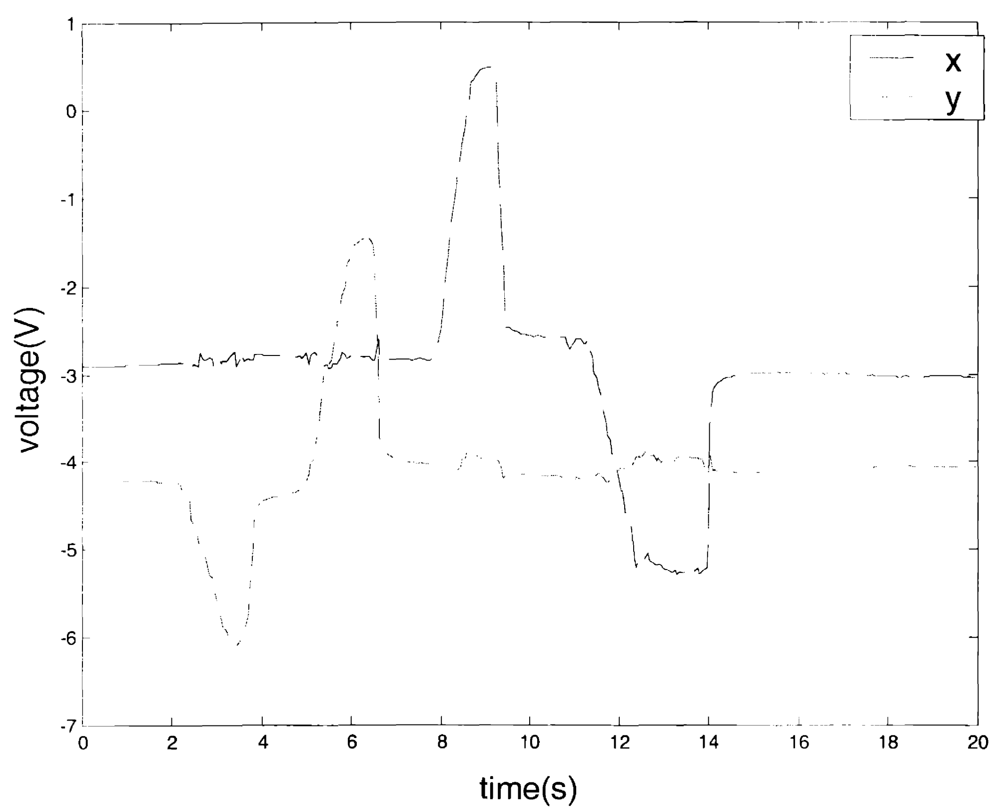

Figure 21: X and Y voltage vs. time for an upright pen with forces in the four principle directions

Though not completely uncoupled, when pressing in one direction, the spike corresponding to that direction is obvious. An X-Y plot of the data, in Figure 22, shows that the data is easily distinguishable as a plus-sign.

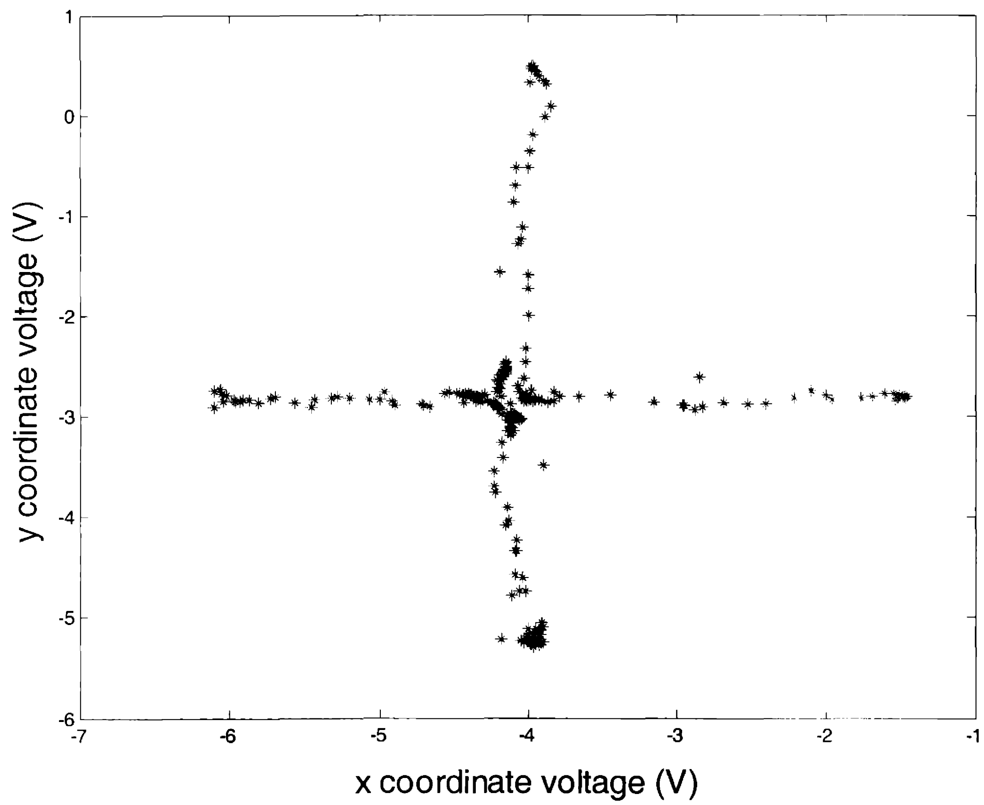

Figure 22: X-Y plot of applying a force in the four principle directions

Writing is different from holding the pen upright and applying a force, because the pen is not upright and as such the responses, even when writing in one of the principle directions the output includes an offset from the constant normal force on the paper in additional to the offset from the PSD circuit. Drawing a box (but picking up the pen at the corners) produces the output seen in Figure 23. The plot shows the characteristic peaks in all four directions, but while there are peaks in the x-direction, the y component also moves, and visa-versa.

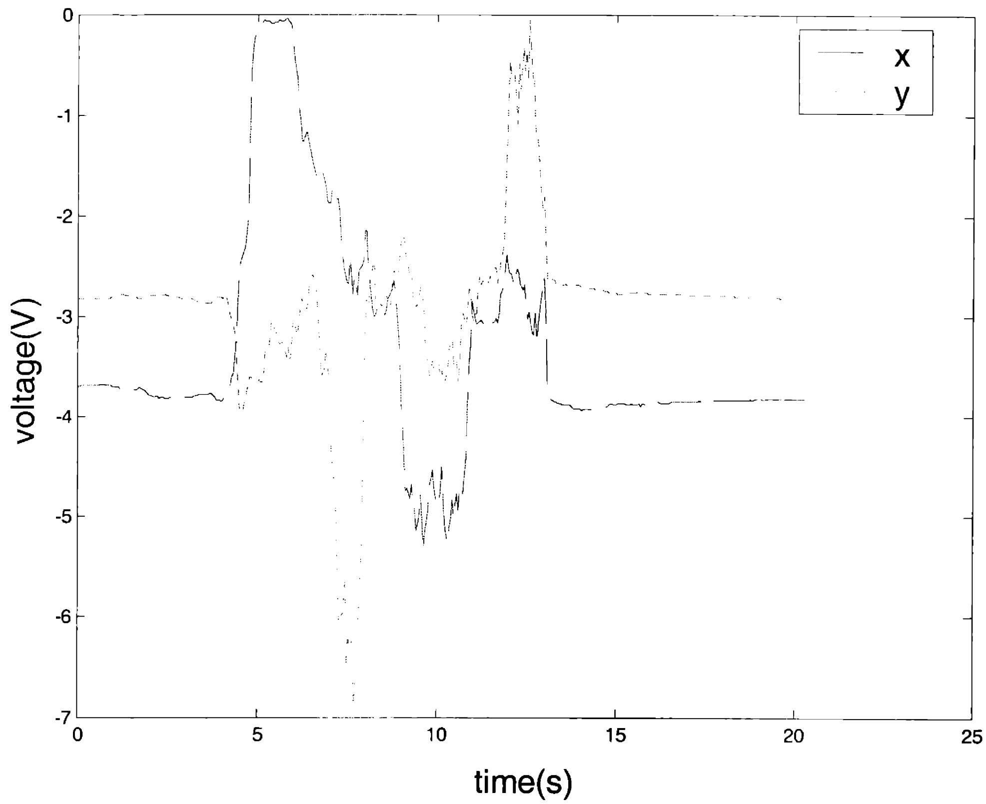

Figure 23: X and Y voltage vs. time for a box

The X-Y plot, in Figure 24, shows a shape like that of Figure 22, but not sharp, demonstrating the added complexity of writing on paper.

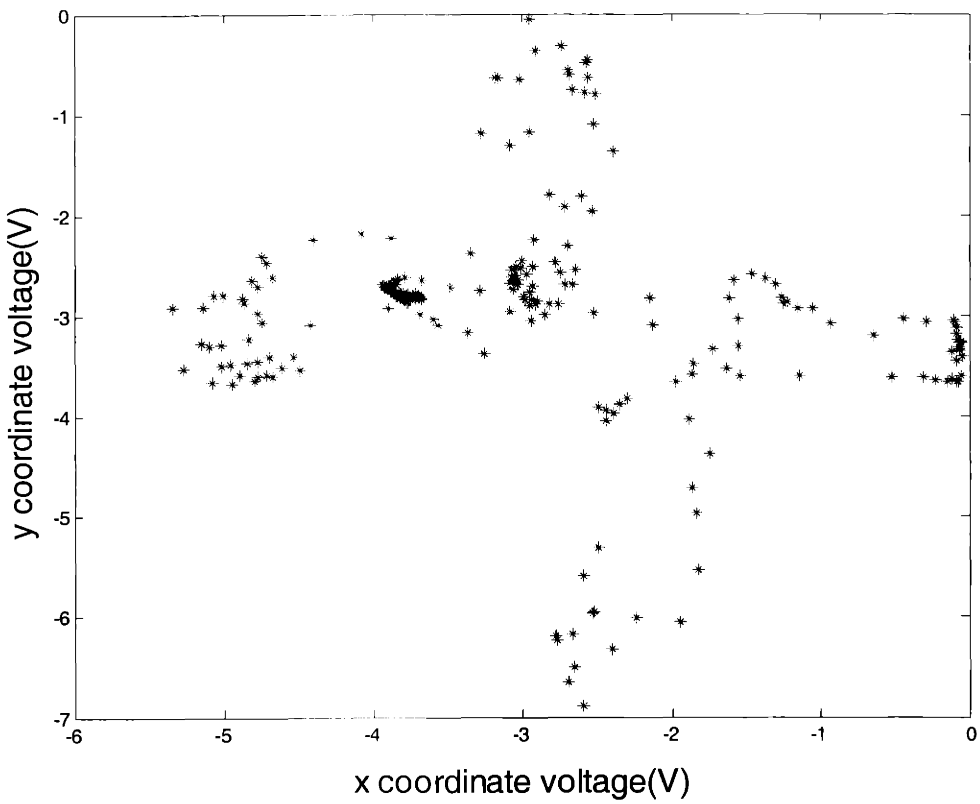

Figure 24: X-Y plot of drawing a box

Another test of the pen is to see how easily it can distinguish between angles. Drawing a horizontal line to the right and then a line at approximately 45 degrees above horizontal demonstrates the difference in the voltage. Figure 25 shows what was drawn to produce the voltages in Figure 26. At the start of the horizontal line the y-component reacts but the voltage stays more or less steady while the x-component peaks. The 45 degree line displays both the x- and y-coordinates peaking.

Figure 25: Two lines used to produce the output below

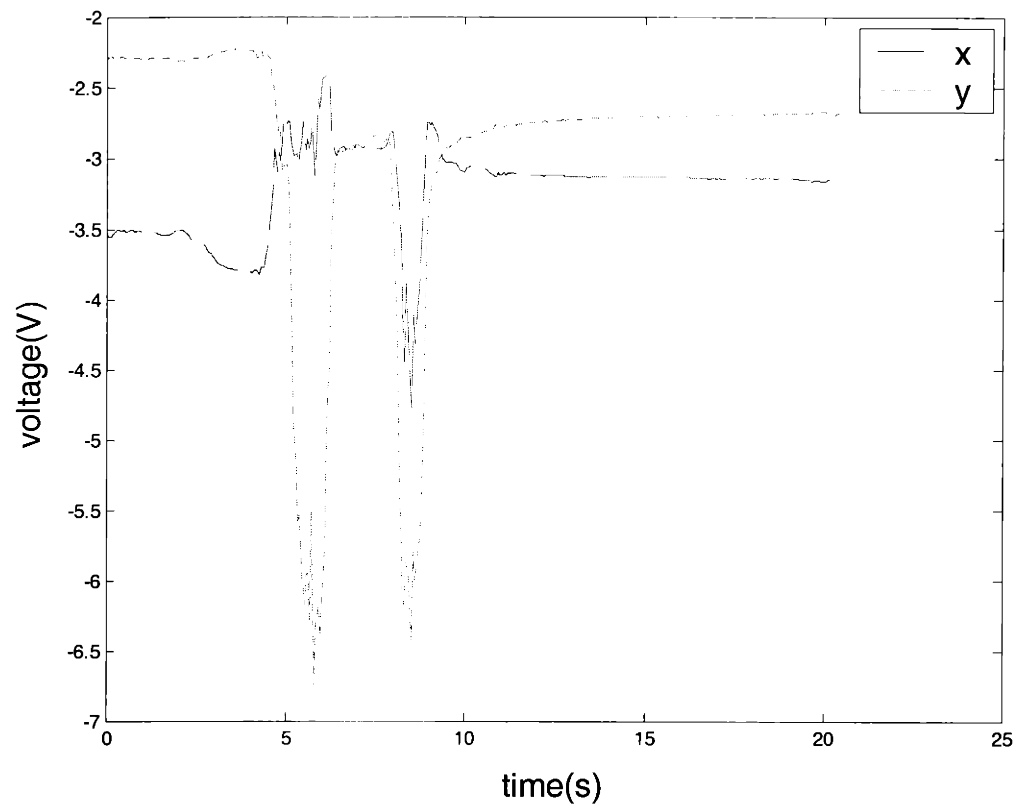

Figure 26: X and Y voltage vs. time for a line to the right followed by a 45 degree line up and right

An X also shows an interesting result. Writing an X in the America manner—some British write is using a v and then draw an upside-down v beneath it—is approximately a 45 degree line down and right and then a 45 degree line down and left. The plot for this letter then should be the x-coordinate peaking twice in the same direction and the y-coordinate peaking in opposite directions, which is what the plot in Figure 27 shows.

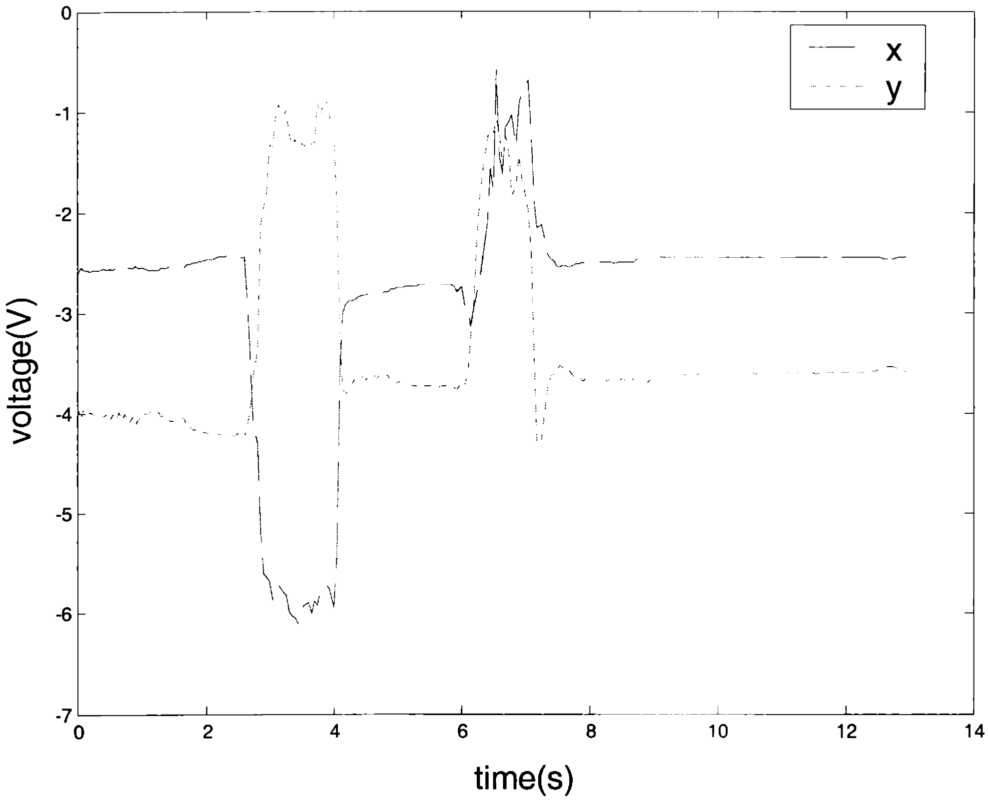

Figure 27: X and Y voltage vs time for the letter *X*

8. Discussion

The discussion of the future of this project takes two forms: improvements to the pen and the handwriting recognition portion of the project.

8.1 Improvements to the Pen

There are obvious improvements and further steps that could be taken with the pen. The PSD unit is bulky and weights the pen in an unusual way compared to most common pens. It is also tethered to the normalizing circuit at this stage and unless a more compact normalizing circuit and data storage are built, this pen is not a stand-alone unit which the specifications identify as a goal.

A problem that is occasionally visible is that the pen acts as an overdamped system. If there is a step-input force at the tip, the voltage exponentially rises to the peak value. The system is a spring-mass-damper system, with the spring and the damper in the O-rings and most of the mass in the LED so either exponential rise or oscillatory behavior is unavoidable, but perhaps a different O-ring material could tune the system to be critically damped and reduce the settling time.

Another important problem is that the steady state value does not always return to the same value it was before a peak. This might be due to the steady-state error of an exponential rise or decay system or it could be a problem inherent in the pen, which could be fixed.

8.2 Handwriting Recognition

A large portion of the viability of this project as a possible alternative to the current electronic pen products is the reliance on the innovative handwriting recognition idea. Many of the current products and much of handwriting recognition uses OCR, which matches the ASCII characters to an image of the writing. A few of the products digitize the writing into a vector format and do handwriting recognition from the vectors. The theory behind the handwriting recognition needed to format the data from this pen into ASCII characters is close to the vectorized format but it is still novel. The only data that is available from the pen is the direction vectors and the time. If one looks at the way one writes all of the letters, there are few ambiguities in the sequence of direction vectors that makes up each letter. Appendix B has all of the capital letters and the direction vectors this author uses to write them. Traditional OCR software might have problems with letters that look quite similar, like the capital letters U and V. If one looks at the data from this pen for U and V, shown in Figures 28 and 29, respectively, one sees that though the plots are similar, the x-coordinate of the U has a stronger, v-shaped voltage dip and there are points where the x-coordinate is essentially not changing where the y-coordinate is because on either side of a U is vertical line. The y-coordinate peaks of the U are shaped more like square-waves compared to the triangular-wave shaped peaks in the V plot. The transition between the positive and the negative peaks of the U shaped plot is more gradual.

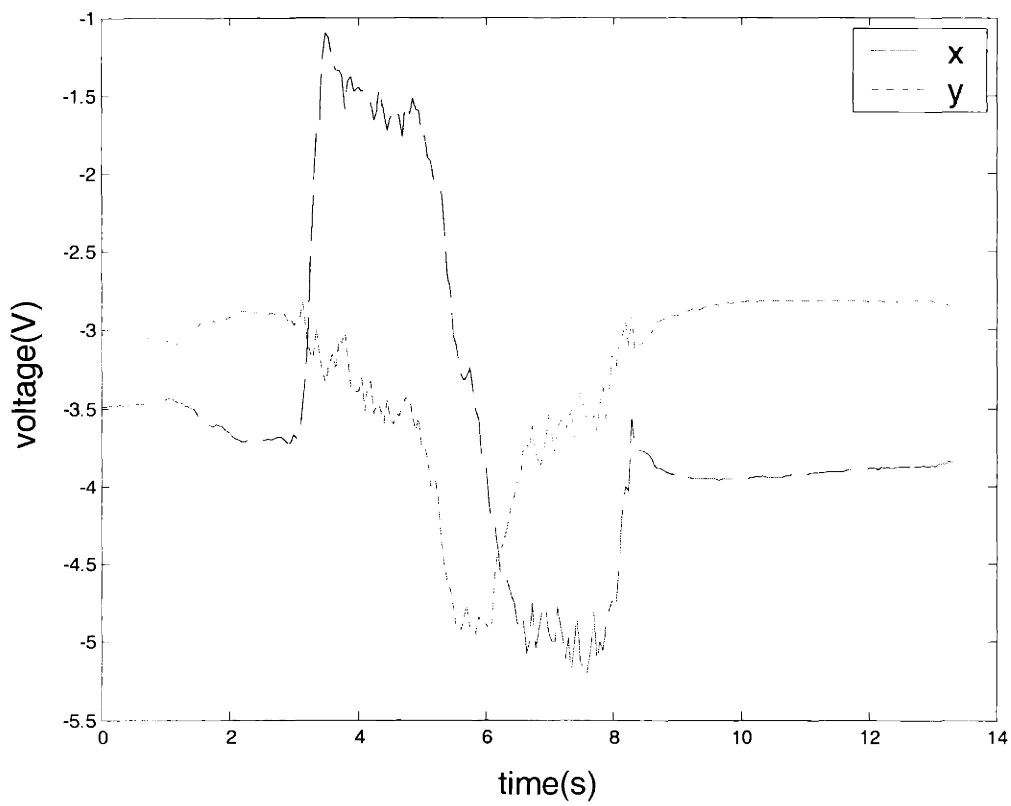

Figure 28: X and Y voltage vs. time for the letter *U*

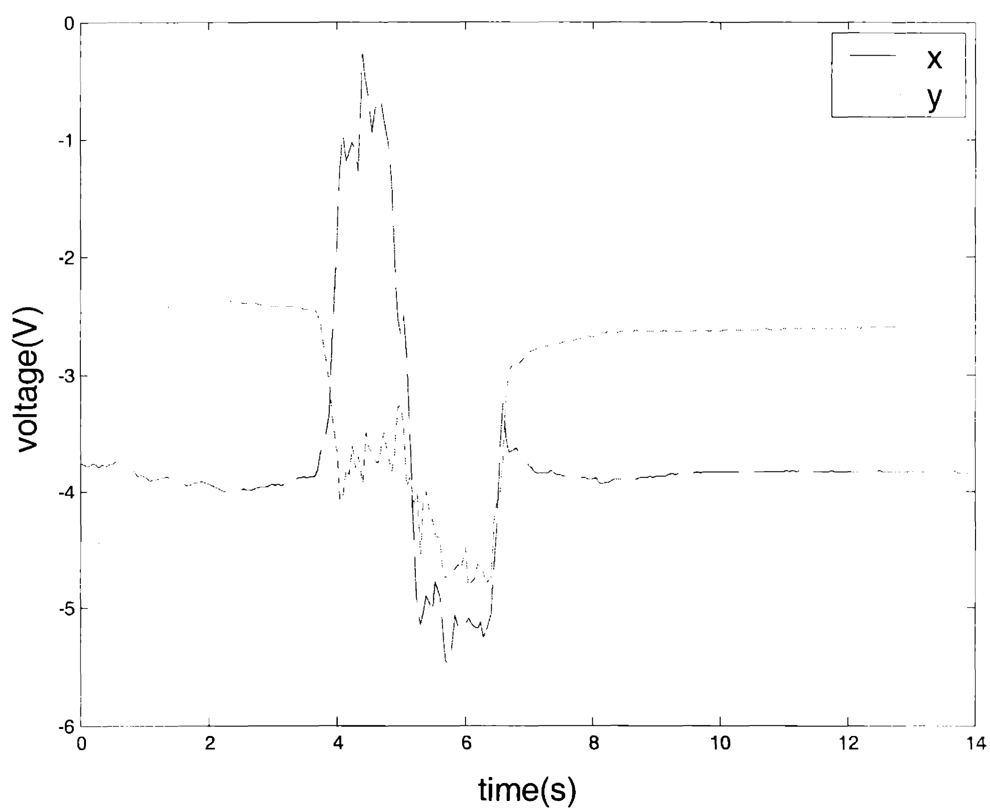

Figure 29: X and Y voltage vs. time for the letter *V*

Another possible ambiguous situation that might arise is the O and the Q. How could the pen know if lifting the pen to make the line on the Q isn't the beginning of the next letter? If one looks at the letters that begin with a down-and-right line, though, one sees very few possibilities: V, W, X and Y. Say one of the combination of letters OV, OW, OX or OY is being written, then the next stroke would be a down-and-left line—thus, a circle would be followed by a down-and-right line and then a down-and-left line. At least in the way this author writes, no letters start with a down-and-left line, so there is no ambiguity.

If one were to tackle numbers or mathematical symbols as well (which would be useful for lecture notes or notes from business meeting), then one begins to have ambiguous circumstances because many people write a 1 like a lowercase *l* and an integral sign like an *S* or a lower case *f*.

The software would need to be able to compare the direction over a periodically-readjusting time scale because people write at different speeds, but they usually have a consistent speed within words and sentences. Similarly there would need to be a changing relative zero for each axis; as pointed out below the steady-state value before and after an impulse might be different and the program should adjust for this. It would also have to be a trainable device because people write quite differently from one another. Two letters that come out looking the same can be written completely differently. Ideally there would be a chunk of initial training data and as the person uses the pen, the corrections he or she makes to the final product would be taken into account to further train the device. After the initial training the program would have a set of values that make up a range of possibilities for each letter and the program should adjust, according to user input, the percentage above and below this range that should be accepted as that letter. There would also have to be some algorithm for deciding if the data falls within two letter's ranges.

9. Conclusion

A pen product has been developed that takes writing and produces voltages proportional to the direction vectors of the writing. Tests show that the axes are uncoupled when forces are applied while the pen is held vertical and stationary but somewhat coupled while one is writing. Preliminary tests also show that the voltages are distinguishable between the lines in a box, a horizontal line and a diagonal line, the two lines in an X, and the letters U and V. Further work needs to be done in making the data from the pen more repeatable and in creating software to convert the direction vectors into ASCII characters.

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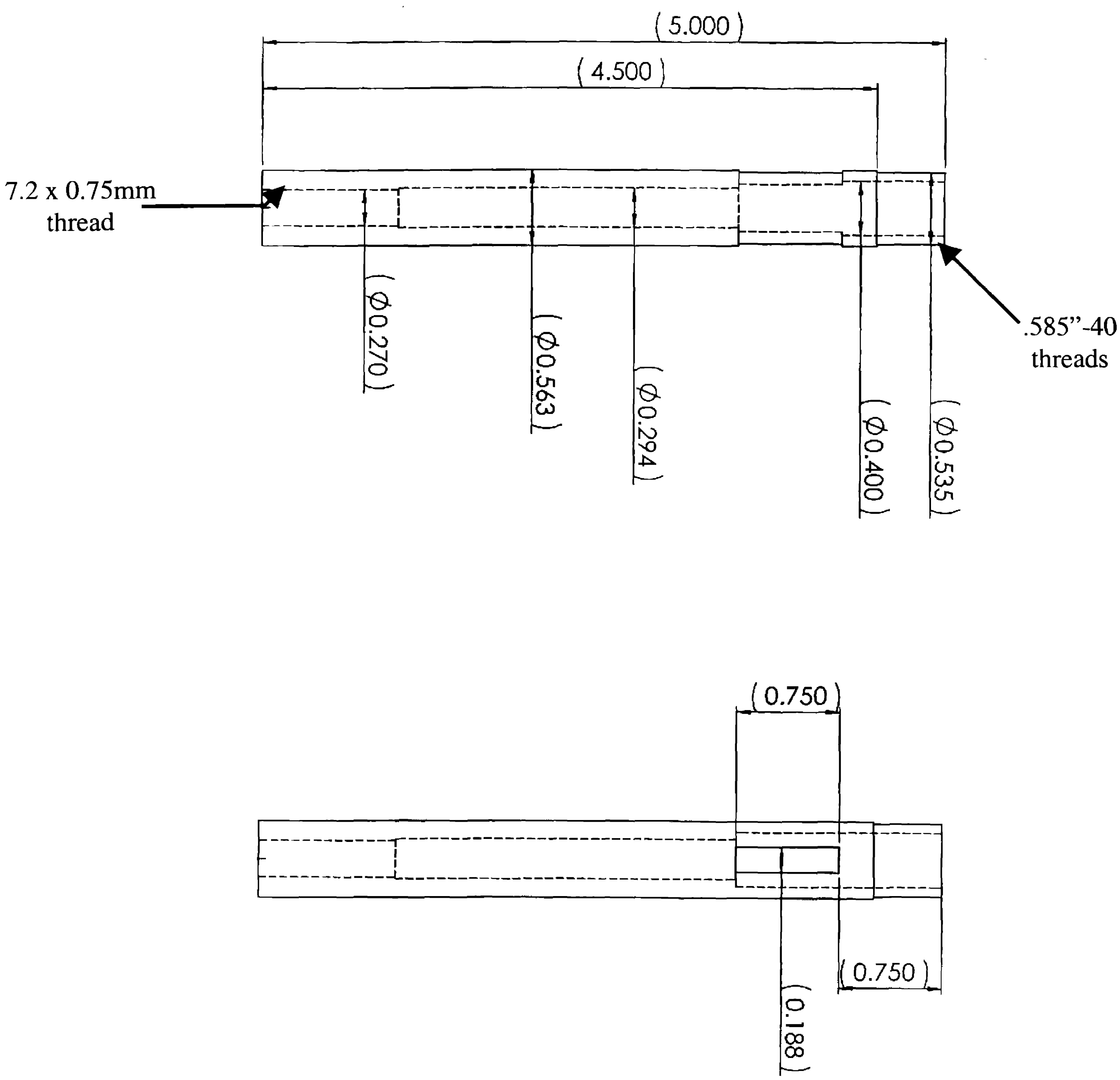
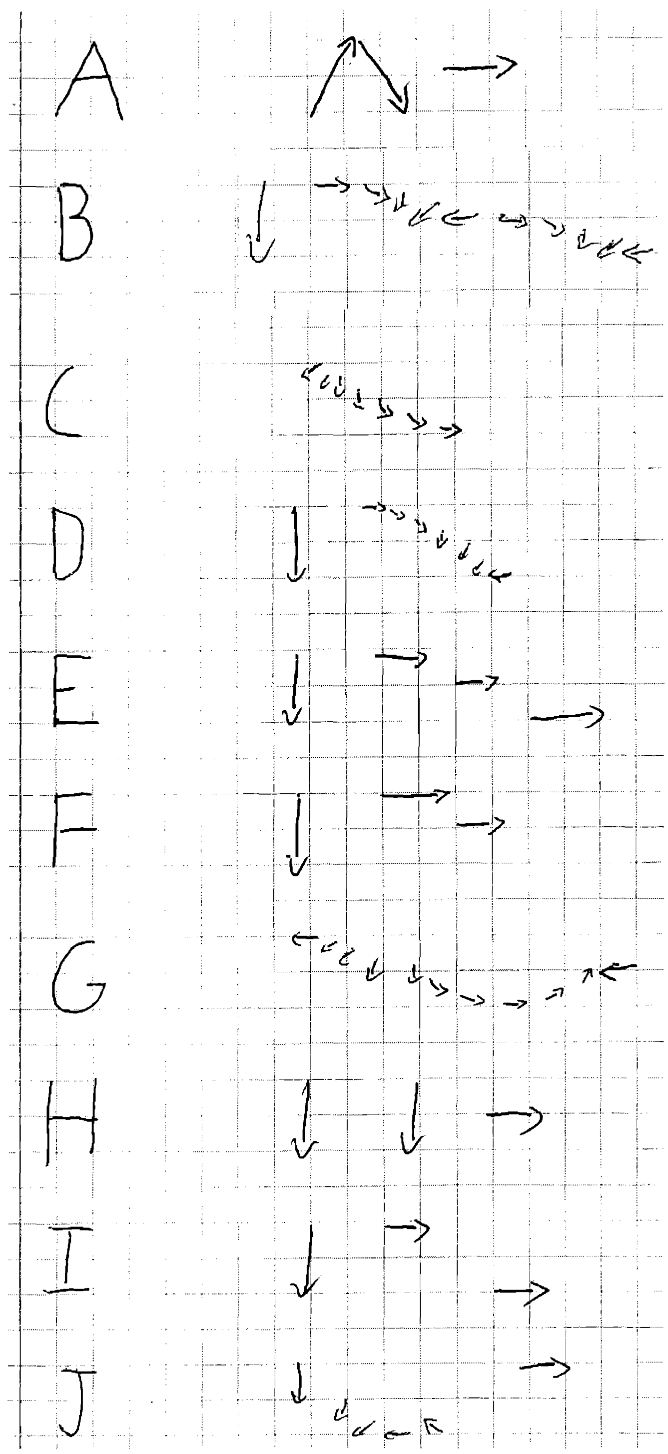
Appendix A: Mechanical Drawing

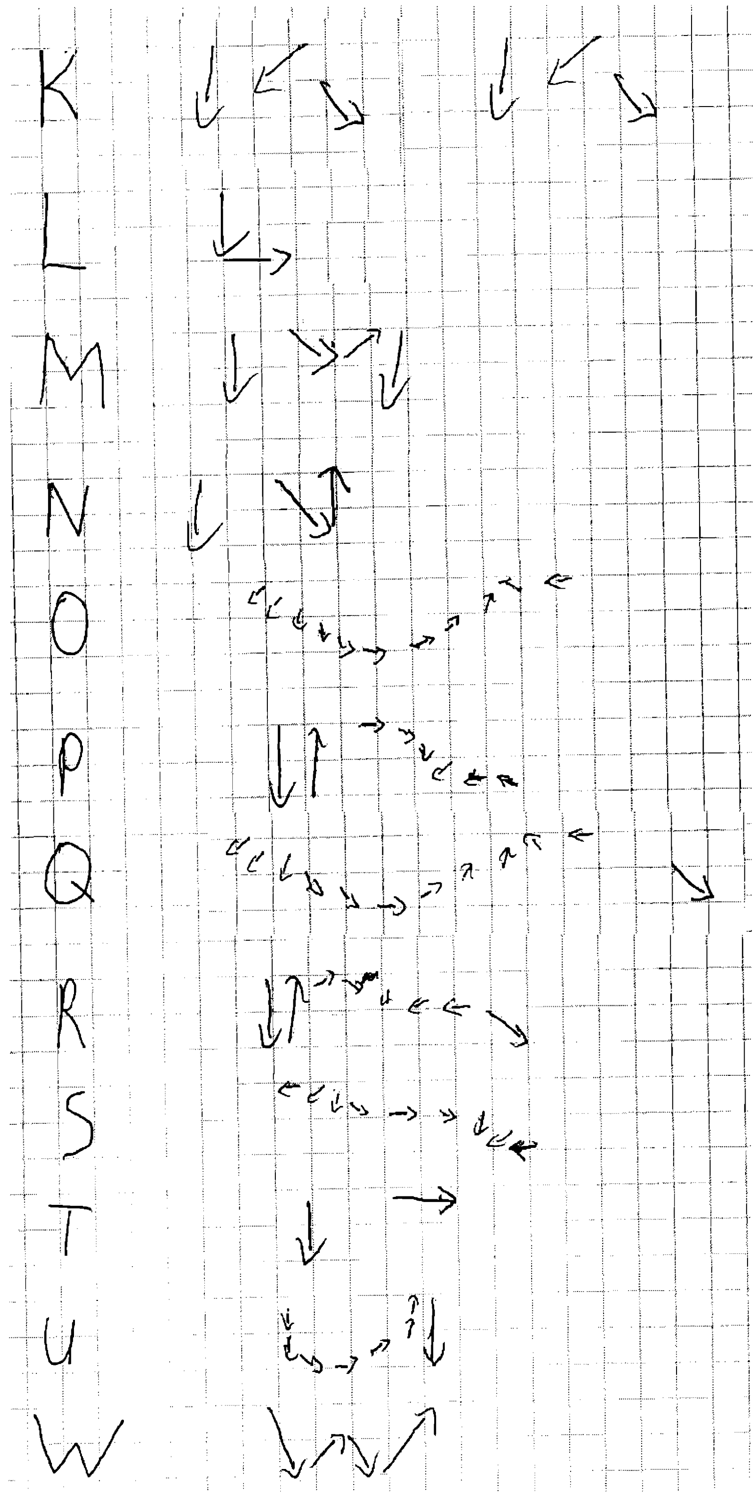
The following mechanical drawing of the pen body was used by the Central Machine Shop at MIT to produce the pen body used for this work. Units are in inches.

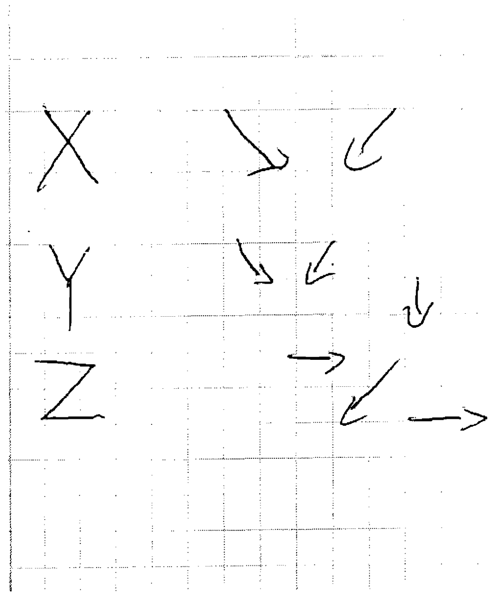


Appendix B: Directions Used in the Capital Alphabet

Here are sketches of how this author writes each letter of the alphabet, with the horizontal axis marking the passage of time as well as the x-axis.




K
L
M
N
O
P
Q
R
S
T
U
W


X
Y
Z