# Our Proposed Plan for the Development of a Cost Effective, Accurate, Digital Flow Meter Using Piezoresistive Technology

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**Fall, 2003-2004**

**November 24, 2003**

## Abstract:

Flow meters are a tool used to measure the volume of fluid that passes through a pipe in a given amount of time. Industry uses these tools in a variety of applications to keep track of their systems and to measure the volume of material that they are using. Presently, digital flow meters on the market command high prices, sometimes reaching several thousand dollars. Inexpensive alternatives to these flow meters do not provide a high level of accuracy. Our objective is to design a cost effective digital flow meter capable of taking readings over a wide range of flows. This meter will use piezoresistive technology with a microprocessor and electronic filtration to convert pressure input into a digitally displayed electronic readout. This flow meter will also have an analog output to interface with a computer for data logging.

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# Introduction:

## Background:

In most major industrial, residential, and commercial applications, keeping track of fluid movement is essential. In order to keep tabs on these arteries of industry, flow meters are used to provide flow measurements and analyze data. Current digital flow meters on the market command high prices (up to several thousand dollars). Inexpensive alternatives do not provide a high level of accuracy. This is because more cost effective devices are hard to read due to “eyeballing”. Producing an inexpensive ($20-40 production cost) digital flow meter that utilizes piezoelectric technology will provide precise readings at a reasonable price. Real world applications for digital flow meters would include areas where flow analysis is needed, such as HVAC systems, industrial piping, etc.

## Problem Statement:

Current inexpensive flow meters are not accurate due to imprecise displays, such as those found on manometers. These displays are too easily disrupted by noise. We feel that there is great interest in integrating cost effective digital technology in order to obtain a more accurate flow reading device. With cost effective digital flow meters, companies will be able to log and edit flow data electronically at a reduced price.

## Objective:

Our objective is to design a cost effective ($150 max retail price) digital flow meter capable of taking readings over a wide range of flows. This meter will utilize piezoresistive technology with a microprocessor and electronic filtration. A PC compatible analog output will also be an integral part of our design. Since the demand is spread out over many different applications, different design constraints such as pipe size will be taken into account.

## Current Technology and Market Need/Feasibility:

In order to further understand the scope of our competition, we conducted a patent search of current flow meter technology. We found some designs that incorporated similar features such as digital displays. However, none utilized piezoresistive technology in the manner in which we plan to use it. This search verified that our current design configuration has not yet been applied. The following is a brief summary of what we have uncovered.

Magneto inductive flow meters: This type of flow meter has a device that creates a magnetic field, which is normal to fluid flow. Electrodes placed opposite one another help to measure the voltage induced by fluid flowing through the magnetic field. This voltage corresponds to the flow rate.

Magnet and Transducer type flow meters: This type of flow meter uses fluid current to displace a magnetic device. The displacement of the magnetic device is read by a transducer, which produces a signal, which differs with changing flow rate.

Photosensitive type flow meter: This type of flow meter places a float within the flow of fluid. A rod attached to the float is tracked by photo sensors, which relay the displacement of the float to a microprocessor, which stores and processes the signal.

Ultrasonic type flow meter: This type of flow meter uses two probes to send ultrasonic pulse trains into the flow of water from probe to the other. Two pulse trains are sent and are then analyzed for difference in phase. The phase difference corresponds to a difference in travel times due to fluid flow velocity. A microprocessor samples the pulse trains and outputs a signal proportional to fluid flow.

Karman vortex type flow meter: This type of flow meter employs a thermal flow sensor and a correcting flow meter. Vortex flow meters measure process fluids by detecting the frequency at which vortices are shed from an obstruction (bluff body) in the process fluid line. Piezoelectric and piezoresistive sensors are mounted outside the flow line, parallel to flow, and act as transducers, converting vortex pulses into electric signals. This technology is the closest to ours but differs from it in the fact that we are not measuring the frequency of vortices. Our piezoresistors are mounted normal to flow instead of parallel, and we are measuring hydrostatic pressure.

After reviewing current flow meter designs, it became apparent that there is a market for our product. This is because our flow meter is economically feasible. An inexpensive (around $150 retail) and accurate flow meter with analog out will open up the market. We believe that it will be chosen over more expensive and less accurate models.

**Constraints on the Solution:**

The proposed flow meter design must stay within certain parameters in order to achieve a truly unique product. Final cost of the flow meter is a critical constraint of its design. The main goal of our team is to produce a flow meter that is both accurate and inexpensive. Many flow meters offered on the market offer high accuracy, but this feature usually comes with a high price tag. Examples of these kinds of meters are electromagnetic flow meters, which offer accuracy within +/- 0.5 percent and can cost upwards of several thousand dollars. Inexpensive flow meters typically use piston and rotameter technology. Accuracy for these meters may be within one or two percent, however, the readout device on these meters is analog and subject to human error from eyeballing. Costs of these inexpensive flow meters typically run from one hundred and fifty dollars and up. The proposed cost for our digital flow meter would be comparable to the costs of meters using piston and rotameter technology. The advantages to our meter would be its digital readout and analog output, which allows it to connect to a computer. Utilizing a digital readout over an analog readout allows for more precise readings and greater accuracy of measurement. The flow meter's analog output will allow for data logging via a computer.

Another design constraint that must be addressed is pipe size. To determine whether the flow meter will be designed to be inserted into a pipe, by way of an insertion tube, or bolted onto an existing pipe with its own flanged pipe piece, several meter designs will be needed to cover various pipe sizes. The best way to meet this constraint will be to design meter internals that are interchangeable with different length insertion tubes or with different diameter pieces of pipe. By making the sensing device modular, engineering costs can be kept to a minimum.

An important constraint that will require special attention is the sensitivity of piezoresistive sensors. Piezoresistive sensors have a strong drift offset with temperature changes. This means that when the sensor experiences large temperature changes, its resistance also changes. The result of temperature variation is decreased accuracy of the flow meter. This can be problematic when the sensor is subjected to fluids with high or low temperatures. However, these sensitivities can be compensated for with electronic circuitry. If constant temperature can be maintained, the piezoresistor will have good linearity.

Another concern is that the size of the sensor itself may prove to be a problem in that it could hinder the flow rate. If one were to have a one inch diameter pipe and a half inch diameter sensor in that pipe, it would occupy more of the cross sectional area than if that sensor was placed in a three inch diameter pipe. Therefore, we need to take this into account when designing.

The biggest constraint on this project is vortex flow meter technology. Vortex flow meters use piezoresistive technology, however in a much different way than we intend to. Vortex flow meters measure process fluids by detecting the frequency at which vortices are shed from an obstruction (bluff body) in the process fluid line. Piezoelectric and piezoresistive sensors are mounted outside the flow line and act as transducers, converting vortex pulses into electric signals. Though this is not how we intend to use piezoresistors, it is important to acknowledge the technology. Our main goal is to make sure our meter uses piezoresistors in a different manner.

## Statement of Work:

### Method of Solution:

Research: The first step in designing a digital flow meter with analog output is to come up with a basic design for measuring fluid flow. We have developed a design that we believe will be able to effectively and accurately determine the volumetric flow rate of a fluid in a pipe. With a basic design formulated, the next step is to research the primary technology that will allow us to accurately measure fluid flow within a known pipe diameter. We believe that using piezoresistive sensors can fulfill this criterion. Therefore, much time and effort will be devoted into understanding the construction, use, and technical limitations of piezoresistors. In addition to the piezoresistor, further research must be done to find a vendor or manufacturer of digital displays that will be compatible with the sensor and display the signal coming from it.

Selection of Technology: Once we have a working understanding of piezoresistive and digital readout technology, we will have to select manufacturers or vendors that sell the piezoresistors and digital display device that will work with or can be adapted to meet our current design needs.

Production and Manufacture: After we chose a sensor and display unit, a prototype of the design can be constructed. We will mount the sensor in the very center of the pipe, so that it is normal to fluid flow. This apparatus will most likely be screwed into the pipe wall via a threaded compression fitting so that fluid cannot leak out of the pipe. The insertion tube will be placed inside the pipe, however the body of the flow meter will remain outside of the pipe. The microprocessor and electronics of the flow meter, minus the piezoresistor, will be contained within the body. The digital readout and analog output will be mounted in the body for easy readings and connection via computer. A detail of our proposed design can be viewed in Appendix A.

Computer programming: To aid in calibration and testing, we feel that the use of a computer is essential. Therefore, we will write a computer program, probably in labview, to interface with the sensor to log data.

Construction of Test rig: To subject the prototype to actual fluid flow, a test rig must be produced. The test rig must have a set diameter and adjustable fluid flows. We feel that the easiest way to create a test rig would be to attach a simple garden hose to a water source with adjustable temperature such as a kitchen sink. The hose will be attached to a valve to give us the ability to adjust the fluid flow rate. The valve will be connected to a pipe of chosen diameter. There will be threaded openings at the top of the pipe every few inches along its length. This will allow us to test the difference in readings as flow develops in the pipe. The flow meter will screw into these openings via compression fitting. Openings unoccupied by the flow meter will be plugged so that water does not leak out of the top of the pipe during testing. Water will flow from the sink, through the valve into the pipe, exert a force on the flow meter sensor, and be collected in a receptacle of known volume such as a five gallon pail, all while being timed. The amount of water collected, divided by the time it took to collect it will give us the volumetric flow rate. The signal generated by the pressure of the fluid flow on the sensor tells us the behavior of our flow meter at that given flow rate.

Testing & Calibration: With a working prototype, computer software, and a test rig, the first step of the testing phase will be to check the maximum output signal range. This will most likely be accomplished by subjecting the sensor to higher pressures than it will normally encounter under usual conditions. The next step is to subject the prototype to actual fluid flow. With the prototype mounted in the test rig, we will subject it to known flow rates, which will range from zero to the maximum flow rate that the unit is designed for. For each flow rate, the corresponding output from the flow meter will be logged. From these readings, the flow rate versus resistance curve can be determined. With this curve, we can calibrate the prototype flow meter.

Further Testing & Refinement: After the prototype has been calibrated, we will begin to scale up the pipe's diameter in order to see how the flow readings change with respect to our initial test results. The first tests will be done with a one inch diameter pipe, which is the approximately the same size as the garden hose in our test rig. We will repeat the experiments with two and three-inch diameter pipes. After these tests have been conducted, we will be able to calculate the effective pipe diameter range for the sensor. From this we can go back and make any design changes if necessary. It is also our belief that we will be able to determine an algorithm from the logged data to reduce noise and make the readings of our sensor more accurate.

## Alternative Solutions:

One concept of design for a digital flow meter utilizes piezoelectric technology with a microprocessor and electronic filtration. In this design a piezoelectric crystal will be mounted into an insertion tube, which will then be installed into a pipe perpendicular to the flow. The inlet of the insertion tube will be placed at the center of the pipe allowing the crystal to experience the maximum force.

The piezoelectric effect is an effect in which energy is converted between mechanical and electrical forms. When pressure is applied to the polarized crystal the resulting mechanical deformation causes an electrical charge. Each cell of the crystal has an electric dipole, and the cells are oriented so that the dipoles align, shown in Appendix B. This creates an excess charge on the surface causing free electrons to be attracted from the atmosphere making the crystal electronically neutral. When force is applied to the piezoelectric crystal, deformation will occur. This will cause a disruption in the orientation of the electrical dipoles resulting in the loss of the crystal's electrical neutrality. This excess surface charge will turn into a voltage across the crystal. A drawing of this can be seen in Appendix B.

In order to utilize this physical principle, the surface charge on the crystal must be measured. This can be done by placing the crystal between to metal plates, creating a capacitor. The external forced applied results in a charge that is a function of the applied force. This measure of voltage can then be sent to a microprocessor, which will use the data to calculate the force that has been applied to the crystal. This information can then be sent to a digital display at the location of the tube, as well as be sent to a main computer, which can log all information calculated.

The main problem with this design lies in the piezoelectric crystal. The excess surface charge that is generated by the crystal deformation due to force is only temporary. Once given time to react free electrons from the atmosphere will be attracted to the crystal allowing the dipoles to re-align. This means that a constant force (velocity) can only be measured during its initial impact with the crystal. Also, any increase/decrease in velocity can only be measured as a change in velocity instead of actual velocity. Due to this reasoning piezoelectric crystals are more ideal for measuring accelerations.

## Project Management and Scheduling

A detailed timetable, which follows our design and production steps, is provided in Appendix C.

## Economic and Budget Analysis

### Economic Analysis:

Design and manufacturability costs for our proposed flow meter should be relatively inexpensive. It is our policy to initially design our prototype in 3-D CAD software. In this step we will ensure all parts of the design will fit together correctly the first time. Modeling the flow meter components in CAD software cuts down on manufacturing costs because all the parts will be made to spec the first time. Modeling the components and finite element analysis testing can be completed in sixty hours. With two team members working on this project, the total cost for designing the flow meter in CAD will cost six thousand dollars.

After all the parts have been modeled and verified, manufacturing of our insertion tube and casing can begin. Insertion tube manufacturing will take place in the Drexel machine shop. This design will be simple and should not require many hours to make. Costs for manufacturing will be covered by the sixteen hours of allotted machining time for our team. There are two options for manufacturing the casing for out flow meter, machining it or injection molding it. The first option is to have the machine shop machine a casing for the flow meter's internals. Advantages to this approach would be less expensive startup costs due to the elimination of a mold needed for the casing and purchasing an injection mold machine. Disadvantages to this approach are long manufacturing time of the casing and long term costs for machining the casing. Injection molding the casing deals with the one time large investment of purchasing an injection mold machine and a mold. For this reason, we prefer the machining of the casing for the initial prototype. We believe that the casing can be machined within the allotted sixteen hours of machine shop time. Table 1 in Appendix D lists our design and manufacturing costs.

**Budget:**

Since it is our goal to design a flow meter that can be sold for around one hundred and fifty dollars, we feel that we can prototype this meter on a fairly tight budget. A budget of three hundred to five hundred dollars maximum has been placed on purchasing components by our advisor, Dr, Cho. Manufacturing costs should be covered by our allotted machine shop time. Piezoresistive sensor testing, as described in the testing section, will not require the purchase or use of testing machines. Programming the microprocessor will require significant testing of the crystal. CAD design of our flow meter would cost six thousand dollars. We believe that the flow meter can be developed and tested for around twenty-five thousand dollars. Table 2 in Appendix D lists our budget costs.

# Societal and Environmental Impact:

## Societal Impact:

In designing a product, one has to take into account all of the effects that its use may cause. This analysis should also include the impact that the product in question may have on society. When reviewing the use of our product, we feel that there will be little to no impact on the general populous. The only area that we can see any impact occurring from our digital flow meter is in industry. We feel that the value and cost effectiveness will cause almost any company that deals with fluid flow through pipes to at least think about using our product. Given low cost and high accuracy, we feel that most companies will purchase our product. We do not foresee a major change in the way that industry moves fluids or does business. The only possible change that we can predict is that companies might incorporate more fluid measuring technology in places where it was thought economically unfeasible. Outside of that, we feel that our product will not impact society or industry further.

## Environmental Impact:

An important aspect of any designing process is the impact the final product makes on the environment around it. These can range from potential hazards of the materials used, the application it was designed for, and air pollution during production. From tractor-trailers to key rings, it is a design constraint that is easy to overlook.

We recognize that it is the responsibility of the engineers and designers of any product, to have incorporated a certain level of environmental concern when making choices. Since our design calls for a multitude of components, some of which we still have to finalize, we have and will continue to be responsible with each choice we make.

Upon the initial review of our process, we hypothesized that there is very little chance of any kind of environmental contamination or disturbance. We have based this on the fact that we have no chemical components (i.e. oils, gases, and other harmful chemicals) in our current design. We do however; realize that since we are making a flow meter that will work in a variety of pipes, there is a chance that the insertion tube could be placed into a pipe that is carrying drinking water to a town, or chemicals through a power plant. Because of this, we will fully research which material to use in the construction of this piece. This information will allow us to select a material that will be cost effective, easily machined, and provide little to no effect to the environment.

Again at this point, it does not appear that there will be any significant risk to the environment. Once we have finalized the prototype we will be able to fully assess its impact and provide warnings, constraints, and even design changes that will remedy any unforeseen problems.

**Conclusion:**

Inexpensive flow meters which are presently offered do not provide a high a level of accuracy, while accurate digital flow meters can cost several thousand dollars.
The world's technological development is increasing at rapid rates. Unfortunately, this new technology comes with an increasingly large price tag. If new materials and new methods can be developed to save on overall cost then perhaps a cheaper alternative can be found. By integrating piezoresistive and microprocessor technology into a feasible design, an affordable digital flow meter with analog output can be produced. The merging of these technologies with new innovative techniques will allow everyone from scientist to students to have access to cost-effective, accurate and reliable flow meters.

# References

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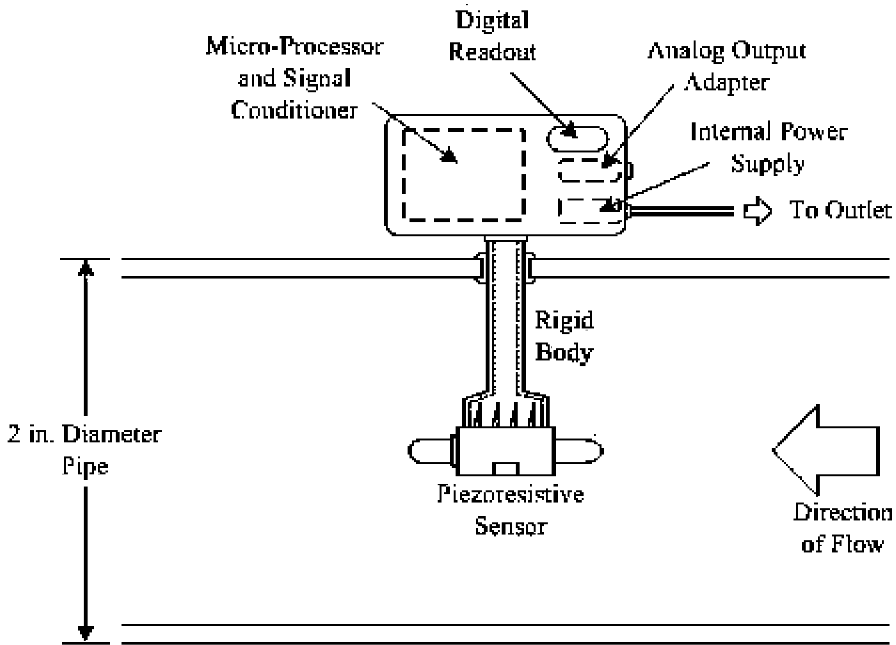
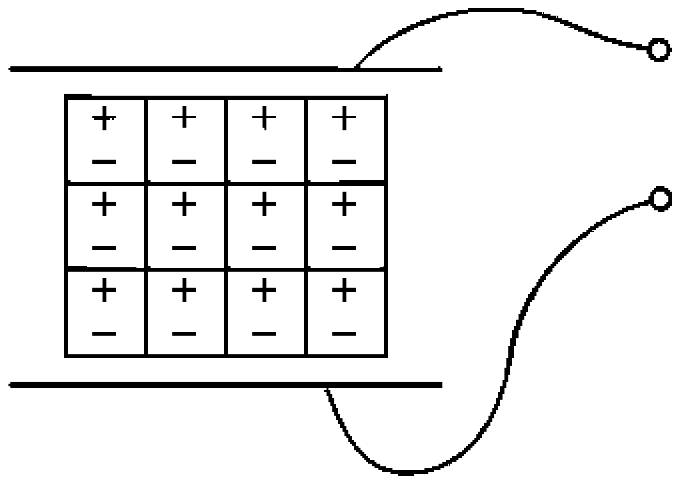
# Appendix A: Digital Flow Meter Design



# Appendix B: Piezoelectric Sensor



# Appendix C:  Gant Chart

Gantt Chart

| Activity | | Date Started | Date Finished | September | October | November | December | January | February | March | April | May |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Fall Semester | | | Winter Semester | | | Spring Semester | | |
| Pick Project | | 22-Sep-03 | 29-Sep-03 | | | | | | | | | |
| Find Advisor | | 29-Sep-03 | 6-Oct-03 | | | | | | | | | |
| Write/Submit Pre-Proposal | | 6-Oct-03 | 20-Oct-03 | | | | | | | | | |
| Pre-Proposal Accepted | | 29-Oct-03 | 29-Oct-03 | | | | | | | | | |
| Outline the Next Year's Events | | 30-Oct-03 | 1-Nov-03 | | | | | | | | | |
| Write Official Proposal | | 29-Oct-03 | 24-Nov-03 | | | | | | | | | |
| Piezoresistor Sensor Selection | | 1-Nov-03 | 12-Nov-03 | | | | | | | | | |
| Selection of Micro-Processor | | 15-Nov-03 | 15-Dec-03 | | | | | | | | | |
| Feasibility Testing of Crystal | | 1-Dec-03 | 31-Jan-04 | | | | | | | | | |
| Program/Testing of Micro-Processor | | 1-Jan-04 | 31-Jan-04 | | | | | | | | | |
| Create Computer Interface with Sensors | | 25-Jan-04 | 15-Feb-04 | | | | | | | | | |
| CAD/CAM design of Components | | 1-Feb-04 | 28-Feb-04 | | | | | | | | | |
| Build Prototype | | 1-Mar-04 | 31-Mar-04 | | | | | | | | | |
| Test Prototype as a System | | 15-Mar-04 | 30-Apr-04 | | | | | | | | | |
| Fall Presentation | | 1-Dec-03 | 5-Dec-03 | | | | | | | | | |
| Winter Report | | 1-Feb-04 | 8-Mar-04 | | | | | | | | | |
| Winter Presentation | | 1-Mar-04 | 5-Mar-04 | | | | | | | | | |
| Final Report | | 1-Apr-04 | 10-May-04 | | | | | | | | | |
| Final Presentation | | 17-May-04 | 21-May-04 | | | | | | | | | |

# Appendix D: Tables

| Component/Action | Supplier/ Contact Info | Cost | Date Ordered | Date Received | Additional Comments |
|---|---|---|---|---|---|
| Piezoresistive Sensor | | | | | Still looking, but this one seems to fit |
| Signal Amplifier | | | | | May be needed |
| Micro-Processor Unit | | | | | Includes multiple components |
| Power Supply | | | | | Need to determine Correct Sensor and in turn correct Micro-processor |
| Display/ Analog Outputs | | | | | |
| Housing/ Pitot Tube | | included under machining | | | Planned to have machined |
| | | | | | |
| Prototyping/ Machining | Drexel machine lab | $50/hr | | | -Granted 16 hours<br>-Includes Housing, Pitot Tube, Test Rig |
| | | | | | |
| Engineering Costs | Senior design team 11 | $50/hr X 4 Engineers | - | - | Depends on if advising costs are needed from an outside source for a particular issue |
| Lab Time | Various testing facilities | $50/hr | - | - | Depends on possible help from proficient lab workers |

**Table 1**- A real-time cost analysis table that will help us to view costs as well as provide a look up chart for key pieces of information.

| Components of our budget | Time expectation to complete | Cost | Anticipated dates of work |
|---|---|---|---|
| Component Budget | | $300-$500 maximum | |
| CAD Design | 60 hrs | $6,000 | 12/10/03 - 1/10/04 |
| Testing | 60 hrs | $9,000 | 12/10/03 - 1/10/04 |
| Programming | 40 hrs | $4,000 | 1/10/04 - 2/10/04 |
| Manufacturing | 16 hrs | Free | 2/10/04 - 3/10/04 |
| Building | 20 hrs | $4,000 | 3/10/04 - 3/30/04 |
| Verifying | 10 hrs | $1,000 | 4/01/04 - 4/30/04 |

**Table 2** – Budget costs