



ECE480 Team 10 Request for Proposal
Screw Machine Condition Monitoring

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Executive Summary:

Great Lakes Controls & Engineering has identified the problem of monitoring tool wear for their clients. Specifically, it is necessary to monitor the wear of a tool in a lathe so as the tool becomes dull, it can be switched out before producing faulty parts.

Team 10 proposes a solution which includes a Nordmann GmbH & Co. force sensor and an adjustable band pass filter to detect frequency range. This signal can then be processed with a microcontroller to produce the correct DC output.

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1. Introduction

The customers of Great Lakes Control and Engineering have identified the problem of tool monitoring in a 6-spindle New Britain lathe. Currently, the machine will produce a set number of parts, but because of environmental inconsistencies, the number of parts a given tool can produce varies. As a result, a large number of bad parts are often produced due to dull tools.

ECE480 Team 10 has been tasked with creating a system to detect dull tools before they begin to produce faulty parts. The system must not interfere with regular machine operation, only requiring the lathe to stop to replace parts. It must also indicate the condition of one, specific tool without interference from parts being machined nearby.

2. Background

Tool condition monitoring is a topic that has been approached by many researchers and engineers without any significant results. Due to the complexity of tooling machines and given that some of these machines are out of production, a device that would accurately detect tool life has been difficult to make. After doing some research into different tool condition monitoring systems and how others have approached the problem the team came across a wide variety of results summarized in the following paragraphs. However, we will start by first introducing what tool wear is and how tool life is modeled mathematically.

a. Tool Wear According to Mikell P. Groover's Fundamentals of Modern Manufacturing, a cutting tool can fail in three possible modes: fracture failure due to excessive cutting force, temperature failure due to material softening at high temperatures, and finally gradual wear that what we are concerned about(2010, Groover).

Gradual wear can be either crater wear which is "a wear mechanism in which pits are formed in the wake face of the cutting tool which is perpendicular to the work piece" or flank wear which is "direct abrasive wear of the cutting edge surface parallel to the work piece" as seen in figures 1 and 2 from (2012, Cook).

In terms of flank wear, which is what we are looking at, one can approximate the tool life according to the Taylor tool life equation where:

$$vT^n = C(T_{ref})^n$$

where:

v = spindle cutting speed

T = tool life

n and C depend on feed, depth of cut, work material, tooling, and the tool life criterion used.

b. Monitoring Methods The current method used for detecting dull tools on the machine depends primarily on the operator's ability to listen to the sounds coming out of the machine as it operates. The tool produces a specific high pitch sound when it is dull. This method is inaccurate as it does not take into account different factors, such as what material is being machined or how long the tool has been used for. According to the team's sponsor, the operator often estimates the tools' life on the amount of parts it produced (80,000 in the case of the carbide boxing tool on aluminum).

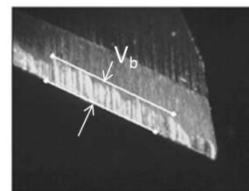
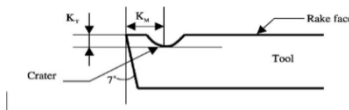


Figure 2: Flank Wear

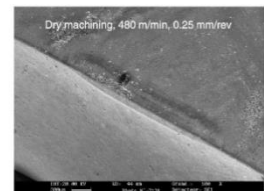


Figure 2: Crater Wear

A previous ECE 480 team attempted this project previously, but did not produce a system that was satisfactory to the customer. The team primarily focused their efforts on recording sounds within the audible range using a low cost microphone. Their device was ineffective because their use of a single, low cost microphone was not directional enough to sense a single tool and could not pick up the very high frequency emissions that indicate a dull tool. Additionally, their analysis of the signal was based on a recording of the lathe in operation that they took with an iPhone.

Previous research in the field has presented theoretical solutions to the problem. These include:

- Sensing of transmitted sound with microphones
- Acoustic emissions sensing
- Direct image analysis of tool
- Tool strain force sensing
- Power consumption monitoring
- Vibration/Acceleration sensing

3. Objectives or Design Specification

The sponsor of this project, Great Lakes Control and Engineering, states the project description as following:

“The purpose of the project is to provide condition monitoring of a standard automatic lathe machine to provide quality improvement of machined parts.

Faulty parts are produced when the cutting tools begin to dull or spindle bearings wear beyond nominal limits. Condition monitoring would provide a way to identify dull tooling and worn out spindle bearings and proactively replace each specific component prior to production of faulty parts and lengthy down time of machine.”

The product design specifications, according to the sponsor:

1. *Use a sensor(s) to identify sharpness of tool life as operation of the machine is ran.*
 - a. *Sensor must only read one tool operation.*
2. *Wire cutting operation not in progress, system will have ability to monitor spindle bearings of machine*
3. *Output a 0 to 10 volt analog signal of the tool life to the Programmable Logic Controller (PLC) of the machine.*
 - a. *Map signal to 0-100% of tool life remaining.*
4. *Ability to eliminate background noise and focus on one tool inside the automatic screw machine.*
5. *Run off supplied 24VDC.*
 - a. *4-pin control cable connector ran from main control panel to device for power and analog signal.*

6. *Sensing device must be compact to fit inside machine without interrupting process and withstand harsh environment.*
 - a. *Size should be less than 2" x 2" x 2".*
7. *\$250 budget for multiple units made.*

After meeting with sponsor, it came to the team's attention that the machine is a 6 spindle New Britain machine that has all 6 tools working at the same time. The sponsor also specified that the sensing method would be by detecting the transmitted sound coming out of the tool as it operates. The sensor should only detect the sound coming out of one tool (2-inch by 2-inch area) from a distance of 2-feet away.

Finally, the deliverables according to the sponsor:

1. *A sensing device to place inside the machine.*
 - a. *An auto calibration routine for new tools or location of sensor change.*
 - b. *User-friendly operator interface for set up.*
 - c. *Accurate 0-10 VDC output signal to main PLC for tool life of specific tool.*
 - d. *Device must have ability to auto-reset itself to continuously monitor tool life.*
 - e. *Device must be able to survive in harsh conditions that are inside machine (coolant, metal shavings, etc.)*
2. *Documentation to place and run the system by operator with high school diploma.*

The fundamental components of such a system must include a sensor, a system to convert output from the sensor into usable data, an algorithm to analyze the data in terms of tool life, and a mechanism to map tool life to a 10 Volt DC output. Figure 3 shows a basic block diagram of a system composed of these elements.

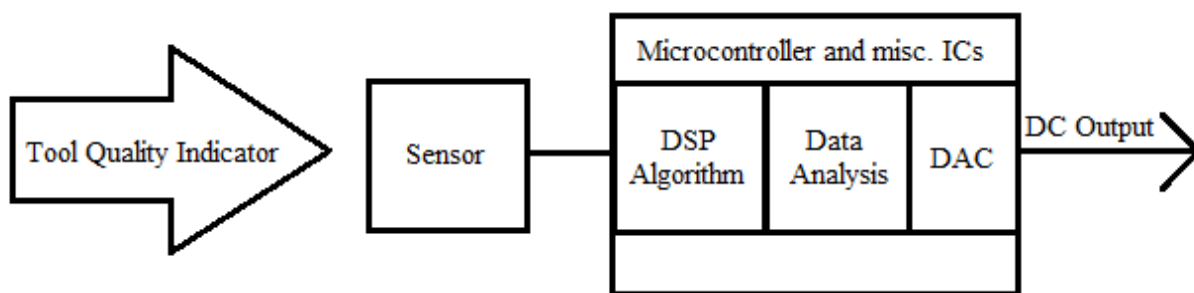


Figure 3: Basic block diagram of system components

The following sections of this paper will evaluate options available for each of these system components.

4. FAST Diagram

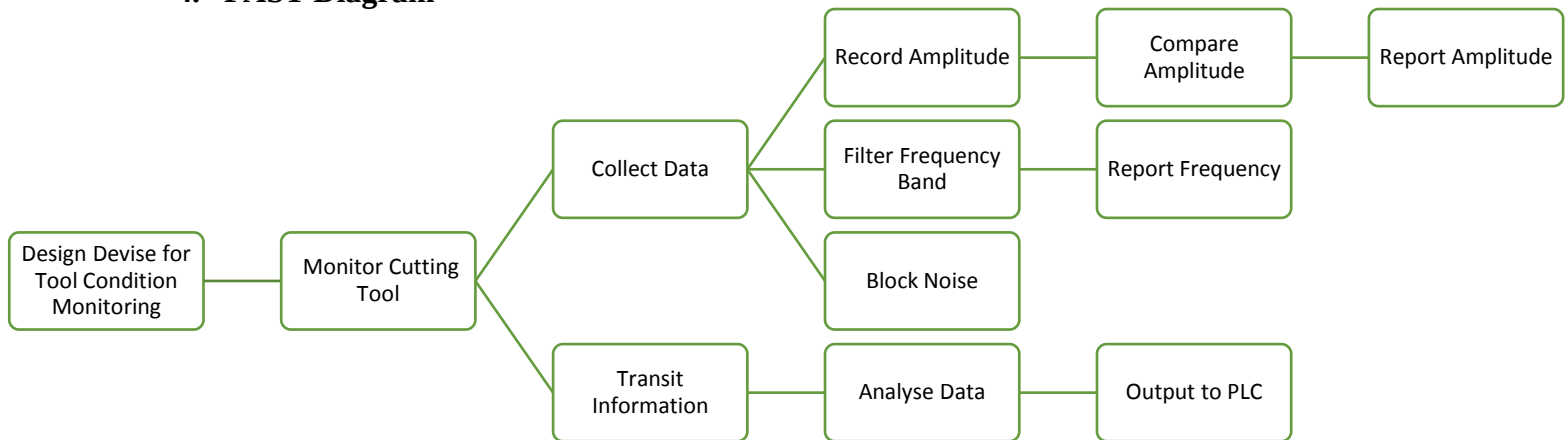


Figure 4: FAST Diagram

5. Conceptual Design Descriptions

Sensing

The first step in creating a tool monitoring system is effectively sensing the condition of a given tool. The primary challenges present are 1) to determine the most effective method of determining tool quality and 2) isolating the response of one tool from those operating in close proximity around it.

a. Audio Monitoring: The first solution we evaluated was audio monitoring because this was the customer's suggested solution. Within the scope of audio monitoring, significant design challenges existed. The primary concern is precision in monitoring a single tool of many operating simultaneously on the lathe. The design specifications indicate that the sensor will be 2' away from the lathe and must listen only to lathe operation in a 2" x 2" square. This means that the total angle of incidence of a microphone must be 4.76 degrees (See Figure 5).

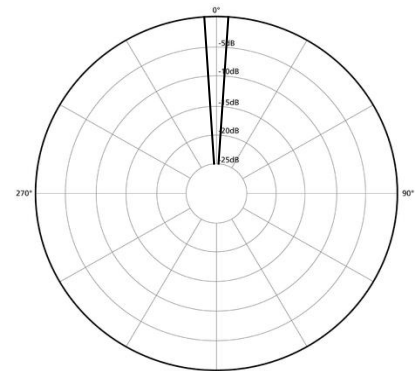


Figure 5: Approximate representation of the polar pattern needed for tool monitoring. Note: does not include magnitude or frequency response information

To understand the directionality of microphones, we can analyze the polar patterns of commercial microphones. The polar pattern of a microphone is a polar coordinate

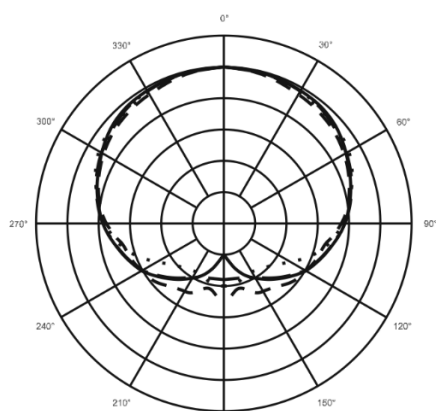


Figure 6: Typical cardioid phase plot of a commercial microphone ("Polar Patterns")

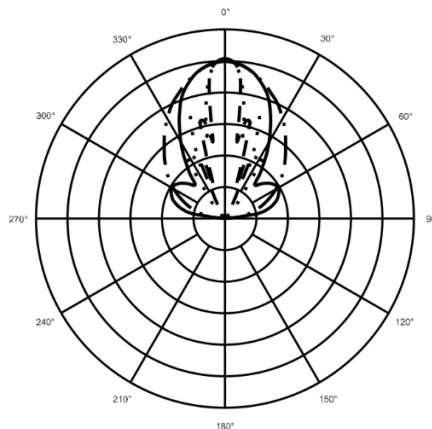
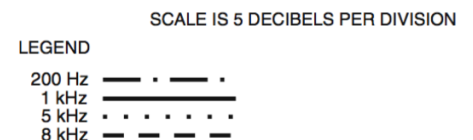


Figure 7: Typical polar pattern of a commercial shotgun microphone ("Polar Patterns")



plane where the sensitivity of a microphone can be plotted relative to angle of incidence (“Polar Patterns”). For example, a microphone may be more sensitive to sound produced directly in front of it rather than to the side or behind the microphone. Further, the polar pattern of a microphone varies with the frequency of sound it is picking up. The most common polar pattern is a cardioid, which picks up sound occurring in a 120 degree range, as shown in Figure 6.

The microphone with the narrowest polar pattern is a shotgun microphone. This decrease in pickup angle is achieved by attaching an interface tube, a long tube with horizontal slats, on top of a microphone. The effect of this addition is that off-axis sound can only reach the diaphragm of the microphone through the slats, and then can partially cancel out other off-axis sound (Robjohns & White, 2013). This technique reduces the pickup angle to approximately 30-60 degrees (See Figure 7) (Polar Patterns). Shotgun microphones are not a reasonable solution for this project because a typical pickup angle is still significantly larger than the requirement and because they do not perform well in confined, highly resonant environments (Robjohns & White, 2013). Additionally, the addition of a long tube to the end of a microphone, as is necessary to make a shotgun microphone, is not functional in the confined space that the sensor must be placed. From analyzing the polar pattern of most commercial microphones, a single microphone would not be able to capture the sound of a single tool with necessary accuracy.

Another possible solution is beamforming, or spatial filtering. Beamforming refers to the use of an array of sensors, microphones in this case, and an algorithm to process data from multiple inputs to estimate the direction from which a signal originated (Van Veen & Buckley, 1988). Recent research using a 24-channel microphone array to locate the source of sound with reasonable accuracy (Kagami et al., 2004). However, this approach will also not be viable in a highly resonant space. Additionally, there would be significant costs to obtain the necessary equipment, the time required to develop necessary algorithms may prove to be outside of the scope of this project, and the size of a large microphone array may not be suitable for this application.

Laser vibrometry is another technique that couple prove to be a possible solution to the problems of a narrow sound capture and a highly resonant environment. Laser vibrometry works by directing the beam of a helium neon laser through a beam splitter, then directing one beam toward the object to be measured. When the beam is reflected back to the system, the frequency shift caused by reflection from a moving object can be measured relative to the frequency of the original beam (“Basic Principles...”). In this way, the velocity at which the object is moving can be calculated. Laser vibrometry is very precise in terms of measuring a specific location without interference from nearby activity. However, systems are expensive, not robust enough for the volatile environment inside the lathe, and generally larger than the customer specifications for this project.

Overall, we determined that audio related solutions are not feasible for this application and therefore decided to continue research on other possible solutions.

b. Power Consumption Sensors: Another monitoring option involves the power consumption of each of the rotating chuck motor. During the cutting operation, the motor will consume more power to maintain spinning at constant RPM, than with no load present. A baseline measurement would be taken at speed with no cutting operation, then again with a sharp tool making the cut. The difference in the two power readings would define the most effective band of use for the tool. However, because the six spindles on the lathe are driven off of a single

common motor, it is impossible to measure the power consumption of each individual spindle. Therefore, it is not a solution for this type of tool monitoring (Trail).

c. Acoustic Emission: Acoustic emissions (AE) “may be defined as the stress or pressure waves generated during dynamic processes in materials,” according to the American Society for Testing and Materials (1971). Acoustic emission sensors therefore detect “short, rapid, release of energy in the form of a transient elastic wave” (“Acoustic Emission Technology”). AE sensing involves the measurement of these vibrational waves within a solid when irreversible deformation occurs. This deformation could be a crack in a material that is caused by different loads and stresses put on the object. AE waves are usually very high frequency (100 KHz-1 MHz) and need direct contact sensors to accurately detect. These signals may or may not be pre-amplified and filtered before further processing occurs by other electronics. They have been generally used to detect fractures due to strains on large structures such as bridges and high rise buildings.

When monitoring tools using AE for a multi-spindle lathe, there are two possible choices for sensors. The first type of sensor uses a cooling or lubricant jet as a waveguide. The sensor is placed on the cooling line directed at the cutting operation, and the vibrations are captured by the constant flow of coolant from the tool to the sensor (Trail). The second AE sensor is simply placed on the tool as close to the operation as possible and the emitted waves are measured directly through the tool itself. Examples of these two sensors are shown below in Figures 6 and 9. These and similar comparable models of sensors are all capable of producing a 0-10 Volt output and can sense a range of frequencies of up to 1 MHz.

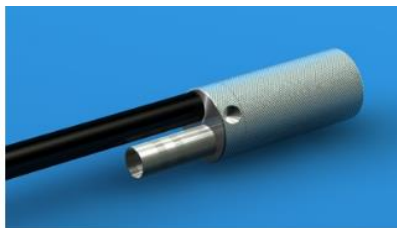


Figure 8: Nordmann SEH sensor
 (“Acoustic and Vibration”)



Figure 9: Nordmann SEA-mini
 sensor (“Acoustic and Vibration”)



Figure 10: Nordmann BDA-
Kralle strain gauge (“Force”)

While these methods present highly accurate methods for monitoring tool breakages, they are not the most practical or feasible solutions for real-time monitoring. The exact bandwidth that needs to be monitored is difficult to establish, and higher frequencies of upwards of 1 kHz or more present processing issues on hardware components. The vibrations of the lathe and other mechanical components also present noise issues that are difficult to filter since AE components are extremely sensitive. Aside from technical specifications, the sensors investigated were not cost effective, as they typically cost over \$1000.

d. Force sensing: With most tools, the applied force required for a cutting operation increases as a tool wears out and becomes dull. The rate at which this force increases is heavily based upon the materials being machined as well as the tooling material. This force can be monitored in relation to the cutting tool to determine its life. In a multi-spindle lathe, a strain gauge sensor can be placed on the rocker arm or the feed rod, as seen in Figure 11, to measure the strain put on the system when the cutting process begins. These highly sensitive gauges can detect micro or nanometer fluctuations in the tool position and can provide valuable data

regarding the moment the cutting tool makes contact with the material to be machined (Trail). By monitoring the transient response at the start of the cutting operation, it can be shown that there will be a difference in the tool movement when a sharp tool is used versus a deteriorated tool.

e. Sensor Mounting:

Figure 11 outlines possible sensor placements within a multi-spindle lathe. The AE sensors (SEH & SEH-mini) are placed on the on coolant lubricant lines as well as directly on the tool surface, close to the physical cutting operation. The feed force sensors (BDA-Q & BDA-Kralle) are placed on parts of the tool feeder. One is used to measure the rocker arm deflection and another is used to measure the compression of the feed rod. In our case, the boxing tool being monitored is mounted parallel to the spindle plate, and cuts orthogonally to the aluminum cylinder being turned by the lathe. The plan will be to monitor the tool movement using a strain gauge mounted near the cutting operation, and compare the performance for brand new and worn out tools.

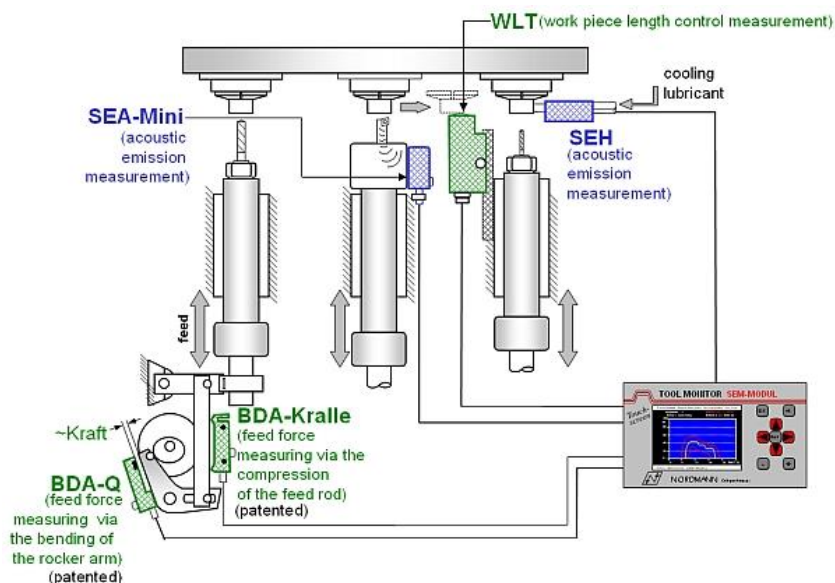


Figure 11: Multi-Spindle Lathe sensor placements (“Possible sensor positions ...”)

f. Accelerometer: Another option for measuring the tool's remaining lifetime is using an accelerometer. The accelerometer is a cheaper alternative to the force sensor and acoustic emissions sensor, but it is more susceptible to noise than an acoustic emissions sensor, and it is less reliable than a force sensor.

Accelerometers are used to measure g-force. This means it will measure 9.81m/s^2 while stationary, and zero while in free-fall; the output is a continuous voltage that is proportional to the g-force experienced by the accelerometer. They are often used to measure vibrations in machinery, and very high frequency accelerometers can measure vibrations of up to about 30kHz.

There are two design solutions using the accelerometer. The first design uses the accelerometer to measure the vibrations of the tool as it is being used. The output voltage of the accelerometer could then sent to the microcontroller, and the Fast Fourier Transform algorithm is used to convert the signal into a matrix of frequency vs time. This matrix is then compared to the frequency response of a good and bad tool; its lifetime is then determined by the deviation from each response.

The second design uses the accelerometer to measure the deceleration of the tool when it makes initial contact with the part. The tool will slow down depending on how dull or sharp the tool is due to how easily the tool will remove material from the part. The analog output is then sent to the microcontroller, and the voltage drop from the sensor at initial impact will determine

the life of the tool. However, this requires a very sensitive accelerometer that can sense small changes in g-force.

Data Conversion

Measuring the quality of a tool acoustically requires the sound produced by the tool to be converted into data that can be analyzed. The natural sound waveform produced by the tool can only be retrieved in its time-domain form, but the condition of the tool is portrayed in the frequency-domain. i.e. A tool's condition is shown by different spikes in its component frequencies. There are two ways to convert the sound emission into readable frequency components: analog and digital. Additionally, for either solution, a microcontroller will be necessary to process data and produce an appropriate output to the PLC.

a. Microcontroller: We have decided that it would be best to use a small commercially available development board. Since it is possible that we would like to do some digital filtering, a high feature, high speed micro controller would be ideal for this project. The Pinguino Micro development board features a 32 bit PIC32MX440 that can be clocked at 80 MHz. It's internal 10 bit ADC has 16 channels with the ability to sample at up to 1000 KSPS (thousand samples per second), which would be ideal for the higher frequencies that we wish to monitor. The controller also features a sizable amount of RAM and flash ROM to contain our control program, as well as non volatile memory that can be used to store calibrations or other data. For these reasons, the Pinguino microcontroller will be an appropriate solution, compatible with either an analog or digital data processing system.



Figure 12: Pinguino Microcontroller

Additionally, the Pinguino has a free Integrated Development Environment and community support from its many users. Its size and form factor makes it easy to integrate to the PCB we will design in the future, and should be able to fit into a project box of similar size to the suggestion by Great Lakes Controls Engineering.

b. Analog: This proposed design solution shown in Figure 13 is focused on offloading computation from the micro controller and on to dedicated hardware. It takes the same sensor element and instrumentation amplifier present in the other designs, but routes the signal path differently. It also adds two other key components, an adjustable band pass filter and comparator. Rather than using digital filtering and FFT calculations, we will adjust the band pass filter to a range of frequencies that we determine to be most relevant to

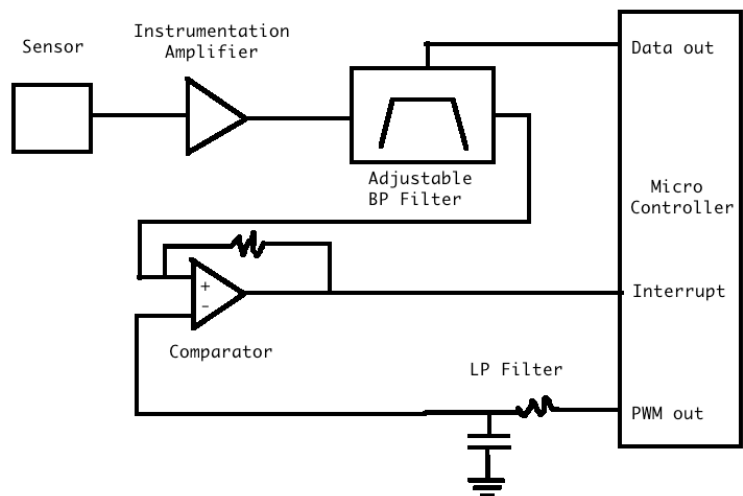


Figure 13: Analog Data Processing Block Diagram

tool life. The idea is that as the tool gets dull, certain frequency components of the signal will become larger in amplitude.

The comparator is meant to compare the peak amplitude of the band pass filter output to an adjustable voltage. The plus terminal of the comparator is fed from the band pass filter output and the minus terminal voltage is determined by a voltage derived from a micro controller output. If the comparator saturates, the signal has been determined to be at least a certain amplitude, and the comparator will interrupt the micro controller. Otherwise, the output of the comparator will stay low and the micro controller can go about its business uninterrupted. The micro controller will output a PWM pulse which is low pass filtered to only its DC component, the same way it is done in the output section. This allows an adjustable voltage to be fed to the minus terminal of the comparator. The hysteresis loop of the comparator will be chosen to reflect the ripple of the filtered PWM waveform.

Once the micro controller is interrupted, we have hit a milestone in tool life. The next steps to take on the software side would be to evaluate this milestone, adjust the overall output of our sensor unit, and adjust the comparator minus terminal to a voltage reflecting the next milestone. This design solution will greatly simplify the control software, while not complicating the hardware by much.

An analog method of this nature requires multiple band-pass filters to separate specific frequency sinusoids from the original waveform. One band-pass filter is needed for each frequency, so this method can be costly. However, adjustable band pass filter ICs are available commercially and will allow us to filter a wide range of frequencies with only one chip.

The MAX262 chip has switched capacitor filters whose cutoff frequency can be changed by software control. The MAX262 has the option to change both the cutoff frequency and filter quality for two on chip filter sections. The chip also provides high pass, low pass, band pass and notch filter outputs for each individually adjustable filter section based on the parameters provided by our micro controller. The filter sections can be cascaded in order to provide sharper filtering. The MAX262 can have a cutoff frequency from 0 - 140 kHz and costs around \$15.

The filter function that we are most interested in is the band pass filter. With a chip like the MAX262, we will have the ability to sweep a frequency range over the course of the machine producing several parts. This way we can listen to frequency ranges of interest and see how the magnitude of those frequencies changes over time. We can then determine milestone levels where the tool is becoming dull and decide an appropriate output signal corresponding to the tool's condition.

c. Digital: The digital method uses an analog-to-digital converter to express the original waveform as an array of numbers; each number in the array represents a voltage step, and each element in the array represents a step in time. This is done by taking samples of the wave at equal time intervals. The samples are stored as numbers that represent a step in voltage; the voltage per step is determined by the resolution of the analog-to-digital converter. The data can then be operated on by an algorithm to get a frequency spectrum for the waveform. Fourier Transform and Fast Fourier Transform are both algorithms capable of doing this. The results are then parsed to find the highest amplitude frequencies. For this application, we will need to

process the output of our sensor so that the condition of the tool can be determined by the presence of high amplitude frequencies.

Fourier Series represents periodic functions as a sum of sinusoidal signals. The sound emission from the tool will not be periodic due to noise from the tool, the part, and from the environment. The sound emission must be made periodic in order to represent it by the Fourier Series. Thus, the period for the Fourier Series is taken as an entire set of data, and the result will act as if that segment of data is repeating. This causes the period to be the number of elements in the data set divided by the sampling rate of the analog to digital converter, and the lowest frequency is one over the entire span of the data set. The first coefficient of the Fourier Series is the DC level. The DC level is found by taking the average of the waveform, but the waveform should have a DC level of zero, so it can probably be omitted for speed. The cosine and sine coefficients are found by multiplying the data by a sine and cosine function then integrating the result over the period. The results are then divided by the period to get the coefficients. It is important to note, that the sampling rate also depends on the type of monitoring desired (real time vs. delayed, as in ultrasonic laser acoustic emission) (Trail, 2006).

d. Data Analysis: Once the initial signal processing has been completed, interpretation of the measurement data can begin. To track and quickly detect faulty or broken machine tools, the measurement curves are tracked with defined limits. When a limit on the curve is violated, the control system can respond by switching operation of the machine via components such as a relay or optocoupler (“Monitor Strategy...”). Straight limits and envelopes are two of the commonly used techniques for tool monitoring systems (“Monitor Strategy...”).

In a straight limit approach, extreme boundaries can be set for a specific tool. For example, this can be a minimum/maximum vibrational or torque value. When the incoming signal monitoring this tool crosses one of these thresholds, as in the case of a breakage, the system can respond appropriately and shut off, pause, or switch the operation (“Monitor Strategy...”).

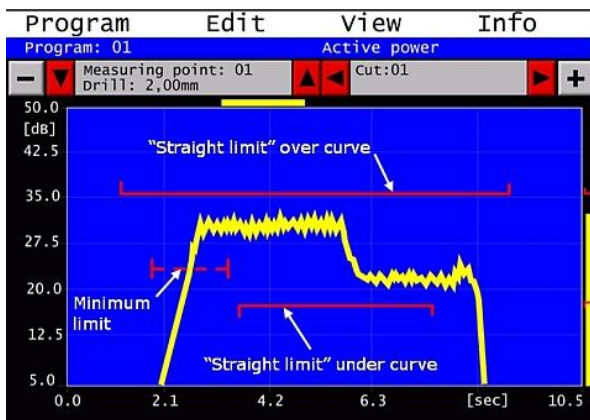


Figure 14: Application of Straight Limits
 (“Monitor Strategy...”)

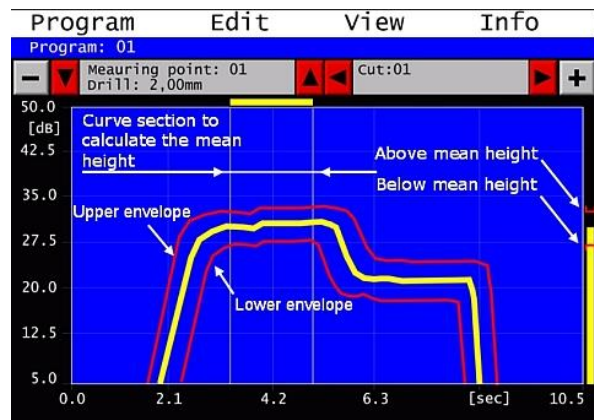


Figure 15: Application of Envelopes
 (“Monitor Strategy...”)

In the envelope approach, the incoming signal is encased in an upper and lower envelope. These limits can be auto-adjustable and adaptive to the tool that is currently being used. This also means that when correctly analyzing the signal, the envelope limit must be set according to tool type and cutting operation. Similar to the straight limits, if the signal chain exits the envelope,

the system can respond as programmed. The envelope is determined by averaging previous measurement values and the limits of the envelope can be set at a defined percentage distance away from the signal (“Monitor Strategy...”). For example, in cases where precision parts need to be produced, the envelope can be set for a higher sensitivity where miniscule changes in tool quality need to be detected. Therefore, the algorithms within the software need to correctly compute averages to determine an adaptive envelope. This detection method also can be processed for the envelope to auto correct itself, such in the case of a false alarm, without disrupting other areas.

e. Output: The required output of our sensor is a simple 0 to 10 Volt analog DC signal which will be read by the existing Programmable Logic Controller (PLC). The remaining tool life of 0% to 100% will be mapped to the 10 Volt DC signal. It was recommended by our sponsor, Great Lakes Controls and Engineering, that our sensor has a Digital to Analog Converter with a 10 bit resolution, which is consistent with other sensors read by their PLC. Thus, the output would be able to sense tool life in approximately 0.1% increments. Our sensor will interface to the PLC via an industry standard 4 strand cable. Of these 4 available wires, we are supplied with +24V DC, a ground reference, and a single wire on which our output signal will be placed. The remaining wire is unused, and intended for sensors that have more than one signal wire.

A 24V DC source on its own would be too high of a voltage to power our micro controller and support circuitry. We will need to design a ‘sub power supply’ that will step this down to a lower level that will not damage our ICs. A simple and cheap way to do the voltage regulation would be to use off the shelf linear voltage regulators. These come in fixed voltage and adjustable voltage variations and only require a few external filter capacitors. Linear regulators however, are very inefficient, creating a lot of extra heat. If it is determined that linear regulators should not be used because of their extra heat and low efficiency, we could look into high efficiency switching regulators.

After regulating the sensor's power supply to 5 or 3.3 volts to power the microcontroller, we need a way to convert the microcontroller output to a DC signal and boost the output to 10 V. There are several feasible options to consider that meet these requirements. All of them will require that we have a 10 V or higher power rail to power the external circuitry.

There are many Digital to Analog Converter chips (DACs) available on the market that meet the requirements for the resolution and can take a 10V supply rail in the \$5 - \$10 range. They include models with parallel and serial data from the micro controller. Such parts would fit well into our budget. A serial input chip would likely be the better option, to cut down on the number of IO pins required to interface with it. There are DACs that use I2C, SPI, and other interfaces.

Another option would be to output a pulse width modulated (PWM) square wave. This square wave would be either 3.3 or 5 Vpp depending on our micro controller selection. The percentage of remaining tool life would be mapped to a duty cycle of the PWM output, with 100% duty cycle being maximum tool life (10V output). In order to get a 0 to 10 volt output range, a low pass filter would pass only the DC component of it and a non-inverting amplifier would boost the level. Some drawbacks to this method would be inevitable ripple on the output signal and potentially lower resolution than an external DAC. It would make up for these drawbacks by being much cheaper and requiring less CPU time to change the signal.

6. Ranking of Conceptual Designs

We have constructed a solutions matrix to evaluate the many possible sensors available to monitor tool wear.

Engineering Criteria	Importance	Possible Solutions					
		Force	Accelerometer	AE	Coolant	Microphone	Power
Sensitivity to Noise	3	9	3	3	3	1	9
Installation	2	3	3	3	1	3	1
Durability	1	9	3	9	3	3	9
Data Correlation to Tool Life	5	9	3	9	3	1	3
Output Compatibility	4	3	3	3	3	3	9
Price	2	1	3	1	1	3	1
Total		101	51	83	43	35	91

Figure 16: Sensor Solutions Matrix

Based on this analysis, it is clear that the best solution will be a force sensor. Second, will be a power sensor. However, it has been determined that a power sensor is implausible for the New Brittan 6-spindle lathe as a single motor drives all tool operation, so fluctuations in power consumption cannot be traced back to the deterioration of a single tool. Therefore, an accelerometer is the second best option.

For data analysis and interface of the sensor to the PLC, there are far fewer options available. Between analog and digital processing options, we believe that the analog design solution is more feasible for this project. Without the adjustable band-pass filter IC, the hardware involved would have prohibitively large and inflexible. However, the ability to change the frequency band will allow us to forgo complex DSP algorithms while remaining flexible in our ability to detect different frequency ranges. This flexibility is key to a design that can interface with any one of the sensors we may chose, that can be adjusted based on data collected after we are able to test the design, and calibrated for a particular machine.

7. Proposed Design Solution

It is our belief that the best solution for the problem is the Nordmann force sensor with the analog data processing system. The most significant barrier to this solution is cost of force sensors, which may prove beyond the budget for this project. If cost is prohibitively high, we suggest the accelerometer with the same data processing interface. This solution will be more difficult to implement but may still be a reasonable solution.

Our test plan has three primary phases: 1) hardware development and verification 2) testing of sensor with hardware on lathes in MSU machine shop 3) testing and implementation with New Brittan 6-spindle lathe.

To complete the first step, we have begun ordering parts necessary for the analog data analysis hardware including the adjustable band-pass IC (MAX262) and the microcontroller (Pinguino). Once we have these parts and have prototyped the system, we can test it using a

function generator and oscilloscope in the lab to verify correct response to various frequency inputs.

Second, we have taken steps to work with the MSU machine shop to test our system. This includes general safety training, training in lathe operation, and communicating with the staff our plans to test the system. When this phase has been reached, we will be able to test the system with a carbide tool on aluminum at the appropriate rpm and feed rate. The results from this test will be somewhat different than the New Brittan machine, primarily because the lathes at the MSU machine shop do not have the same constant stream of lubricant during machining that the New Brittan lathe uses. Nonetheless, this should provide useful data and verify functionality of the system.

Finally, it will be necessary to test the system on the customer's New Brittan lathe. This will be necessary in order to calibrate the software for the particular machining process to be monitored. This will allow us to account for differences between the New Brittan lathe and the tests carried out including the use of lubricant, exact size and shape of tool, mounting of tool feeder arm, and the 6-spindle design.

8. Risk Analysis

This project contains many risks due to its complexity. There are many sensors that are theoretically capable of detecting information that can be used to ascertain the remaining tool life; possible solutions have been well researched, but a general solution that applies to all tools does not exist. In order to find the best possible solution, prototypes need to be made and tested on the specific tool. However, the most promising sensors are already priced beyond the project budget, so the possibility of producing more than one prototype is low. This means that the risk of choosing the wrong initial sensor is most severe. The consequence of picking the wrong sensors to test could result in project failure. Thus, careful planning and research by the team must be done. An additional step being taken is in-depth documentation of possible design solutions for future design reference.

A sensor causing the lathe to have unwanted behavior is another risk. The risk is higher when using mounted sensors than when using the microphone and acoustic emission sensors, because the mounted sensors add weight to the tool. The consequence of this is also a failed design, so testing of the design must be done in advance incase changes to the design must be made to accommodate for mounting and spatial requirements.

The lifetime of the sensor system must be taken into consideration. Mounted sensors experience vibration from operation, and all sensors are exposed to lubricant. The design must be made to withstand these conditions. The consequences of failing to meet this requirement will result in a design that only works for a short time. Furthermore, the cost of replacing the parts for the sensor must be less than the amount of money it saves on replacing tools, or the sensor and system will be worthless.

9. Project Management Plan

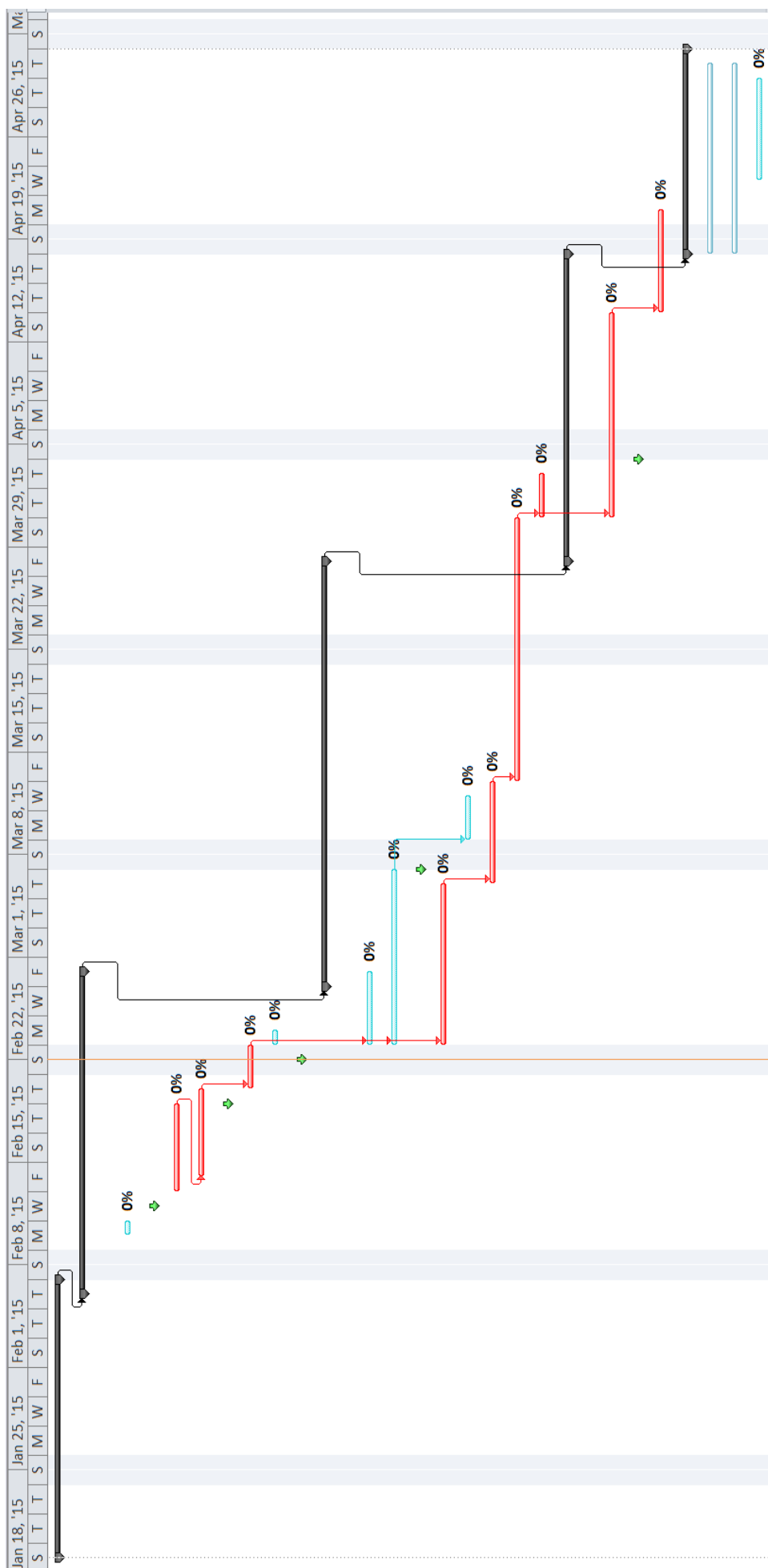
The project management plan consists primarily of executing the test plan outlined earlier. Tasks in this process will be delegated to various team members though all members have participated in machine shop training and will be involved in testing and implementation.

Several lab experiments need to be constructed and analyzed in the initial data collection and testing of prototypes. Initial data collection can begin by obtaining two or more bits from a drill and capturing the sound when drilled into a piece of aluminum. One of these bits must be brand new and the other must be of deteriorating or poor condition. This data can be used to determine the frequency ranges produced by various tools and to what extent there is single noise present.

After acquisition of a raw measurement, different algorithms to process the signal can be tested. Software may need to be adjusted to implement an envelope system, as described earlier, or hysteresis before the signal enters the comparator. Before obtaining data from an actual machine, it will be difficult to anticipate the specifics of which technique will be most useful. Further, a simple mechanism for calibrating the software for different machines can be developed from this data.

Additionally, we have produced a Gantt chart to ensure we will stay on schedule throughout the semester. The following the list of tasks within the Gantt Chart, while the Tracking Gantt schedule is seen on the following page.

± Initial Research Phase	15 days	Mon 1/19/15	Fri 2/6/15	
▣ Design Development Phase	16 days	Fri 2/6/15	Fri 2/27/15	1
Meeting with Prof.McGough	1 day	Tue 2/10/15	Tue 2/10/15	
VOC assignment due				
Research and order sensor	4 days	Fri 2/13/15	Wed 2/18/15	
Design circuitry based on Sensor selection	5 days	Sat 2/14/15	Thu 2/19/15	9
FAST assignment due				
Circuit parts ordering	2 days	Fri 2/20/15	Sun 2/22/15	10
Design Presentation	1 day	Mon 2/23/15	Mon 2/23/15	
Proposal Due				
▣ Prototyping and Testing Phase	21 days	Fri 2/27/15	Fri 3/27/15	6
Initial testing of individual components	5 days	Mon 2/23/15	Fri 2/27/15	12
Build Prototype	10 days	Mon 2/23/15	Fri 3/6/15	12
Present Prototype				
Software design and finalization	9 days	Mon 2/23/15	Thu 3/5/15	12
Design PCBs	3 days	Mon 3/9/15	Wed 3/11/15	17
Product Validation at Jackson facility	5 days	Fri 3/6/15	Thu 3/12/15	19
Software tuning	12 days	Fri 3/13/15	Mon 3/30/15	21
2nd Round of testing at facility	3 days	Tue 3/31/15	Thu 4/2/15	22
▣ Final Design Building and Testing	16 days	Sat 3/28/15	Fri 4/17/15	15
Final Design build	10 days	Tue 3/31/15	Mon 4/13/15	22
Technical Presentation				
design device aesthetics	5 days	Tue 4/14/15	Mon 4/20/15	25
▣ Conclusions	11 days	Sat 4/18/15	Fri 5/1/15	24
Final Report writing	10 days			
Website prep	10 days			
Presentation prep	5 days	Thu 4/23/15	Wed 4/29/15	
Design Day				



10. Budget

This project should only cost up to \$500 in the making. Furthermore, the sponsor also required a budget of only \$250 for multiple parts made as a final design solution.

After dividing the project into multiple parts, it became clear to the team that the bulk of the budget would eventually go toward the purchase of a high precision sensor. The following chart displays the exact costs for each part of the project.

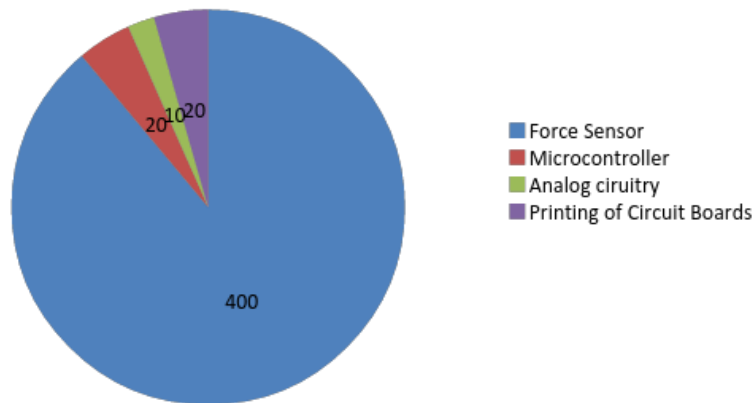


Figure 18: Proposed Project Budget

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