MONITORING SYSTEM FOR ROTATING TURBINES:

Design Review

Asm Fariz Khandker, Alaa Qarooni

UIN: 676283060, 670832813

NetID: akhand8, qarooni2

TABLE OF CONTENTS

1. Introduction....1
1.1 Objective.... 1
1.2 Background.... 1
1.3 High-Level Requirements....1
2. Design
Block Diagram....2
2.1 External Power Sources....3
2.1.1 Main Power Supply....3
2.2 Internal Power Sources....4
2.2.1 Secondary Power Supply....4
2.2.2 Batteries....4
2.3 Photonics/Sensor Unit....5
2.3.1 Packaged Diode Laser....5
2.3.2 Collimator....7
2.3.3 Si Photodetector....8
2.4 Control Unit....10
2.4.1 Voltage Adder....10
2.4.2 Secondary Voltage Regulator....11
2.4.3 ATmega328....12
2.4.4 Discriminator Circuit....13
2.5 User Interface....15
2.5.1 LCD Screen....15
Tolerance Analysis....16
3. Cost and Schedule....18
3.1 Cost Analysis....18
3.2 Schedule....19
4. Ethics and Safety....20
4.1 Safety....20
4.2 Ethics....20
5. References....21

1. Introduction

1.1 Objective

Turbines are an essential electromechanical component in many large systems. They are used for propulsion in planes and submarines. They are also used in cooling systems such as the ones in nuclear power plants, high performance computers, etc. However, most of these do not have a sophisticated monitoring and control system that maintains the operational speed of the fan. The standard way of detecting RPM is through the use of a dynamo that generates a current proportional to the torque. The problem of using a dynamo, however, is that it is bulky, requires a mechanical split-ring commutator, requires various rectifying circuits to convert the alternating current to an acceptable DC, and is overall unreliable due to the complexity of the components involved. Furthermore, it is not a purely electrical system and relies on the integrity of various mechanical components. Our solution is to use a photonic integrated system that can be implemented into existing machines in a relatively non-invasive way. It will be more precise and more reliable. It will also allow us to control the speed and correct it if shifts away from the optimal.

1.2 Background

The main inspiration for this came from studying the operation of ultra high-vac pumps that are used in semiconductor processing plants and state of the art clean rooms such as the ones found in the university's micro and nanotech labs. Here the pumps use a variation of the old dynamo system and this poses potential problems in the fabrication process. For example during the metal organic chemical vapor deposition process, the speed of the turbine in the machine needs to be within very narrow limits. For this, very precise sensors need to be in place. Furthermore, the environment where the fans exist do not allow for a large electromechanical monitoring systems to be adequately implemented. Another problem arises from the fact that if there is no way to immediately correct the turbine in case of power failure for which the turbine is drawing less power from the source; the whole process needs to be stopped and this can be very expensive. Our design, however, solves all those problems and creates a standalone, easy-to-transport, modular and cheap system that can be implemented on existing machines with minimal modification and ensures optimal operation of the fan until the further repairs can be made. This removes the problem of having to shut down entire systems in the case of a turbine failure.

1.3 High level Requirements

- Portable and mobile, with an overall width that does not exceed 50cm, and a height or depth that doesn't exceed 20cm for the control unit..

- An area to insert the rotating turbine or mechanical object for detection, with an adjustable size to accommodate different turbine diameters.

2. DESIGN:

Our design is made up of 5 essential sections: an external power source, internal power sources, a control unit, a photonics sensor module and a user interface. The external power source is the initial source that powers the turbine we are monitoring. It is required to go through our device, which sacrifices modularity, to combine with the microcontroller-manipulated internal secondary power source. The control unit processes the mechanically pulsed laser beam data coming from the photodiode in the photonics module and dictates how much the secondary source should contribute to the turbine to compensate for power loss in the case of a mechanical failure. The user interface is a simple low resolution LCD Screen to display the RPM value of the turbine.

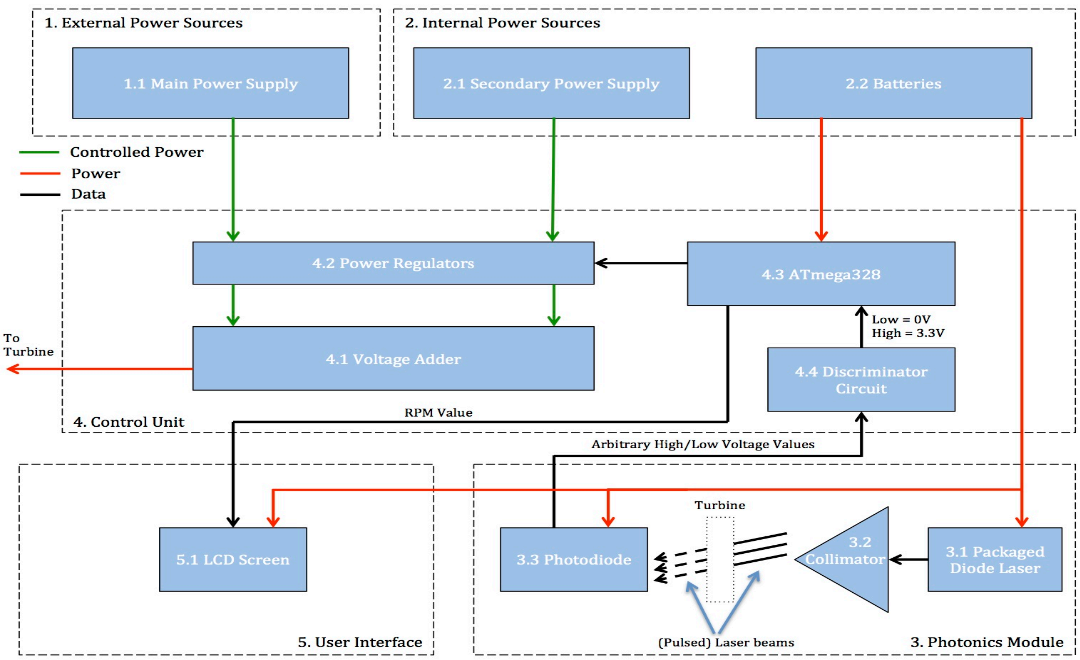


Figure 1: Block Diagram

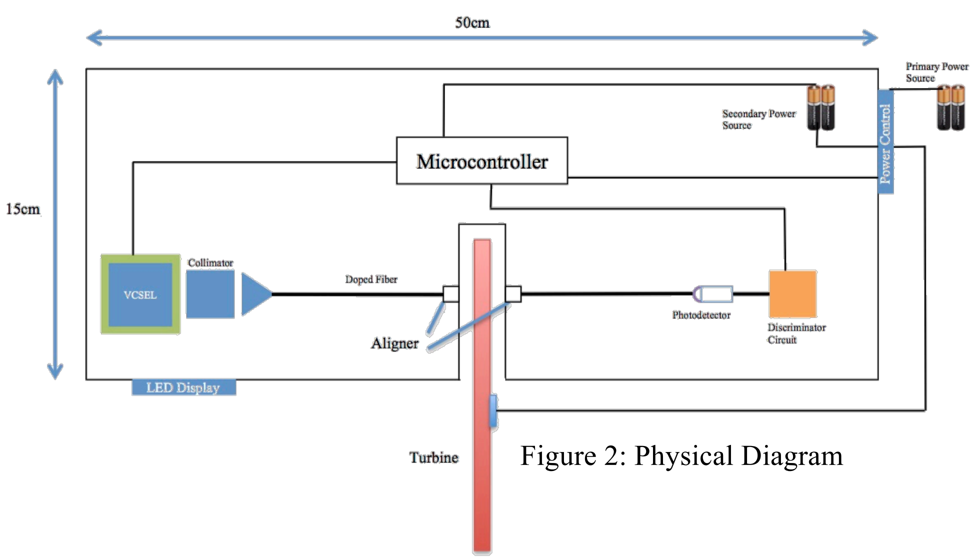


Figure 2: Physical Diagram

2.1 External Power Sources

2.1.1 Main Power Supply

The main external power supply, a 12V battery, directly operates the turbine. Some modularity is sacrificed in this block, since the wire from the power supply to the turbine needs to be cut and inserted into an input port in our device, and then redirected through the control unit back to the turbine through an output port. This is done to internally couple the secondary source with the first as it passes through our control block. The control block, through the microcontroller and additional circuitry, will route the secondary power supply to the turbine if it sees that its RPM value is below the one required by the power supplied. Maximum power consumption for our purposes will be approximately 18W [1]. This indicates a high current (1.5A) flowing through the device; however, our design routes this external power (and secondary power) away from the microcontroller and other low current components, directly to the turbine, thus avoiding damage to these components.

Requirements	**Verification**
Outputs 12V with a capacity of 1500mAh.	Place voltmeter in parallel with the battery to measure 12V output voltage. Use OPA548 to draw 1.5A from battery and wait for an hour, and measure output voltage again.

2.2 Internal Power Sources

2.2.1 Secondary Power Supply

The secondary power supply needs to match the main power supply's requirements and verifications, mainly because it is the fail-safe that is used when this main supply is malfunctioning. It is connected to a power regulator (detailed in the control unit section) that routes the chosen supply to the turbine.

Requirements	**Verification**
Same as Main Power Supply	Same as Main Power Supply Confer with control unit section to ensure that current doesn't damage voltage regulator

2.2.2 Batteries

These need to operate at 4.5V. The main two constraints that made us choose this value is the ATmega328 chip, our microcontroller, which has an operating voltage range of 1.8V-5.5V, and the LCD screen used (and described in Section 2.5.1), which has a maximum supply voltage of 4.8V. The voltage provided to the Photodiode and Packaged Diode Laser can have an arbitrary constant value (that should be low enough not to damage them, of course), and we found that 4.5V works (See Photonic Module and User Interface). This does give a tolerance of 0.3V however. Use common 5V batteries, which, as detailed in the next sections, will operate at 30mA, and place a load resistor whose value is calculated accordingly: 5V–4.5V = 30mA * R, giving a resistance value of R=17Ω, to ensure that 4.5V are being drawn.

Requirements	**Verification**
Output 4.5V with a capacity of 30mAh.	Buy common 5V batteries then insert ~17Ω resistor in series. Place a voltmeter between the end of the resistor and ground to ensure 4.5V is being drawn. Place load of 4.5V/30mA = 150Ω in parallel with the battery and wait for an hour to ensure the battery's capacity.

2.3 Photonics/Sensor unit

The sensor module will use a packaged diode laser to to send a focused laser beam through an optical cavity where the turbine blade will act as a mechanical chopper/modulator. This will produce a pulsed beam the same frequency as the turbine. This pulse is detected using a photodetector. This is similar to a type of modulation known as Q-switching where we periodically introduce an optically denser medium (in this case opaque) inside the cavity and change the quality factor, Q. Here every time the blade slices the beam, it corresponds to a low Q value and a small photocurrent at the detector. Once the turbine blade completely passes the cavity and releases the beam, it corresponds to a high Q value and a substantial photocurrent at the detector.

Our RPM calculation will utilize this alternating photocurrent. A discriminator circuit will convert the fluctuations to a distinct "high" and "low" and the microcontroller will calculate the time between consecutive "lows". The inverse of this will give us the frequency of the turbine.

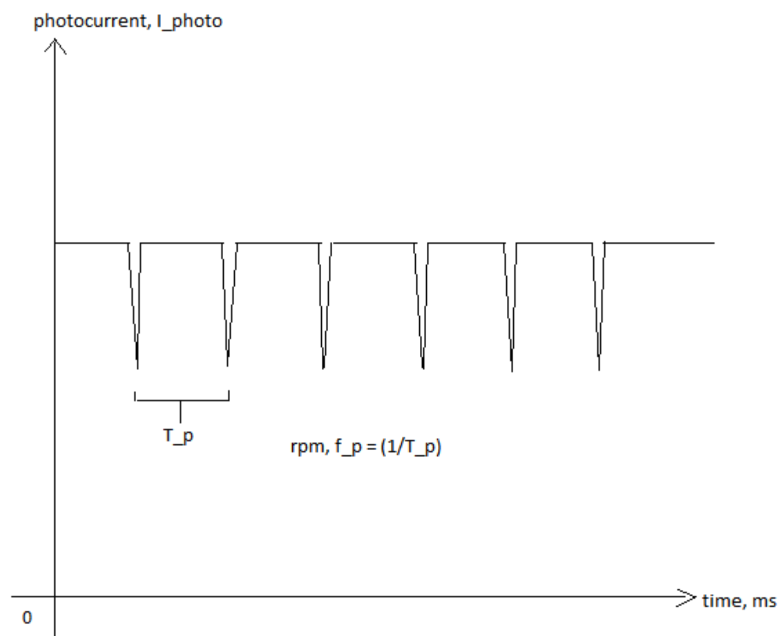


Figure 3: Photocurrent waveform

2.3.1 Packaged laser

Our implementation is centered primarily on using a photonic integrated system that employs a fiber coupled laser diode. We are using the Thorlabs 635 nm single mode laser with built in coupling optics. The particular variant is the LP635-SF10 pigtailed laser diode. The use of a fiber means that we can easily direct and manipulate our beam for a system where the turbine and hence the sensor module is further away from the control unit. This is one of the features that makes the design truly modular. Fibers are relatively easy to slip into a turbine cavity where the design of the overall machine restricts a more elaborate electromechanical implement.

An important thing to remember is that we must restrict the current drawn into the laser diode using a JFET current limiter circuit (described in the tolerance section). This will make sure that the laser is not damaged. We will use an arbitrary drive current of 10mA and the rest of the photonic devices will be selected accordingly.

The output power of the laser is determined using the following equation:

$$P_{opt} = \frac{hv\ (i_d - I_{th})}{q} \eta_i \eta_e$$

Here, η_i is the current utilization energy which is fixed for a given material. η_e is the quantum extraction efficiency which is also fixed by the dimensions of the material:

$$\eta_e = \frac{\alpha_l}{\alpha_m + \alpha_l}$$

$$\alpha_m = \frac{1}{2L} \ln \left(\frac{1}{R_1 R_2}\right)$$

Here, α_l and is cavity loss in the laser diode [fixed] and α_m is the mirror loss which is also fixed by the laser cavity length, L and "mirror" reflectivities, R_1 and R_2 inside the diode. All this means that we can combine the efficiencies into a differential quantum efficiency, η_{ed}:

$$\eta_i \eta_e = \eta_{ed} = const.$$

This shows that the efficiencies are only determined by physical factors and that the output power is directly proportional to the drive current, i_d. Here the I_{th} is the minimum current required by the device. The input voltage doesn't matter. Matter of fact, once I_{th} is passed, the voltage across the photodiode is clamped and is no longer relevant as seen below:

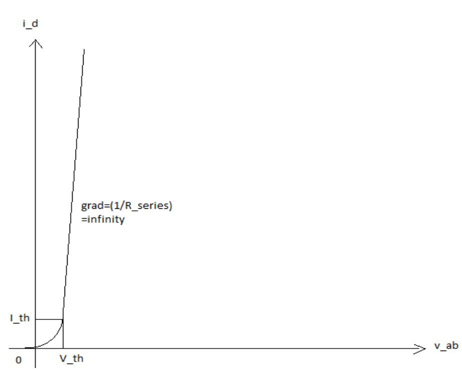


Figure 4: Photodiode functionality

Once established that the voltage is clamped and that, according to the first equation, output power is proportional to the drive current only, we can calculate the optical power output of our device from the max power and current rating:

$$\frac{P_{opt}}{10mA} = \frac{10mW}{50mA}$$

$$P_{opt} = 2mW$$

Requirements	Verification
635nm beam (this is important to verify because it will determine our choice of photodetector and collimator) 10mW maximum optical power or 50mA/ 60mA maximum drive current. (whichever occurs first. Important because anything greater will burn the diode) Output power of 2mW at 10mA drive current.	Use an Agilent spectrometer with built in fabry-perot cavities Check the input current drawn from the current limiter (described later) using ammeter. Check the output power using Agilent spectrometer. Supply 10mA and check the output power using the Agilent spectrometer.

2.3.2 Mechanical Aligner/Collimator Unit

This unit contains a mechanical aligner that will physically hold the two fibres on either side of the turbine blade. The gap between the fibres can be adjusted to accommodate for turbines of different widths. However, an important feature of this unit is the collimator.

The problem with using two fibers placed more than a centimeter apart is that the coupling efficiency between the two will be in the order of 0.01 to 0.02. This means that beams, upon exiting the fiber, will be so divergent that it will be virtually anisotropic. Furthermore, the medium between the fibers may have varying refractive indices due to impurities. So a collimator will focus the beam so that it is practically non-divergent, and is incident on every differential slice of the varying refractive index almost normally, i.e. perpendicular to the slice or plane. This will ensure minimal divergence and signal loss. Alternatively, instead of using the second fiber to collect the pulsed beam we can use the photodetector directly. This will eliminate insertion loss.

The fiber core diameter for the packaged LP635-SF10 pigtailed laser diode should loosely match the collimator input diameter to ensure decent coupling efficiency. To ensure this we use the ST Fibre Optic Collimator. The fiber coupled diode we are using has a fiber diameter of 150um. This is the closest matching collimator we could find with a diameter of 200um.

Furthermore, our laser output is 2mW and this particular collimator can handle 12W.

Requirements	**Verification**
Fiber input at 600-800nm Coupling efficiency	Pass the laser through the collimator and see if the given range accommodates the laser by checking the output wavelength using Agilent spectrometer. We simply measure the output power using the Agilent unit. The output power should be appr. 2mW.

2.3.3 Si Photodetector

For this unit we will use a Hamamatsu APD photodetector diode [S6045-02]. This component is selected to match the wattage and wavelength of the collimator and fiber coupled diode laser. The advantage of using a semiconductor photodetector instead of some of the more elaborate ones is that we can easily implement a discriminator that will convert the photocurrent to a simple “high” and “low” to be fed into the microcontroller. Also, silicon has the right responsivity [35A/W] so that it is not saturated by a 2mW laser operating at 635nm.

Requirements	**Verification**
Operating range 600-800nm	This can be easily verified using another 635 nm laser operating significantly below saturation [1~2mW] and seeing if the photocurrent is substantial.

Responsivity 35 A/W at 635nm	This is important to avoid saturation of the detector. This can be verified using simply connecting an ammeter to the output terminals of the detector and using a tunable laser to saturate detector and determining at what optical power the photocurrent becomes constant.

2.4 Control Unit

2.4.1 Voltage Adder

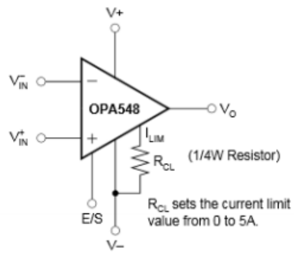
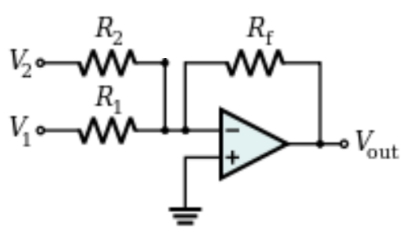


Figure 5: Simplified Schematic of OPA548 [2]

In this block, TI's OPA548 High Voltage, High Current Operational Amplifier will be used for its ability to handle very high currents (up to 5A) and voltages (up to 60V). This robustness is needed by the turbine, as we have discussed in section 2.1.1. It will function as a voltage adder of the main power supply and secondary power supply, who will both be controlled by a voltage regulator that turns one off and the other on using resistance values. In addition, it has an adjustable current limit, which is controlled by the ILIM pin. This control signal can take values from 0μA to 330μA, and this range corresponds to the output current range of 0A to 5A (this is a very powerful feature, in our opinion). I_{LIM} is determined by the following equation:
I_{LIM} = 19/(4*Resistor + 55000), with the resistor placed between the I_{LIM} and V^- pins.
Therefore, since our turbine will operate at 1.5A, we will need I_{LIM} to be 100μA, corresponding to a resistor value of 150kΩ.
Another consideration appears when examining the following figure and formula for the op amp adder:



$$V_{out} = -\frac{R_f}{R_1}V_1 - \frac{R_f}{R_2}V_2$$

Figure 4: Voltage Adder Op Amp [3]

To turn the power supplies on or off, the resistors R_1 and R_2 need to be controlled (see section 2.3.2). The values that correspond to on are equal to those of the arbitrary feedback resistor, R_f, as the equations above show. The values corresponding to off are much larger than R_f, however. Therefore, choosing a small R_f value relative to the maximum values that R_1 and R_2 can take is reasonable. Therefore, R_f should be of the order 10^1Ω and R_1 and R_2 should be to the order of 10^4Ω.

Requirements	Verification
150kΩ resistance placed between the I_{LIM} and V^{-} pins of the OPA548. Op amp feedback resistance value chosen to the order of 10^1Ω. Secondary power supply resistance value chosen to the order of 10^4Ω.	Place ammeter in series with op amp to ensure that the required current is achieved with the chosen resistor. Consult color coded resistor charts to ensure the chosen resistors are the ones we require. Place voltmeter between op amp output and ground to ensure voltages are being added appropriately.

2.4.2 Secondary Power Regulator

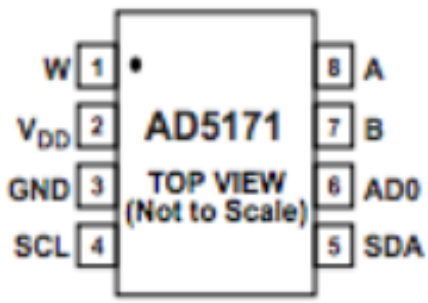


Figure 5: Pin configuration of AD5171 [4]

This block is essentially the variable resistor R_2 described in the previous section. We found that the AD5171 Digital Potentiometer fulfills the exact purpose detailed in that section. This device has several pins, as shown in Fig 5, but the most important ones are SCL and SDA, which I will discuss in a bit, and A, B and W. Its output resistance is governed by the following equation [4]:

$$R_{WB}(D) = \frac{D}{63} \times R_{AB} + R_W$$

The previous section determined that R_{AB} (the maximum value of R_2) has to be of the order 10^4 or 10^5. Therefore, we choose a resistor value in that range and connect its terminals to pins A and B, while R_W is 60Ω[z]. The resistance R_2 is therefore R_{AB}+60Ω. The SCL and SDA pins are then connected to the microcontroller, which transmits the integer value D. D ranges from 0 to 63, corresponding to an output resistance that ranges from 60Ω to R_{AB}+60Ω.

Requirements	Verification
Requires 2.7-5.5V power supply yet draws at most 10µA. Very low power consumption. R_{AB} has to be of the order 10^4 or 10^5.	There is no way to verify that this works independent of the ATmega328, therefore, the verification steps are taken with that connection assumed to be working: 1. Provide a 5V signal to pin B 2. Send a 0 from the ATmega328 3. Place ammeter in series and ensure that 5V/60Ω = ~83mA is being drawn 4. Send a 63 from the ATmega328 5. Place ammeter in series and ensure that $5V/10^4\Omega$ = ~0.5mA is being drawn

2.4.3 ATmega328

The ATmega328 chip is a powerful, low-cost and low power microcontroller that is used in our design to dictate how the control unit actually controls and links the rest of our design components. The first most essential part for the functionality of this block is understanding how to connect the chip to the computer for use with the Arduino IDE. The scope of this task is too big to tackle comprehensively, so we settled for a Youtube video showing us the steps that achieve this for us [4]. With the full power of the Arduino IDE, a lot of the control unit's functionality can be achieved rather easily:

1. The discriminator circuit will be connected to an input of the microcontroller, after which a simple code is written to process the information received and calculate an RPM value.
2. Arduino's Liquidcrystal Library will then be used to communicate with our LCD Screen (See Section 2.5.1) and output this RPM value.
3. Beforehand, back-of-the-envelope calculations and tests will need to be done to see what the ideal RPM value is for the given wattage of the main power supply. Using them, we can determine if we need to contribute more from the power to the turbine from the Secondary Power Supply.
4. This leads to the final step of communicating with the AD5171 Digital Potentiometer (see Section 2.3.2) and decreasing its resistance value. As discussed in Sections 2.3.1 and 2.3.3, this allows the voltage adder block to contribute more of the Secondary Power Supply to the turbine to compensate for the lost RPM.

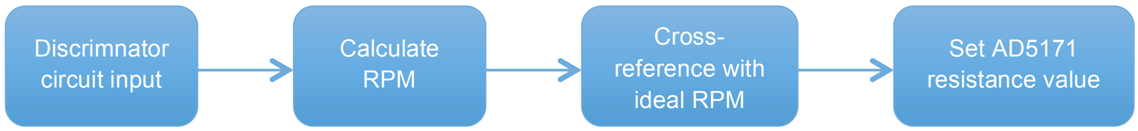


Figure 6: Flowchart describing logic of Atmega328 code

Requirements	Verification
Draws around 20mA of current and battery operated (at 4.5V). At least 9 I/O pins to connect to the different components of the device (6 needed from LCD Screen, 2 from AD5171, 1 input from discriminator circuit).	An ammeter connected in series will allow us to verify the amount of current drawn by the ATmega328. The ATmega328 datasheet details 23 programmable I/O pins available.

2.4.4 Discriminator

The discriminator will basically set the alternating photocurrent to distinctly high and low values. The photocurrent will already be "high" and "low" due to the Q-switching phenomenon that is described later. However, the photocurrent may not be a steady/constant pulse at the "high" and "low" realms of operations. So the discriminator will take the signal and make it a constant "high" and constant "low" for the benefit of the microcontroller which requires only a trivial, almost arbitrary high and low signal to calculate RPM.

The discriminator circuit basically selects a minimum pulse height. Once the input signal exceeds the discriminator preset level, the circuit will generate an output pulse where slight remaining fluctuations may be flattened using a simple RC design. Below is a simple discriminator design:

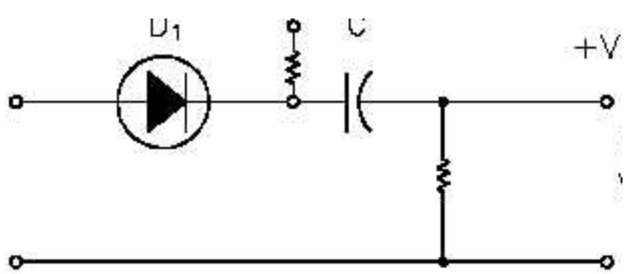


Figure 6: Discriminator Circuit Implementation

Here, we may need to amplify the photocurrent and pass it through a resistor. This is because the photocurrent is in the order of µA. This is easily done with the help of the OPA548 op amp. We will then take the input to the circuit across the resistor as the microcontroller will take voltages as input.

Requirements	Verification
Input voltage that alternates above and below 0.6V for the RPM cycle	This is easily measured using a voltmeter. The "cleanliness" or the approximate DC behavior of the output waveform can be verified using an oscilloscope.

2.5 User Interface

2.5.1 LCD Screen

The 20x2 Parallel Character LCD will be used for this block, which is compatible with the industry standard Hitachi HD44780. This is necessary for communication with the ATmega328, which will output the RPM value onto this screen through the Arduino IDE. It draws 1.2mA of current, and has a maximum operating voltage of 4.8V, so it can be connected to the 4.5V batteries (described in Section 2.2.2).

Requirements	**Verification**
Draws no more than 2mA, and powered by the 4.5V source.	The Arduino library has the LiquidCrystal Library, which facilitates writing code that's output onto the LCD screen [y]. Check using ammeter that the current drawn is no more than 2mA.

Tolerance Analysis

For the LP635-SF10 laser diode the maximum allowable drive current is approximately 50mA-60mA. We are going to try driving our laser diode well below this at ~10mA.

The following setup provides a constant source from our 5V internal supply that will clamp the maximum current delivered to the laser diode to about 10mA with the right selection of R:

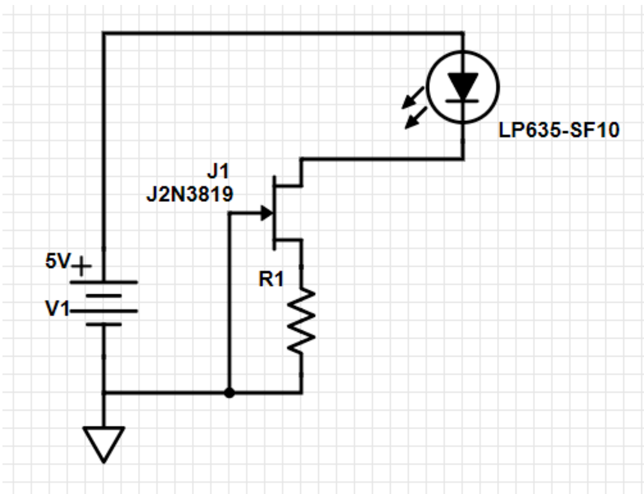


Figure 7: Self-biased JFET

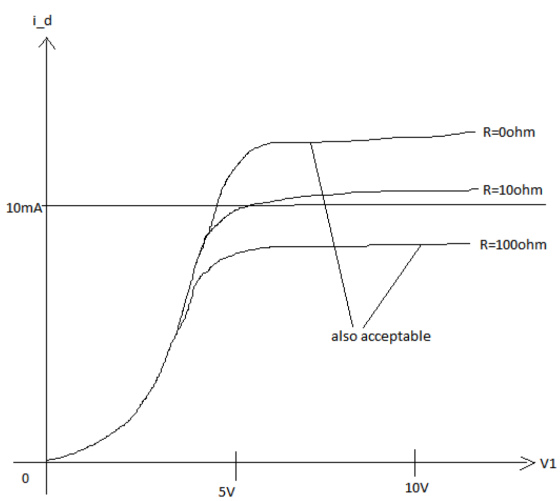


Figure 8: Laser diode functionality with different R values

So, we can select a drive current of about 10mA~12mA by driving the JFET at 5V-10V. With R~10ohm. For the above implementation, a 100ohm resistor is also suitable or anything between 10 to 100ohms essentially.

Also, for the actual laser diode the operating regime is shown below. We must make sure that out configuration of the current inhibiting circuit outlined above and the selected operating point keeps the diode above threshold but well below breaking point.

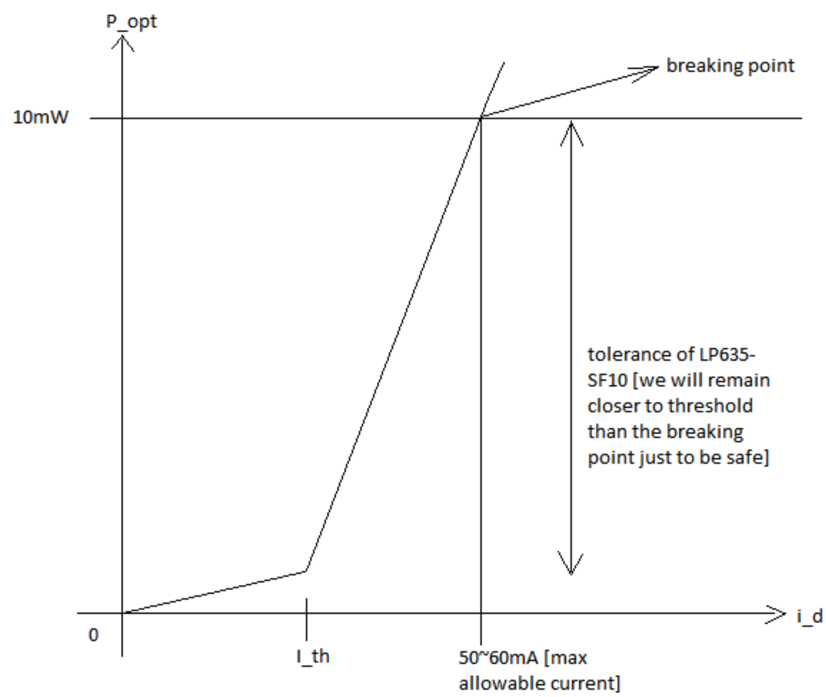


Figure 9: Power output of laser diode with respect to driving current

3. COST AND SCHEDULE

3.1 Cost Analysis

Labor: We are assuming a salary of $10/hr and a total of 60 hours of work; must finish 6 weeks from now and work an average of 10 hours per week. Since we have 2 members, the total labor cost comes out to be **$1,200**.

Part	Cost
LP635-SF10 pigtailed laser diode	$37
Hamamatsu APD photodetector diode [S6045-02]	$39.99
ST Fibre Optic Collimator	$57.15
OPA548	$15.00
ATMEGA328-AU Microcontroller	$1.83
AD5171 Digital Potentiometer	$3.46
20x2 Parallel Character LCD	$9.69

Total Parts = **$164.14**

Grand Total: **$1,364.14**

3.2 Schedule

Week of	Schedule	Division of Labor
10/9	Purchase parts and start assembling and connecting the Power Supplies with the Secondary Voltage Regulator and Voltage Adder blocks.	Both team members work together to build these components.
10/16	Microcontroller and discriminator circuits built and tested with dummy high and low signals to simulate the photodiode's photocurrent. Also build User Interface block.	Alaa: Microcontroller and User Interface Fariz: Discriminator Circuit building and testing
10/23	Integrating control unit blocks with test turbine to ensure its and power supplies' functionality.	Both team members will work on these tasks together.
10/30	Begin building Photonics module by separately testing and integrating the laser diode, collimator, photodetector and optical fiber.	Fariz: Building and Integrating photonics module components. Alaa: Helping test and integrate.
11/6	Integrate all the photonics module components and test the photodetector's output to the microcontroller, and begin building the aligner.	Fariz: Finishing up the Photonics module and the mechanical aligner Alaa: Testing output of photodetector to microcontroller and helping finish the photonics module.
11/13	Finish building the aligner. Assemble all the blocks and attempt to test our complete monitoring/control system.	Both team members will work together in this final week to complete the design.

4. ETHICS AND SAFETY

4.1 Safety

The most dangerous part of our project appears during testing, where we will be using an actual turbine. The turbine will be rotating at a high frequency, its size will be relatively large and its material rather strong, so it poses a threat of physical injury. In addition, we will be placing it in a narrow slit that will be just large enough to accommodate the blade (smaller gaps are desirable to minimize losses); damage to this aligner due to improper adjustments is very probable. So care must be taken when handling the fan. Alternatively, during the initial setup process we can operate the fan at a lower frequency to ensure that it does not physically touch the aligner; we can then carry on with the rest of the demonstration.

Another major risk is the collimator. Semiconductor lasers are typically not powerful enough to cause physical damage, however, the collimator can condense the beam to one of exponentially larger intensity (often powerful enough to engrave, etch or even cut). Therefore care must be taken when adjusting the lenses in the collimator so as to not generate a beam of high enough intensity where it would not only be a safety hazard but also risk gradually cutting the blade of the fan through multiple passes through the cavity. If this were to happen at a high enough RPM the blade could fly off and cause serious injury.

Another more obvious risk is eye damage from the laser. The diode laser will be a class 3A as it will operate between the 400nm to 700nm range at an output power of less than 10mW. So direct exposure to the eye should be avoided. Also, since we are using a collimator, direct physical contact with the beam should also be avoided.

As far as the electronic components, we are not dealing with extremely high voltages, however care must still be taken when dealing with power sources. Soldering should also be done with caution.

4.2 Ethics

Ethics include the proper handling and care of the testing equipment such as the Agilents, oscilloscopes, etc. all of which are much more expensive than the components we are using to build our devices.

We should also keep in mind the safety of the people we will share the lab spaces with. Another thing to be weary of is the admission of non-authorized personnel into the lab spaces. This includes but is not limited to allowing other people who are not enrolled in ECE 445 into the design lab.

If any other professor has agreed to let us use their resources it is our responsibility to know exactly how much of the resources we’re allowed to use or which parts we are allowed to borrow. Finally, we should give them a complete list of parts we intend to remove from their lab and wait for their authorization before we do so.

5. REFERENCES

[1] O'Neill, Brendon. "Pedestal, Desk, Tower & Bladeless Fan Running Costs." Canstar Blue, 29 June 2017, www.canstarblue.com.au/energy/electricity/portable-fans-running-costs/. Desk Fan operating at Low/Medium Setting

[2] Texas Instruments, "OPA548 High-Voltage, High-Current Operational Amplifier, " OPA548 datasheet, Oct. 1997 [Revised Jun. 2015]

[3] "Operational Amplifier Applications." Wikipedia, Wikimedia Foundation, 29 Sept. 2017, en.wikipedia.org/wiki/Operational_amplifier_applications.

[4] Analog Devices, "64-Position OTP Digital Potentiometer," AD5171 datasheet, [Revised Feb. 2017]

[5] "How to Program ATmega328 Chip Using Arduino IDE." Performance by Fahim Rahman, Youtube.com, 2 Nov. 2016, www.youtube.com/watch?v=CojmolVruDk.