VARIABLE SPEED SUMP PUMP

ECE 445 Design Document- Spring 2019
Team 35 – Variable Speed Sump Pump
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1. Introduction

1.1. Objective

A current ⅓ HP sump pump uses an average of 650 watts per hour [1] and can flood when it does not necessarily need to. This project improves upon these shortcomings in current sump pump design by making a variable speed sump pump. By varying the speed instead of turning the motor on and off many times, energy can be saved. The sump pump would also flood less in high water flow situations because instead of only turning on once the sump is full, it would detect the high rising water sooner and turn on to its highest setting quicker than a current sump pump could. It is dangerous to build a 250 Watt sump pump in only one semester so the sump pump this project will build is smaller than a home sump pump and will use 40 W. The end product will be a proof of concept, not a device ready to be sent to market.

1.2. Background

A sump pump is a device that displaces water from a sump pit. [2] In order to do so, this device usually contains a motor and a fan-like apparatus called an impeller. One reason this is needed in a house, is because excessive amounts of rain in a short period of time can overload basement waterproofing systems, saturating the earth around your basement and then pushing in through foundation cracks. [3]

Some houses have multiple sump pumps. The reason for this is it distributes the load of removing water from different areas of the house. also, some sump pumps have different designs such that one might be used as the primary pump, and would be the first pump to run whenever one is needed. But another sump pump might be designed as a backup sump pump. Being a backup sump pump, it may run on a battery because a power outage is a failure point that would keep the main sump pump from running. Also, parts may wear out or malfunction in the main sump pump and that is also where the backup sump pump gets involved.

Our sump pump will be designed to replace a backup sump pump but with some modification, it can also be redesigned to be used as a main sump pump. Since ours is a back up, we are designing it to run on a battery. Also, the device needs to be more efficient in how it uses power because it has a limited amount of power to run on since it is using a battery, so that the battery can sufficiently supply the pump for as long as possible. But, as stated before, since our device should be more power efficient, it can also be used to save power compared to a main sump pump.

1.3. High-Level Requirements

- The energy used to power the motor needs to increase as the water intake rate increases, ideally up to 36 W.

- The sensors need to detect the water level rising and signal to the rest of the system to turn on the motor before the water level reaches halfway up the model sump, which would be at 6 inches.
- It needs to be able to pump a reasonable amount of water, ideally over 80 fluid ounces per minute at maximum power.

2. Design

2.1. Block Diagram

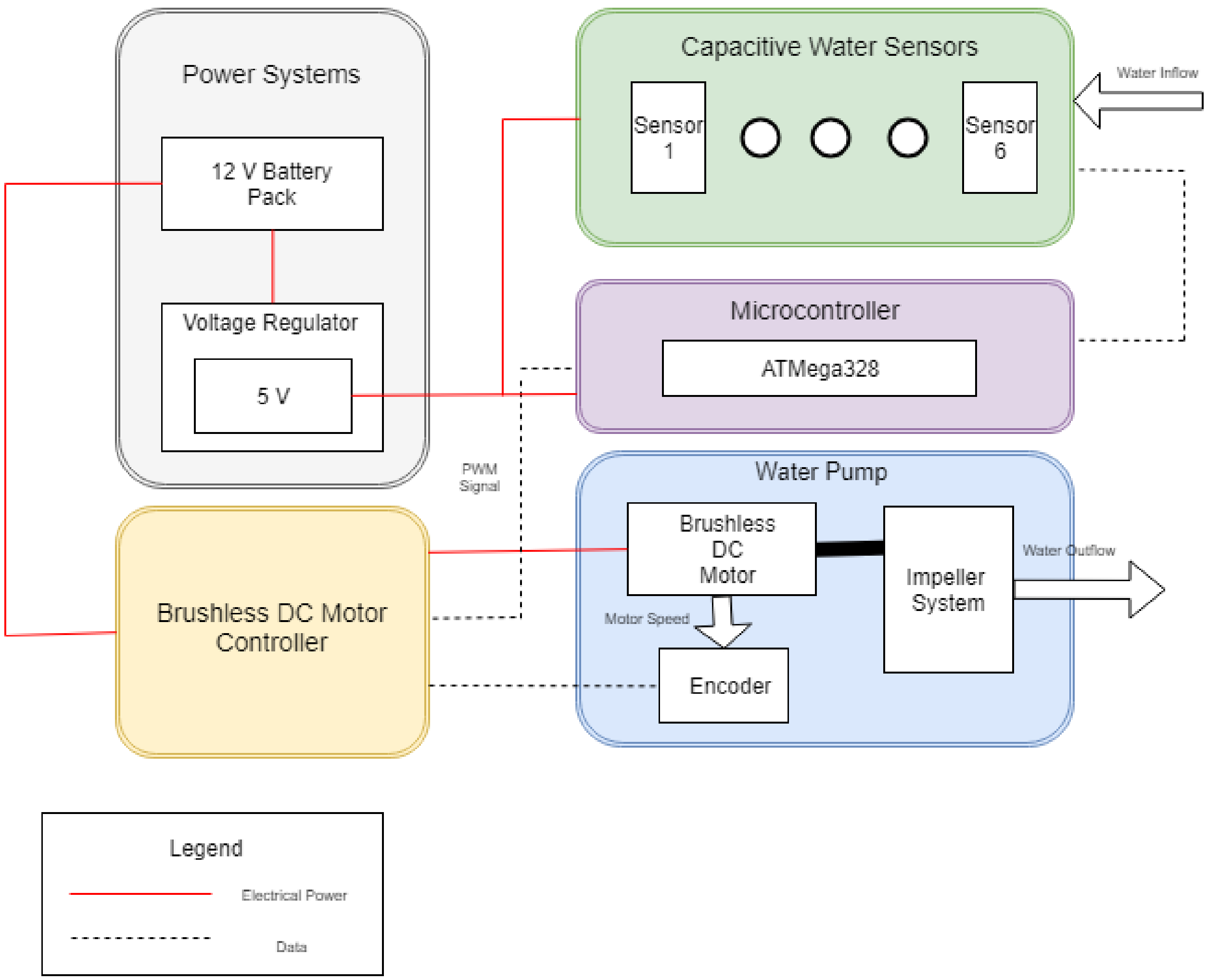

Figure 1. Block Diagram

2.2. Physical Design

A diagram of the model the sump pump design is seen as follows:

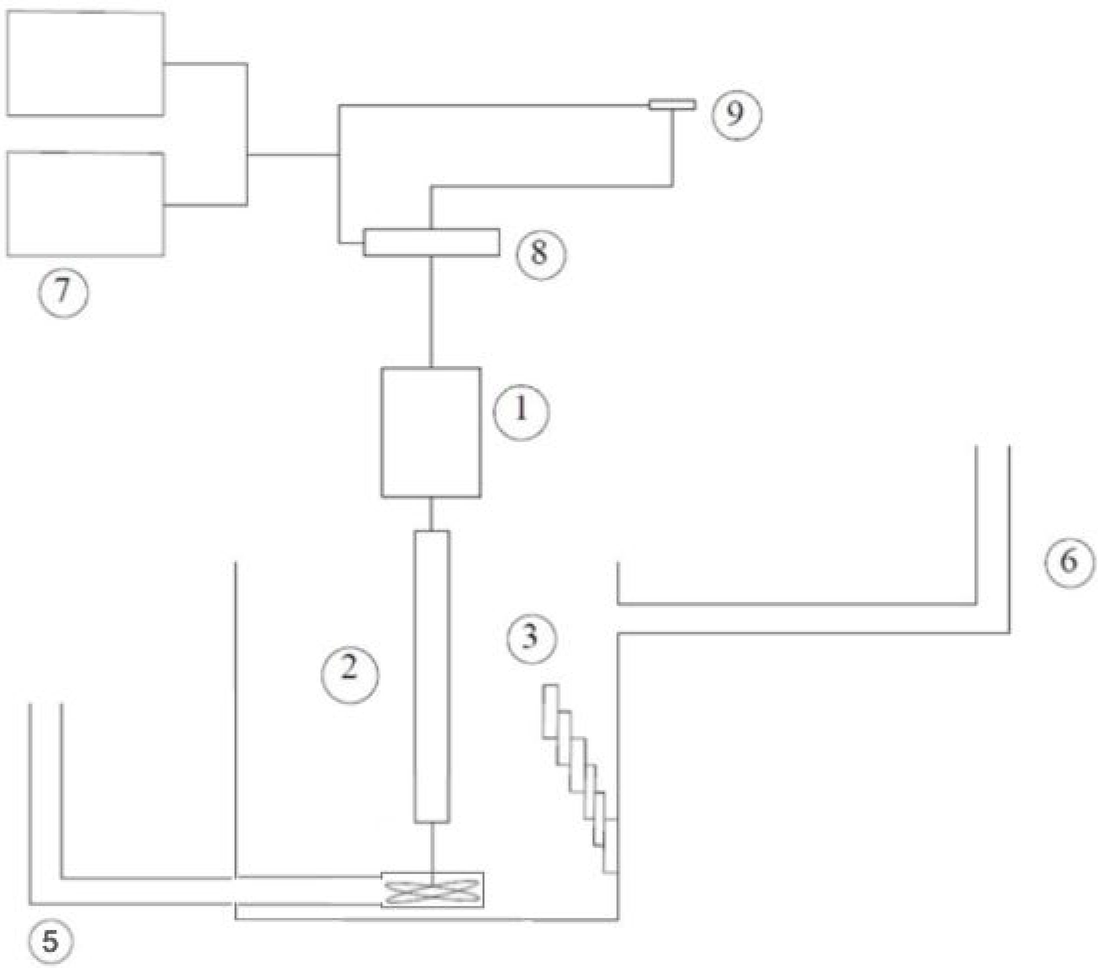

Figure 2. Physical Design (Tub used for safety precaution of containing water during testing and demo not pictured here. When actually used in the home, there would be no tub, and that is why the tub is not displayed here.)

Part Number	Part Name
1	DC motor
2	Axel
3	Sensors
4	Impeller
5	Output Pipe
6	Input Pipe
7	Battery Pack
8	Motor Controller
9	Microcontroller

Table 1. Legend

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2.3. Functional Overview and Block-level Requirements and Verifications

- Microcontroller
    - The function of the microcontroller is to receive data from the water level sensors and then send data to instruct the motor on how quickly to operate to the motor controller in the water pumping mechanism. The benefit of this approach compared to traditional sump pumps is the control and reduced latency it provides, as mentioned in the high level requirements. Also, the microcontroller receives power from a 9 V battery, receives data from the water level sensors, and sends data to the motor controller.
- Water Droplet Depth Detector
    - The project is using a Water Droplet Depth Detector in order to measure the water level in the sump pump. Using this water level reading, the rate at which

the water level is changing can be estimated, and the speed of the motor can be changed based on that.

Requirements	Verification
1) Microcontroller is able to send PWM signal to the motor controller.	1) PWM signals can be checked by measuring the voltage output with an oscilloscope.
2) Water level sensor needs to be accurate within at least 1.5 inches.	2) Test the readings sent to the microcontroller against viewing the water level with a ruler and the naked eye.
3) Microcontroller needs to be able to estimate the water level and rate of change of the water level based on analog signals output by the sensor(s).	3) a)The analog output can be made human readable through a connection from the microcontroller to the serial com port of a pc. b)This can be compared to a ruler in the bucket.

- Power
  - This project will have a battery instead of the wall plug to power the motor, the microcontroller and the sensors. The wall plug is directly connected to such a huge grid that if there is any inconvenience in the circuit, it would be too dangerous to have direct connection to that grid, which may lead in a fire in extreme cases.
  - A battery back of 8 AA batteries in series will power the motor controller, the sensors and the microcontroller. Two regulators will step down 12V to 5V for the sensors and the microcontroller.

Requirements	Verification
1) Battery must be able to provide 12 V of power to the voltage regulator and the motor controller within a ± 10% margin.	1) This can be verified by using a voltmeter to check the voltage of the battery.
2) The regulators must provide 5 V to the sensors and to the microcontroller within a ± 10% margin.	2) This can be verified by using a voltmeter to check the voltage to the microcontroller and to the sensors.
3) The motor controller should give the motor	3) This can be verified by using a voltmeter to

a maximum voltage of 12 V and a minimum voltage of 0 V depending on different PWM signals from the microcontroller.	check the voltage is 12 V to the motor when the microcontroller sends a signal for maximum voltage and 0 V for minimum voltage.

- Water Pump
    - Motor: The electrical motor would be an DC motor. Its rated voltage is 12V and rated current is 3 Amps. This is a motor for a RC boat, with a rpm ratio of 3800 rpm/V. This means that at maximum speed can run ideally at 45,600 rpm, but this number is unloaded. As our motor will be pumping water, this means that it will have a considerable load, so its maximum speed would be much lower.
    - Impeller: An impeller is a rotating component of a centrifugal pump which transfers energy from the motor that drives the pump to the fluid being pumped by accelerating the fluid outwards the center of rotation. An impeller is a short cylinder with an open inlet (called eye) to accept incoming fluid, vanes to push the fluid radially, and a splined, keyed or threaded bore to accept a drive shaft.
    - The motor is connected to the impeller by an axel and the impeller is funneled into an output pipe.

Requirements	Verification
1) When water reaches the top of the bucket, which will be 1 foot high, the motor should get 12 V from the motor controller.	1) a) This is a DC motor, so the motor runs at its highest speed at its highest rated voltage. The motor that is going to be used for this project is rated at 12 V. [4] b) A voltage probe can be used to check that the voltage to the motor is 12 V when water reaches the top of the bucket.

Table 2. Requirements and Verifications

2.4. Supporting Material

2.4.1. Water Pump Calculations

In order to get a better idea of the maximum rate the pump could theoretically work at, Water Pump Horsepower is calculated. WPH is calculated with the following formula [5].

$$WPH = HQ/3960$$

H is the height in feet and Q is the flow rate in gallons per hour. The maximum power the motor could theoretically output is the maximum voltage, 12 V, multiplied by the maximum current 3 A. This is a theoretical maximum, but it gives a reference for how much water can be reasonably be expected to be pumped given the motor used. Another factor to consider is the efficiency of the pump. The pump has not been built yet, but typical pump efficiencies range 65%-80%. [6] However, this pump is very small and will be handmade in a semester so its efficiency will likely be significantly lower. For the purposes of this calculation, 40% efficiency will be used. Therefore, the power supplied will be 36 W multiplied by .4, or 14.4 W. 14.4 W in Horsepower is 0.0193 HP. The height will be one foot.

$$Q = (3960 * WPH)/H = (3960 * .0193)/1 = 76.47\ GPH$$

76.47 gallons per hour is 163.136 US fluid ounces per minute. This is the theoretical expected maximum for the pump, which it shouldn't run at for most of the time. Half of this, or 80 US fluid ounces is the pumping goal for the high level requirements which seems achievable for a hand built pump in a semester.

2.4.2. Microcontroller PCB Design

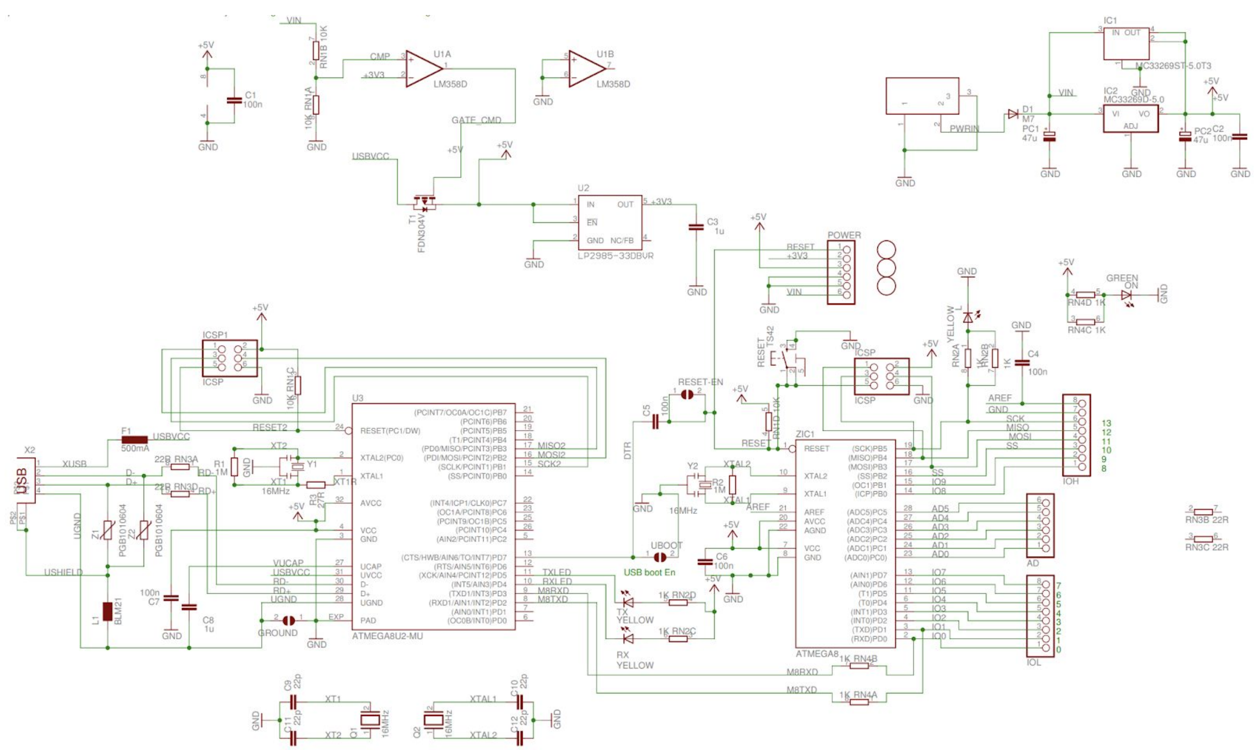

Figure 3. Schematic of the microcontroller and all other components on an Arduino Uno (not all of which will be used) [7]

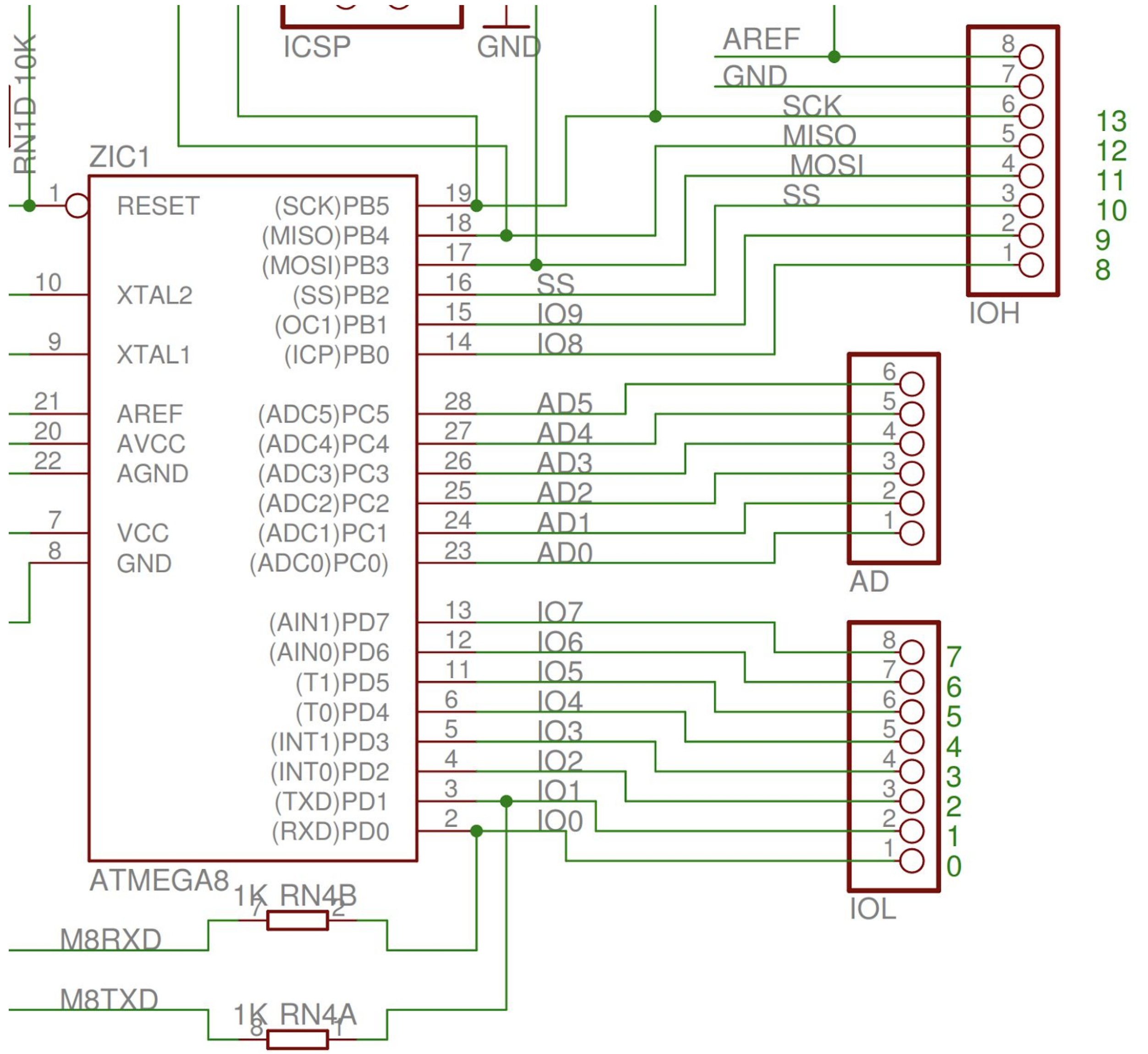

Figure 4. Zoomed in view of the microcontroller and its connections to the outputs on the arduino board. To be clear, we will mount the microcontroller on a PCB and NOT use an arduino board for the final design. [7]

The main component of interest in figure 3 is the ATMEGA8 which is almost the same as the ATMega328 microcontroller which we will be using. They differ in inconsequential which will not have any effect on our project and its outcome. They differ in ways such as being a surface mount device vs being a through hole device. Also, they differ in the amount of memory they have that is capable to hold a program. In figure 4, notice that the microcontroller has its own Analog to Digital Converters built-in. These are labelled ADC0 through ADC5. This is important because the signal we are taking from the sensor is analog. So, it simplifies the design to use this type of chip by just connecting the analog signal directly to the corresponding port. The other important port to take note of is the (OC1)PB1 port which is port 15 on the device. This port is also called IO9 on the arduino board. The significance of this port is that we will use it as the output for our Pulse-Width-Modulation (PWM) signal. Using a duty cycle, this signal will be used to control the speed of the motor. Our plan is to have the the motor not be running when the duty cycle is 0%, and when the duty cycle is 100%, the maximum amount of torque (and eventually the maximum speed as well after an expected amount of latency) will be output by the motor. In-between those two values, the output of the motor should be directly (and most likely linearly) related to the duty cycle of this PWM signal.

2.4.3. Programming Flow Chart

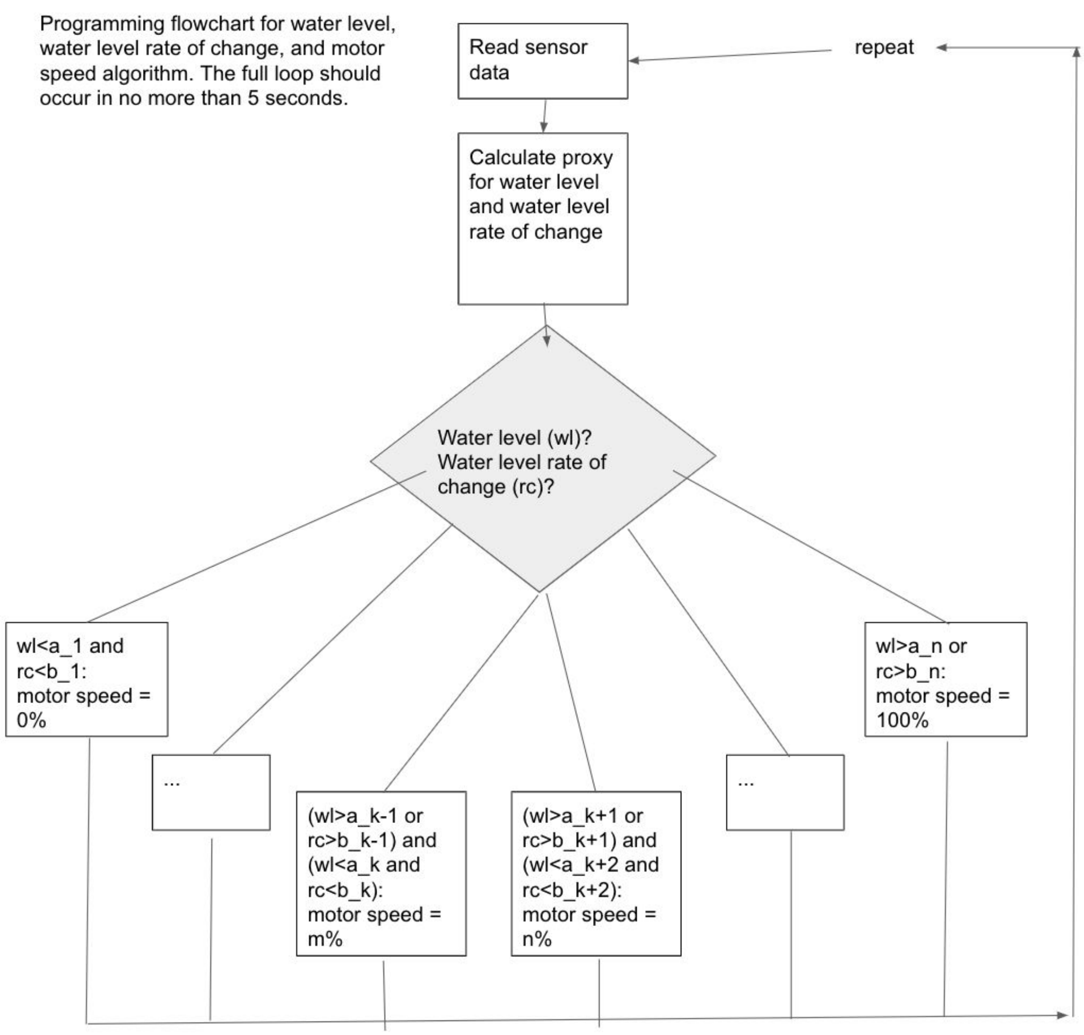

Figure 5. Programming flowchart

The programming flow-chart used above in figure 5 is self-explanatory. Just to give some context, this program will be written in C, and the source code will be flashed onto the microcontroller. Also, we will be using a microcontroller that already comes with the arduino bootloader. The bootloader is responsible for setting up the microcontroller when it is turned on and also for handling the interruption and resetting of the whole device when the RESET button is pressed.

As long as the microcontroller is powered on and has the source code flashed on it, the loop seen in the flow chart will run virtually forever. Ideally, the length of time it takes the program to complete this loop would be very short. But, optimizing the time this loop takes is not one of the main goals of this project this semester. Even without devoting much development time into the optimization of the latency of this loop, this loop should run in under 200 ms.

2.5. Tolerance Analysis

The main component we will need to conduct tolerance analysis on is the sensors. There are a couple different ways in which they can be technically specified and therefore, in which they can fail to meet their stated specifications. The first specification is latency. Through some preliminary testing, we have determined that the minimum time to take a reading using our current sensor and microcontroller set up is 5 milliseconds. The microcontroller is capable of sampling at least every millisecond, but the sensor only outputs data about every 5 milliseconds. This is still very fast compared to our requirements of reacting to changes in the water level within 5 seconds. But, there are other places in this system in which we can lose time. For instance, after 5 milliseconds, we only get a single data point. What if that data point is not very accurate? We have to expect that it will not be perfectly accurate all the time especially considering the chaos and randomness of a liquid, such as waves and droplets from splashing. Therefore, we need to take multiple readings and combine them to get a better estimate of which ones are probably accurate. So this can take an additional amount of time on the order of 10’s to 100’s of milliseconds depending on how many data points we want to sample. Next, the algorithm itself takes some non-zero amount of time to do its computation. I have not written it yet, but my estimate is that it will take no longer than 1 second to compute but will probably be much shorter than that. The biggest source of time delay is what comes after the microcontroller, the motor controller and the motor. The motor controller might take some time to adjust the signal from the microcontroller to one appropriate for the motor. But, the motor itself will take the longest time, especially since it is a physically moving part that needs to change its angular momentum while interacting with a liquid which slows it down nonetheless. The goal of this project is not to do detailed fluid dynamics, but to create a proof of concept. That is why it is reasonable to allow for the motor taking around 3 seconds or so to change its angular speed based on the signal it receives.

Aside from the latency, the accuracy of the water level measurement coming from the sensors is very important. The way the sensors work, is they report a value using an analog signal based on how much of their surface is covered in water. There is some variation here compared to a strict reading of water level with a ruler because sometimes water droplets splash onto the sensor or stick around on the sensor even after the water level has receded. This is where duplication and multiple sampling will help. Our plan is to have each sensor slightly overlapping the vertical height of the one before it and after it, that way you get 2 readings for each possible water level that can be measured. A way in which we are easily able to tolerate this as well is that our priority is to make sure the pump doesn’t allow overflowing more than the priority of saving energy. Our tolerance coincides with this because if a sensor falsely reads that the water level is higher than it actually is, and therefore the motor runs faster than it needs to, the pump will mistakenly pump out more water than it needed to. So, we are sacrificing a little bit of energy efficiency for reducing flooding risk. Regardless, these 3 inch long sensors should be an improvement over the current float switches even if they are not that precise. Float switches currently measure water level with a precision as low as 6 inches, whereas the sensors we chose, even if they were used with a binary threshold, would have a precision of 1.5 inches, which is a great improvement.

3. Cost & Schedule

3.1. Cost Analysis

3.1.1. Labor Costs

The average UIUC EE BS graduate earns $68,000 according to the UIUC ECE website and the average CE BS graduate earns $84,000. [8] Given an average work year of 45 hours/week and 50 weeks/year, the average salary of an EE graduate is $30/hour and the average salary of a CE graduate is $37/hour. When these two are averaged together, the average ECE graduate makes $33.5/hour. The following formula can be used to determine the total labor costs given the length of production time.

$$10\ hours/week\ * \$33.5/hour\ *\ 2\ people * 2.5 * 16\ weeks\ =\ \$26,800$$

3.1.2. Parts Costs

The cost of each of the components would be:

Part Name	Quantity	Price
WINGONEER Water droplet depth detector	6	$1.60/unit
SparkFun RedBoard - Programmed with Arduino (Includes ATmega328 microcontroller)	1	$19.95/unit
DC-DC converter 12-5 V (KNACRO DC-DC Voltage Regulator Buck Converter	2	$6.99/unit

Module)		
Jrelecs 3660 3800KV RC Brushless Motor	1	$25.50/unit
8-Cell AA Battery Holder	1	$1.95/unit
Duracell AA Battery	8	$2/unit
Qunqi L298N Motor Drive Controller Board	1	$6.89/unit
Premade Impeller	1	$5.05/unit
Axel	1	$2.00/unit
Total		$93.93

3.1.3. Total Costs

The total cost can be calculated by adding the parts cost to the labor cost.

$$Total\ Cost\ =\ Labor\ Cost\ + Parts\ Cost\ = 26,800\ +\ 68.43 =\ \$26893.93$$

3.2. Schedule

Week	Carolyn	Edward
2/25/2019	Revise design document to rescope project. Order motor.	Rescope project. Begin running experiments. Test/optimize sensor accuracy.
3/4/2019	Revise design document to rescope project and accommodate a a two person group.	Test/optimize sensor reliability
3/11/2019	Buy water pump building supplies (axel, impeller, batteries) and build water pump.	Create physical design that allows fastening the sensors inside the sump pump tank.

		Design and test microcontroller PCB schematic. Send in at the end of the week.
3/18/2019	Continue building and testing the water pump. Make test tub setup.	Confirm sensor reliability (in case you need to design and manufacture a water proof enclosure in the machine shop)
3/25/2019	PCB board design final check/revisions.	Start developing water level and water level rate of change algorithm
4/1/2019	Connect water pump to motor controller and assemble test setup.	Connect microcontroller to motor controller to motor.
4/8/2019	Debugging	Debugging
4/15/2019	Test how much water the sump pump can pump out. Test energy efficiency of sump and that it activates earlier than at the top of the sump.	Begin final presentation. Finish anything that needs to be done before demo.
4/22/2019	Begin final paper	Begin final paper
4/29/2019	Finish final paper	Finish final paper

Table 3. Schedule

4. Ethics and Safety

In regards to our project, since it pretty closely resembles the sump pumps that are currently in use around the world, it basically has the same ethical and safety issues as current sump pumps. In accordance with the IEEE Code of Ethics, line 1, we are “to hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, and to disclose promptly factors that might endanger the public or the environment”. The way in which this applies to us is the safety of the moving parts being properly controlled, and the water being manipulated in a safe way. Some safety precautions include things like never allowing children to use or get too close to an accessible sump pump without adult supervision.Our sump has the same safety warnings as any high power home appliance with a high rpm (rotations per minute) moving part. Caution needs to be used such that whenever the moving parts (impeller, axis, and motor) are being exposed or interacted with, especially for maintenance or replacement, the whole device must be completely powered off and you need to wait until all parts stop moving before interacting with it.

What is unique about our project is that the motor can run at different speeds. So, the safety and ethical concerns related to that include making sure that the motor doesn't attempt to run faster that it is capable of. For instance, in an adversarial condition, someone may try to make the pump run so fast that it damages the pump and pieces fly out of the mechanism because it is rotating at such a high speed. This is not something to worry about though because the rotating impeller will be in an enclosure. Also, the pump will not be connected over a network, so the only will an adversary can tamper with the pump is by having physical access to it.

Sump pumps are a critical defense for homeowners in protecting their property from water damage. Flooding costs the United States 3 billions dollars a year. [9] Therefore it is critical that the variable speed sump pump is reliable as failure in the pump could costs thousands or hundreds of thousands in dollars to homeowners. Unreliable pumps or incorrectly installed pumps could cause millions in litigation. [10]

Some caution does need to be taken while working in the lab since we will be working with water. During testing, we need to make sure we always keep the water contained. We can do this by always conducting our experiments in a larger enclosure such as a tub. We also need to properly handle the amount of power our device is drawing. If we find any safety concerns in addition to this, we must disclose them to anyone who will be working with this device immediately. This includes everyone in our team, and our TA. Once found, we need to come up with a plan on how to deal with any of these newly discovered issues before proceeding to work with the pump again.

The experiment requires working with lithium-ion batteries which can be dangerous and explode or catch on fire. A way to mitigate the danger of lithium-ion batteries is by using batteries from reputable companies.

5. Citations

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