Multi-Instrument Suite

ECEN 495
Group 159
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Abstract

The project covered in this report is a scientific instrument that is designed to be inexpensive and easy to use, therefore lending itself to middle and high school academic settings. The group was chosen to continue a project started by a previous senior design group. That group was contacted by Dr. Peter Sutter, a professor in the Department of Electrical and Computer Engineers. Dr. Sutter helps with STEM outreach in parts of rural Nebraska and identified a need that rural schools have for inexpensive, easy to use scientific tools. The idea for this project is to construct a device that uses a number of different sensors with an ATmega328P microcontroller. This was accepted as the microcontroller because the Arduino programming environment is simplified compared to other microcontroller Integrated Design Environments.

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Introduction

The measurement suite designed is suited to perform classroom based measurements for middle and high school students. The device contains a custom made PCB with all circuitry needed to measure temperature, pH, mass, vertical and horizontal displacement, and voltage in real time. External memory is added to store measured data to be outputted to a personal or lab computer.

The device contains a keypad that is used to maneuver through the user interface. The keypad will allow the user to move between and select sensors. Once selected, the user may read real time measurements or choose to store data for output. A memory menu of the user interface will show the remaining memory space, with an option to clear or output the data into the Arduino IDE through a connection from the device. Each sensor will be able to connect directly to the device, after which the corresponding sensor must be selected in the user interface.

This device is meant to be easily reproduced for any classroom that desires it. All sensors can be replicated or only a few that are desired. The files containing our PCB design, 3D models, and code are made available on the below website along with links to tutorial videos on the use of the device.

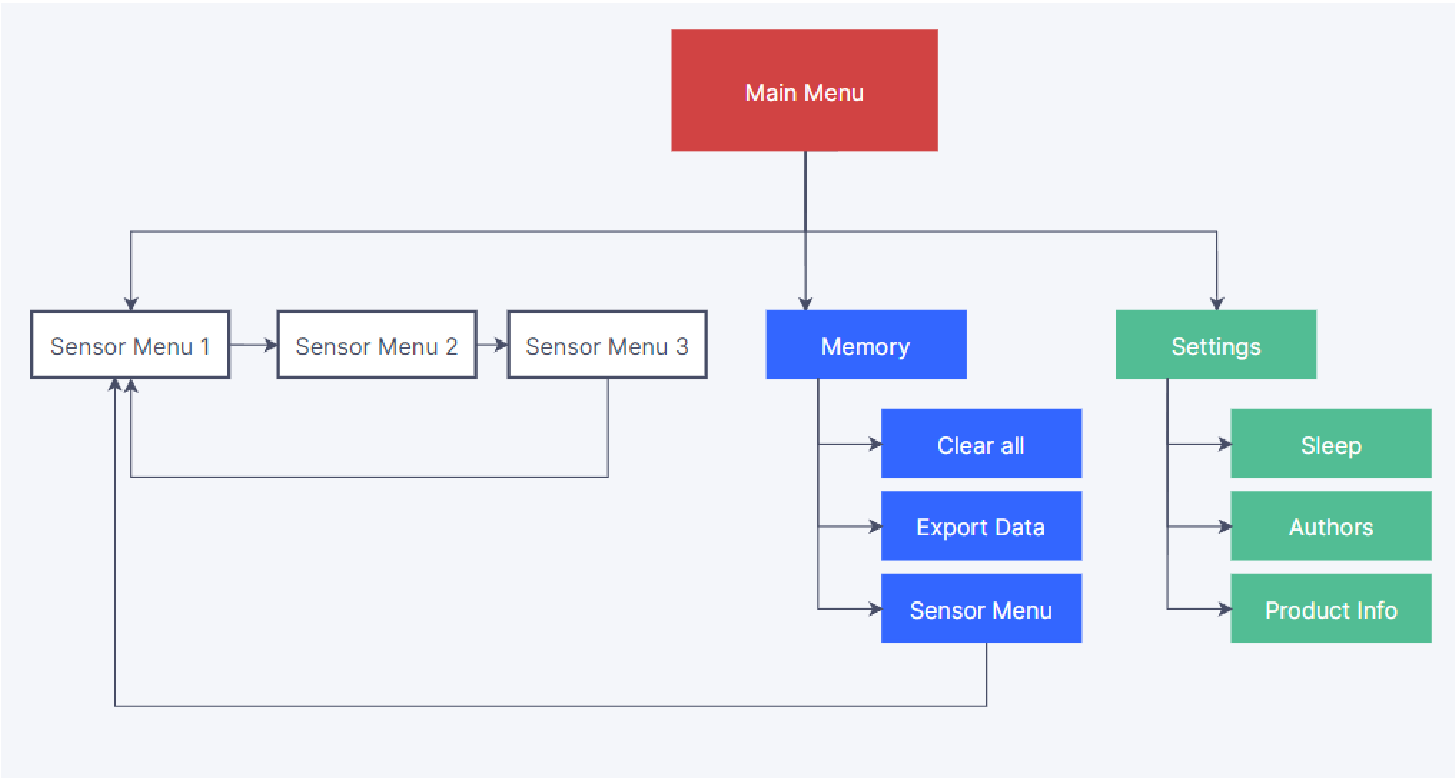
User Interface

The user interface is navigated using a keypad on the device and the mounted LCD display. The UI toggles through menu options in a list vertically, with options nested inside of each vertical menu option that can then further be navigated through. The keypad provides inputs in the cardinal directions, with up and down toggling through options in a given menu while the left key is used to go back a menu and the right key is used to progress to the next menu.

Keypad Control

The keypad is composed of 4 mechanical keyboard buttons. The PCB for the keypad is attached to an ADC pin on the ATmega328P. Voltage division is used to determine which key was pressed. The up and down keys toggle the menu options vertically on the present screen – the left and right arrow keys are used to go back a menu or advance, respectively.

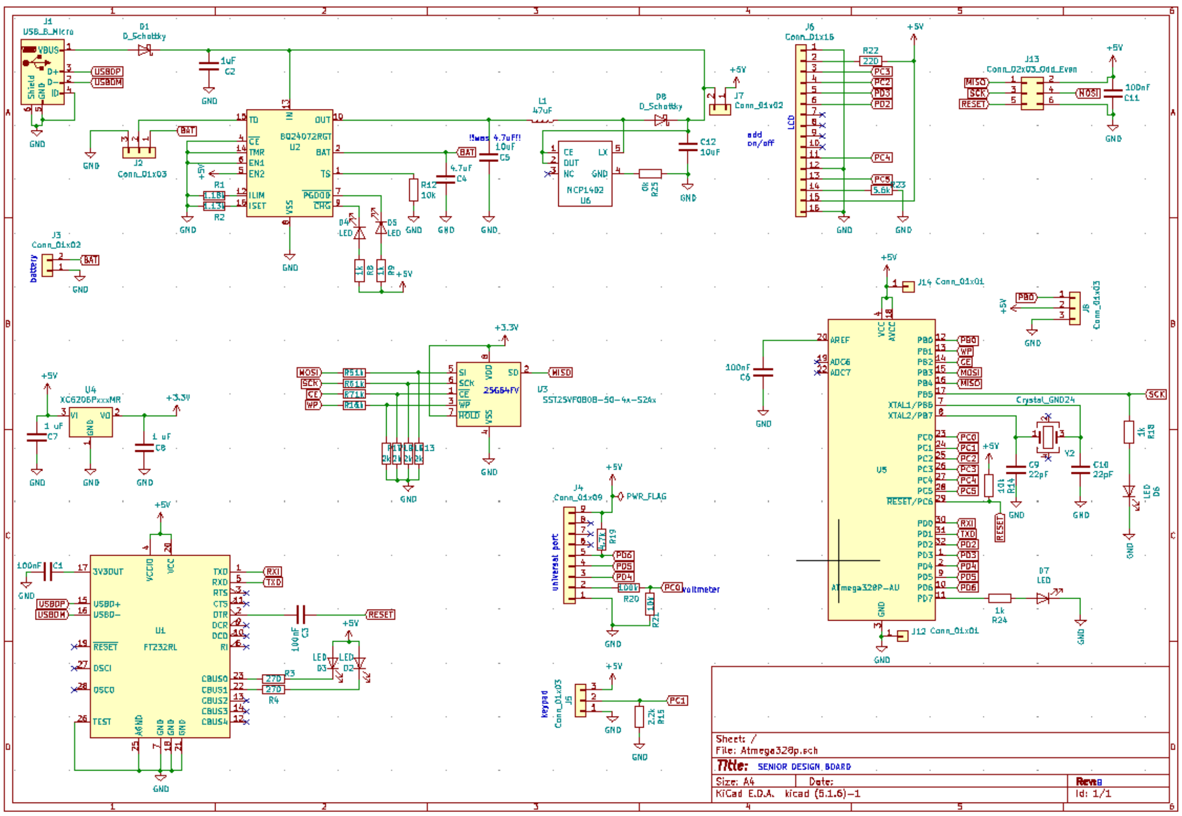
GUI Map



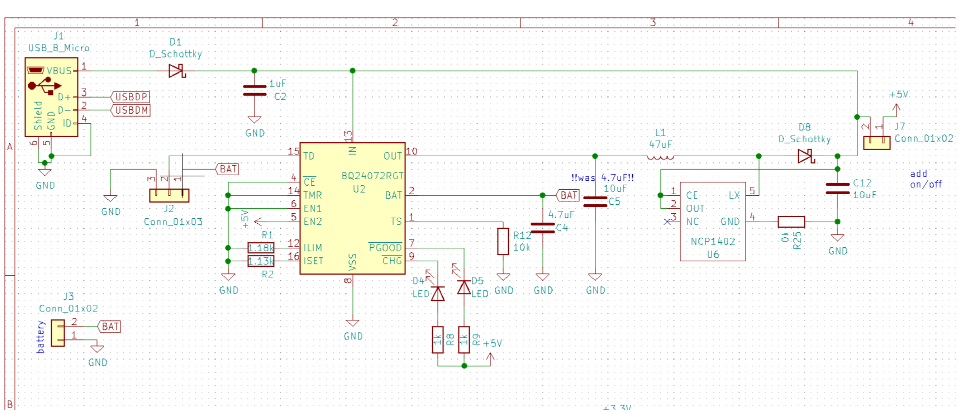
Main Menu
Sensor Menu 1
Sensor Menu 2
Sensor Menu 3
Memory
Clear all
Export Data
Sensor Menu
Settings
Sleep
Authors
Product Info

PCB Design

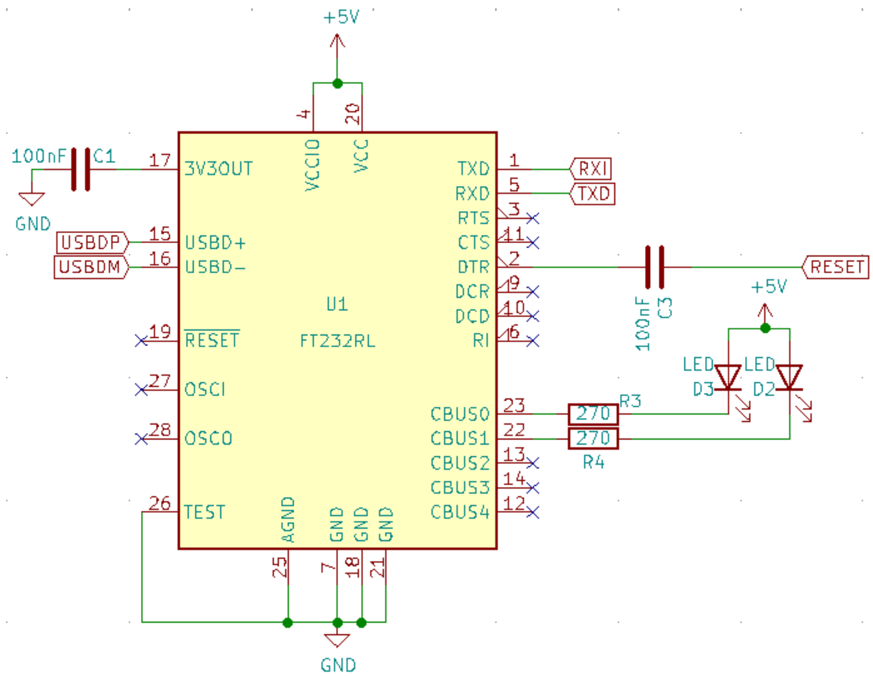
Below is the most recent version of the printed circuit board schematic.



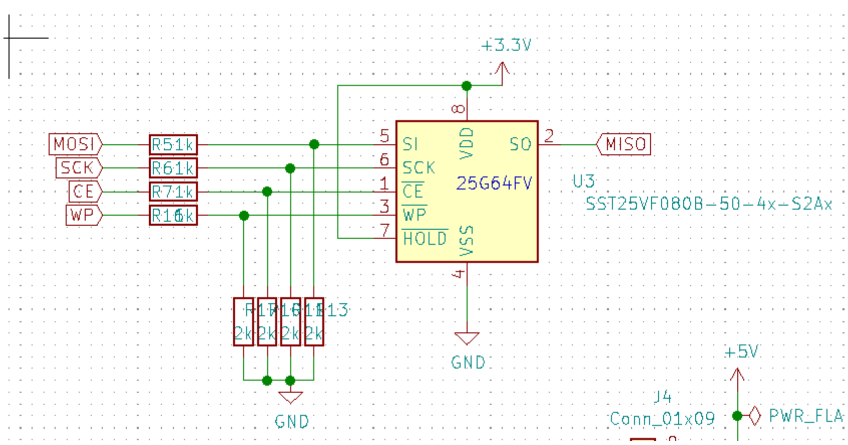
Below is the Power Management circuit.



Below is the USB to UART circuit.

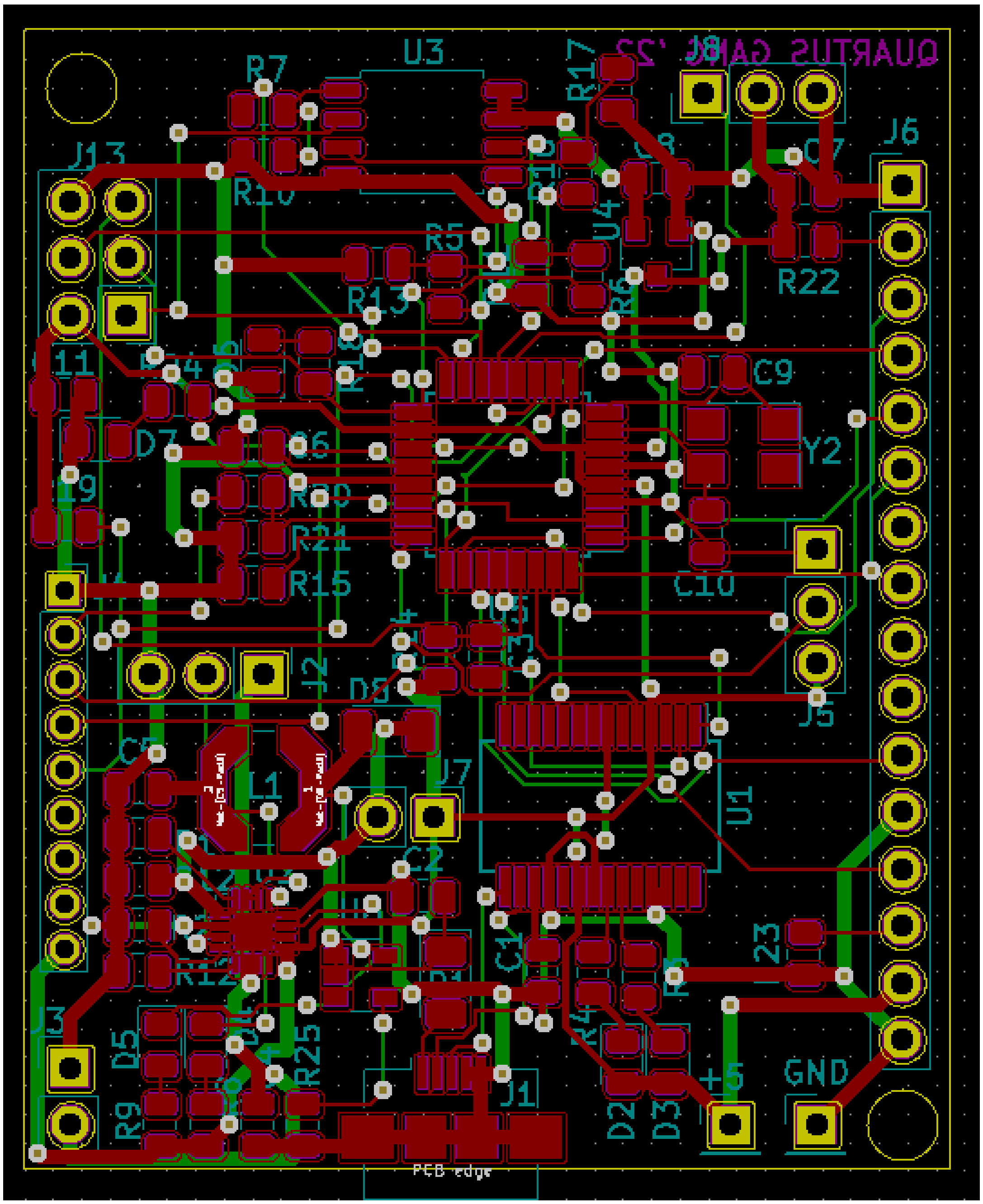


The memory circuitry is below.



PCB Layout

Below is the most recent PCB layout.



ATmega328P and PCB Pin Connections

Our PCB is built around using the ATmega328P microprocessor used in the Arduino Uno. The external connections on the board are as follows:

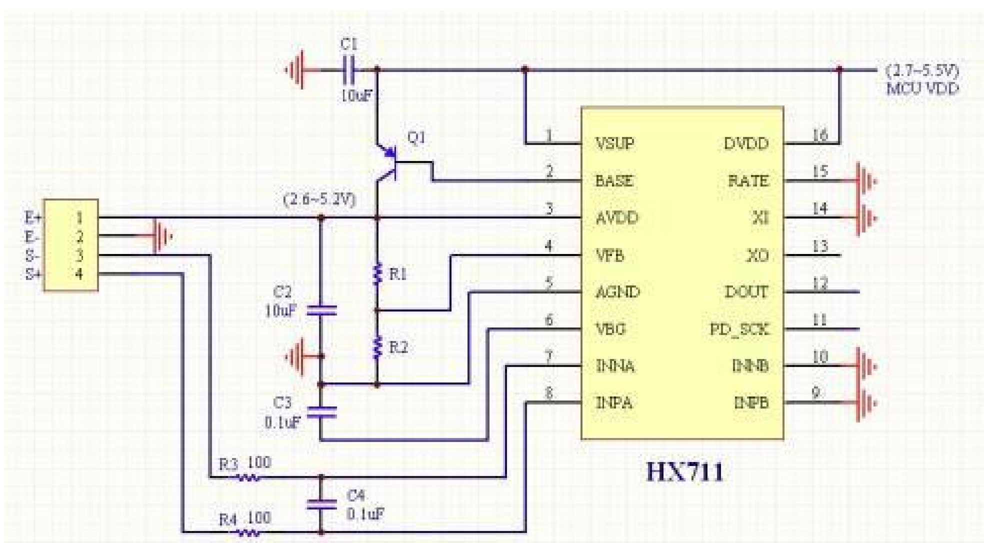
- FT232RL to Micro-USB
- 16-pin rail for LCD
- 9-pin 440055 to 440129-9 for sensor connections

Voltmeter Circuit

The voltmeter is limited in input to 5 VDC and 40 mA. Due to these constraints the input voltage needs to be scaled down so that users can measure a wider range of voltages. This down-scaling is achieved through the use of a voltage divider circuit. For this sensor a maximum input of 50 V is desired which requires the use of a 10:1 voltage divider. This is achieved by selecting R1 to be a 100 kΩ resistor and R2 as a 10 kΩ resistor.

Digital Scale Circuitry

The Digital Scale requires extra circuitry outside of the microprocessor and 1 kg load cell. The load cell has four connections to it that measure voltage variations across internal resistors in the load cell. These values change when the load cell is stressed from mass applied to it. Two connections (E+ and E-) are used as a reference voltage and ground for the internal resistances. The other two (S+ and S-) are used to measure voltage variations. These variations are too small for the ADC of the ATmega328P, as an external 24-bit ADC is used called the HX711. This ADC and required extra circuit is built into our PCB and detailed below.



LCD

A 16x4 LCD was used to display the user interface for the device. The 16x4 LCD has a 16 pin interface that connects one-to-one on the ATmega328P.

Connections and Communication

The ATmega328P communicates with the display using one 16-pin connection. The display is written to by using the built-in LCD library provided by the Arduino IDE.

Data Logging

Read/Write Functions

The Multi-Instrument Suite has limited data logging capabilities. These functions are enabled by the use of a Winbond W25Q16JV 16Mbit Serial Flash chip. This non-volatile memory communicates with the ATmega328P using the SPI serial communication protocol. Certain sensors contain this Read/Write functionality, and will continually write samples at the specified rate until the sensor's allotted memory is filled. Currently the ability to save a single sample at a time is what is enabled for all sensors. This can be done by entering the sensor's UI interface and selecting the "Save" option, which then writes the current sensor value to memory. The memory chip can also be erased entirely through the settings menu in order to clear saved samples.

Issues

One major issue the project is facing is the battery. It is currently using a BQ24072 chip to regulate the switching from usb power to battery power along with assisting in charging. With the boost circuit added on, the NCP1402, the output voltage from the BQ24072 drops from 4.2v to 0.3v. The same thing happens when the boost circuit is removed and a 1k resistor is added to ground from the output. There seems to be an issue only when there is a load. Our solution would be to remove the boost circuit and change the battery from a 3.7v battery to a 5v battery.

Sensors

Temperature & Humidity

The temperature sensor will allow users to measure the temperature of the air or anything the probe is placed in or touched to with a high degree of accuracy. Experiments regarding temperature (either ambient or in an experimental setting) are very common in science classes, especially chemistry. This could be used to monitor how temperature changes during an exothermic or endothermic reaction. In addition, we will allow for data logging to be performed with this sensor. An experiment where this would be useful would be monitoring outdoor temperature for an extended period of time. With this tool, students could monitor ambient temperature and humidity for a week and see how these values change over time.

The temperature sensor used is the Mouser DFRobot DFR0198 waterproof digital temperature sensors. It is a 3-pin design connected directly to a probe. It has an operational range from - 55 to 125 C but is recommended to keep under 100 C. Beyond this, a temperature and humidity sensor are included in order to gather data on the ambient temperature in the room. This sensor is unable to be used in liquids which is why the waterproof temperature sensor is included.

pH

The pH meter is a device that measures the acidity of a liquid. The reading will be a value from 0 to 14, with 0 being the most ‘acidic’, and 14 being the most ‘basic' or ‘alkaline’. A reading of 7 indicates a ‘neutral’ substance, which is that of pure,distilled water. In the classroom, the pH level of a solution is often an important characteristic in chemistry experiments.

The module being used for our application is the Arduino Gravity Analog pH sensor. The board itself has an on-board voltage regulator, to support supply voltages ranging from 3.3 V to 5 V.

The probe connects to the breakout board via BNC connector, and has a +- 0.1 pH degree of accuracy at 25 degrees Celsius, although the electrode can operate between 5 and 60 degrees Celsius. The electrode itself is a glass membrane, usually containing water (pH 7), which creates an environment of constantly binding H+ ions on the inside of the membrane. When dipped in a solution the ions on the membrane begin exchanging with the positive ions in the solution, creating an electrochemical potential across the membrane.

Beam-Break Sensor (Vertical Displacement)

The beam-break sensor is a device designed to help students with making experimental measurements for basic kinematic experiments such as time of flight, velocity, and calculating the acceleration due to gravity. The sensor has a very simple setup, an infrared LED is placed directly across from an infrared receiver sensor. At a resting state the IR LED is constantly hitting the receiver and inducing a voltage that is read through an analog I/O pin. When the beam is broken the analog pin drops low indicating that an object has passed through the beam.

For beam-break experiments such as measuring the acceleration due to gravity or calculating the velocity (given that the initial velocity when the beam is broken is zero) two sensors are required. These sensors will be inserted in 3D printed housings that can be placed on a standard chemistry ring stand. Knowing the distance between the sensors is key for making calculations, so each sensor has the capability to be adjusted so the distance between the two sensors is controlled. Once the first beam is broken, the custom Arduino will write to an initial timer variable and begin counting using the internal clock. When the second beam is broken a new final time variable will be written to and the initial time will be subtracted from the final time to display the total time the object was falling between the sensors.

Digital Scale

A method of finding the mass of objects is important in high school physics and chemistry courses as it is fundamental to kinematics, force relationships, and chemical reactions. The digital scale is based on a 1 kg load cell that, when stressed, outputs varying voltage levels dependent on the stress on the load cell.

Voltmeter

The digital voltmeter functions through the use of the ATmega328P's analog input/output pins. Since the analog pins are limited to 5 volts DC and 40 mA the input voltage needs to be scaled down to avoid damaging the microcontroller. The sensor utilizes two simple leads connected to the ADC through the universal connector.

This voltage scaling is done through the use of a voltage divider. For a maximum input voltage of 50 V a 10:1 voltage divider needs to be constructed to properly scale down the high input.

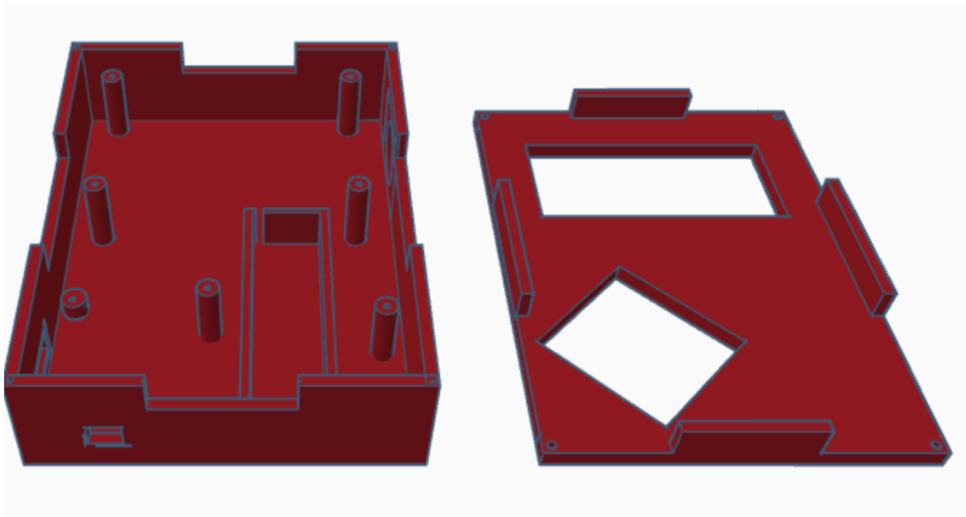
Linear Displacement and Velocity

Linear displacement and velocity are measured using an HC-SR04 Ultrasonic Range Finder. This sensor uses 40 kHz pulses combined with a microphone to accurately measure the distance from the sensor with an accuracy of 3mm. The sensor takes a 5V DC input and draws 15 mA while operating. From the horizontal face of the transmitter an object can be placed 15° above or below the microphone before going undetected. It is recommended that a large surface area object is used when taking measurements.

As previously stated the HC-SR04 uses a 40 kHz sound pulse to measure the distance an object is from the sensor. If the measured object is within the sensor's field (+/- 15° from the horizontal axis and less than 4m away) the output pulses bounce off the object and are received by the sensor. The ATMEGA328-P performs this calculation by reading digital values produced by the “Trig” pin (output) and the “Echo” pin (input) and utilizes an on-board crystal oscillator to determine the amount of time it takes to receive the echo. By calculating the time it takes between a pulse and the echo the sensor is able to calculate the distance from the microphones to within 3mm.

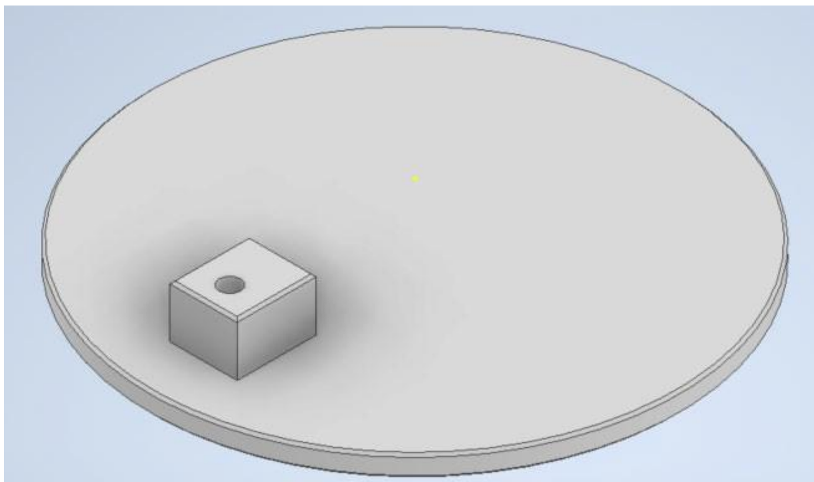
Housing

The housing for this device is made from two separate 3D printed pieces. The first piece is the main box that the board, battery, switch, keypad, and LCD screen all go into. This is printed as a single piece with supports and screw holes for the LCD, Keypad and board. The button is pressed into the side of the piece while the battery rests inside in a smaller box. Two holes are left on the bottom left of the case for the universal connector and micro USB power cable. The second piece is the lid that is pressed fit on top of the first piece and can be screwed down if need be. The lid allows for the keypad and screen to be accessible while hiding all of the other components and wiring.



Digital Scale Platform

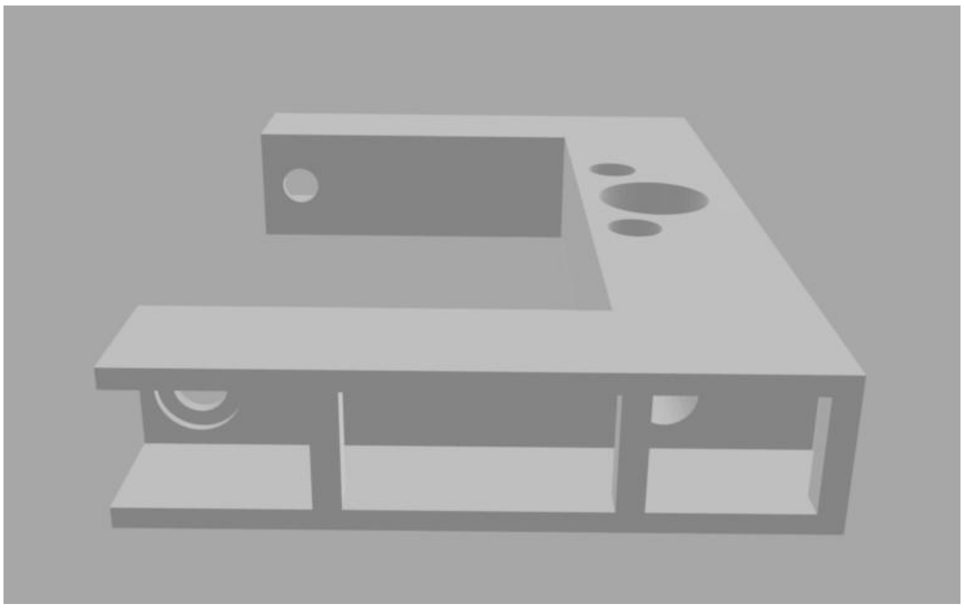
The digital scale is based on the 1 kg load cell. This cell requires a 3D printed platform so that items can be easily placed on the platform to be weighed. The platform consists of two identical pieces shown below.



The load cell is then placed on top of the extruded piece shown above, with the arrow on the cell pointing down, and screwed in from the bottom with the nut placed on top. The top side of the platform will be spun 180 degrees relative to the picture above and then inverted. The platform will screw into the load cell from the top, fastened with the nut, so that any weight added to the load cell causes it to bend, producing the voltage variations needed for measurement. This platform will have to be tared so that the initial value is 0 aftering going through the calibration procedure.

Beam-Break Platform

The two sets of beam-break containers will be built so that the sensors can be held directly across from each other and can be adjusted so that distance between the sets can be controlled.



In order for the infrared sensor to function properly the IR LED and sensor have to be directly across from each other. If they are not across from each other the sensor will not be generating a voltage indicating that the beam is broken.

Complete control of the separation between sensors is very critical. For kinematic experiments such as calculating the final velocity and measuring the acceleration due to gravity students need to be able to control the displacement variable. Being able to mount the sensors and adjust them allows for experiments to be unique as well as provides an easy setup.

Power

The largest constraint when designing attachments for the measurement tool is the power consumption. At normal operating voltages (5 V) the ATmega328P microcontroller draws 2.4 mA. When operating with some safety considerations the maximum power consumption of the board is limited to around 200 mW. When power consumption is above 200 mW sensors may not work, code may not be able to be updated, and inputs may begin to break. It is important to also note that when attaching sensors to the analog input and output pins that the maximum DC voltage must be below 5 V.

Future Product Expansions

An important expansion would be to fix the issues with the BQ24072 when placed under load. Remedying this issue would add the ability for the device to be used without being connected to a PC by using the battery. It would also enable simultaneous charging of the battery and use of the device. Another important expansion would be to add greater capabilities to the working memory platform that was started on this device. This could include continuous data logging, sorting organized data, and other functions that would help expand the capabilities of the device.

Production Ramifications

In terms of ramifications, our project does not pose a significant environmental threat with the exception of the type of solder used. Switching this to a non-lead-based solder would be a simple resolution to this issue. Along with this, there are some ethical concerns to be noted with regard to which capacitors are used in production. If ceramic capacitors are used, there are few issues to be noted, however, tantalum capacitors are known to be sourced from highly unethical production methods. Aside from these two issues, nothing in our project is a major cause for concern so it can be scaled up to large volume production with little consequence assuming these issues are kept in mind

In terms of repairability, our project is fairly modular meaning if a sensor stops working, it can be easily swapped out since none of them are hard-wired to our PCB. However, if an issue with the PCB arises (components burning out or the memory chip being exhausted), either a new board will need to be printed or the individual components that failed will need to be removed and a new component will need to be re-soldered by hand.

If we were to scale production up to the level of 100,000's of units, the main issue that would need to be resolved would be to ensure a proper supply chain is implemented which can fully assemble the PCB's and casings automatically.

Conclusion

The unit being constructed, a set of scientific test equipment controlled by an Arduino based microcontroller, has the opportunity to provide a low-cost alternative for precise scientific measurement tools. Not only does it broaden the range of experiments that can be performed, but it also introduces middle school and high school students to coding in a very user-friendly environment. This is particularly helpful for lower-income schools and schools located in rural parts of the country that cannot afford proper equipment for STEM classes. It is the hope of the group that once this unit is delivered to students that they will take the creative liberty to explore microcontroller programming knowing that all of the sensor code is accessible and available for upload in the event that students get lost or confused.

User Manual

All source code, CAD files for enclosures, schematics, and instructions for building and operating the unit are available through a website. Videos tutorials relating to the usage of the GUI and each sensor will also be linked through the website.

Parts List

1x ATmega328P
1x NCP1402
1x XC6202
1x FT232rl
1x W25Q16JV
1x BQ24072
1x 16MHz
1x 18650 Li-ion battery
1x 440055-9 connector
7x 440129-9 connectors
1x Micro USB connector
4x 100nF Capacitor 0805
3x 1uF Capacitor 0805
1x 4.7uF Capacitor 0805

2x 10uF Capacitor 0805

2x 22pF Capacitor 0805

2x Schottky diode 1206

6x LEDs 0805

1x LP55030 - 47 uH Inductor

10x 1kΩ Resistor 0805

2x 270Ω Resistor 0805

4x 2kΩ Resistor 0805

4x 1kΩ Resistor 0805

3x 10kΩ Resistor 0805

1x 2.2kΩ Resistor 0805

1x 4.7kΩ Resistor 0805

1x 100kΩ Resistor 0805

1x 220Ω Resistor 0805

1x 5.6kΩ Resistor 0805

1x 0 Ω Resistor 0805

4x Gateron Blues

1x 16x4 non graphical LCD display

Sensors

Digital Scale	PH	Temperature
2 M4-.07 x 20 mm Screws	Arduino Gravity Analog pH Meter	Mouser Temperature Sensor Mouse P/N: 426-DFR0198
0.3 mm Allen Wrench	3 Male-Male Wires	3 Female Headers
1 kg load cell		3 Male-Male Wires
50 g Mass		

‘Scale Platform’ x2		
4 Female Headers		
4 Male-Male Wires		

Voltmeter	Linear Displacement	Vertical Displacement
Male-to-Male Jumper Cable x2	HC-SR04 Ultrasonic Range Finder	5mm IR Beam Break Sensor set x2
		‘Beam-Break Enclosure.stl’ x2

Graphical LCD

1x 16x4 non-graphical LCD display

Casing

The case is constructed out of 3D printed PLA as it is the most widely available filament and the easiest to use in terms of 3D printing difficulty.

Printing of Devices

To build the device you will need the files for the scale, beam break sensor, and casing all mentioned in the parts lists.

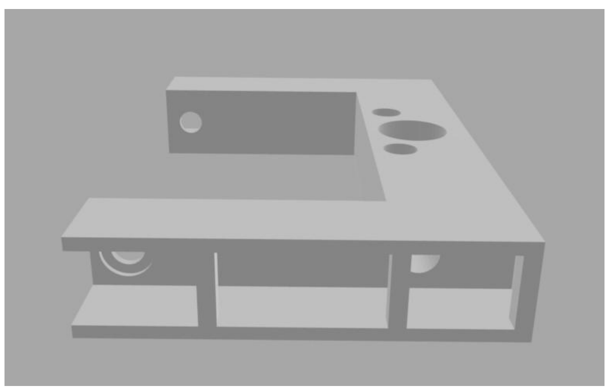
Print the required number of each of the listed 3D files listed in the parts list above. Ensure that each file will fit in the print volume of your printer. If any of the files are too large, it is recommended to use a free program called Meshmixer, to slice the files into smaller components.

It is recommended that all items be printed with a brim, all supports enabled, and PLA plastic filament at 25-30% infill. The exception is the scale platforms, which should be printed at 100% infill. The infill pattern can be left as whatever the default pattern is for your slicing software.

Building of Device

Building of beam break

1. 3D print two of the beam-break mounting brackets.



2. Insert an M3, 3mm long threaded insert to the back hole of the bracket.
    a. To do this line the insert up with the hole.
    b. Screw an M3 screw partially into the threaded insert.
    c. Using a soldering iron touch the screw to indirectly heat up the threaded insert and melt it into the plastic. Continue to press fit the insert until the insert is flush with the back of the bracket.
3. Insert one infrared LED and one infrared receiver into the front mounting holes.
    a. Make sure to run to the back of the bracket before inserting the LED and receiver.
4. Using an M3 screw the brackets can be mounted to a standard chemistry ring stand and adjusted for different experiments.

Power On and How to Use Interface

How to Use Sensors

Each sensor has its own section in the UI. Upon selecting a sensor option, if that sensor is connected, the display will begin refreshing with the values produced by that sensor's measurements.