

**Title:** A portable wave tank and wave energy converter for dissemination and outreach

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**Abstract:** Wave energy converters are a nascent energy generation technology that harness the power in ocean waves. To assist in communicating both fundamental and complex concepts of wave energy, a small scale portable wave tank and wave energy converter have been developed. The system has been designed using commercial off-the-shelf components and the all design hardware and software are openly available for replication. Educational curriculum has also been developed to assist in using this hardware for classroom education.

**Keywords:** wave energy, educational, outreach

**Specifications table:**

<b>Hardware name</b>	Sandia Interactive Wave Energy Education Display (SIWEED)
<b>Subject area</b>	<ul style="list-style-type: none"><li>• <i>Educational Tools and Open Source Alternatives to Existing Infrastructure</i></li></ul>
<b>Hardware type</b>	<ul style="list-style-type: none"><li>• <i>Electrical engineering and computer science</i></li><li>• <i>Mechanical engineering and materials science</i></li><li>• <i>Ocean engineering</i></li></ul>
<b>Open source license</b>	GNU GENERAL PUBLIC LICENSE
<b>Cost of hardware</b>	<i>\$7736 - Approximate cost of hardware (complete breakdown included in the Bill of Materials).</i>
<b>Source file repository</b>	<a href="https://github.com/SNL-WaterPower/siweed">https://github.com/SNL-WaterPower/siweed</a>

## 1. Hardware in context

The SIWEED is a small scale wave tank that is designed to be portable and serve in outreach and dissemination of wave energy research. The development of this system was inspired by previous research at Sandia National Labs in the areas of wave energy converter (WEC) device and control design and testing. Specifically, the SIWEED demonstrates the causal feedback control and device design principles described in Bacelli and Coe [1] and Coe et al. [3].

A wide variety of similar educational wave tanks and tow tanks have been built, but few have been documented. Unger [8] reworked a tow tank at MIT to enable remote operation via the

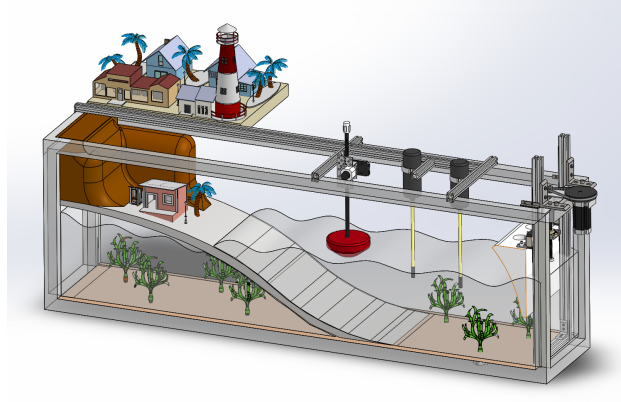


Figure 1: SIWEED CAD Assembly

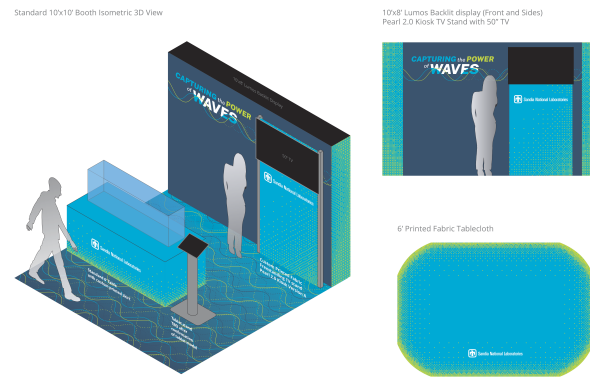


Figure 2: SIWEED Presentation layout

internet. Trust [7] created a tank with a similar size and objective, but oriented at demonstrating the effectiveness of coastal flood controls. There seem to be two major iterations, one electrically driven by a paddle like wave maker, and one plunger type driven mechanically by hand. That team has also make multiple similar hydraulic flume tanks for demonstration purposes. Ivan [5] has an educational wave tank on display in the National Museum of Scotland, but the waves do not explicitly interact with any bodies on the surface.

This is a novel expansion on similar small-scale educational wave tanks, as the wave maker is driven by a ball screw, and the user is able to control both the waves and the WEC device. The parameters of the wave are also much more controllable in this project than in similar small wave tanks. Users are able to select various control modes, the primary being a sine wave with variable amplitude and frequency. Another control mode dictates a static position, and the last is a JONSWAP spectrum, a combination of many sine waves, meant to imitate the chaos of a natural wave environment. The primary intended audience is college students and above, but there is implemented functionality to run a simplified version of the GUI for lower age groups, as well as additional curriculum for those younger groups.

## 2. Hardware description

The SIWEED is composed of a  $1.5\text{ m} \times 0.3\text{ m} \times 0.5\text{ m}$  acrylic tank, filled to roughly 0.3 m deep, housing a vertical plunger style wave maker (see, e.g., [4]), and a single body WEC modeled on the WaveBot [2]. The system is centrally controlled by a Windows PC running a graphical user interface (GUI) developed using Processing<sup>1</sup> and the controlP5 library<sup>2</sup>. Seperate hardware nodes are then manages by two Arduinos.

### 2.1 Hardware

A system diagram is shown in Figure 3. Two Arduino Due micro controllers are used to control and acquire signals from the WEC and wave maker, communicating with the GUI through USB Serial. The Windows laptop acts as the core of the system, with the two Arduino Dues attached through USB. Each Arduino is then attached to the various devices it communicates with. It is worth noting that Dues are used for their higher clock speeds, but since they operate at 3.3v, multiple level shifters are used to enable communication between the Arduino Dues and the components that use 5v logic.

The Windows laptop runs a Processing application that acts as the GUI, data logger, and serial communication manager. The Arduinos receive their commands from Processing over usb serial, and perform individual control loops based on control states dictated by the GUI. One Due controls the movement of the Wavemaker plunger, while the other controls the torque feedback of the WEC and lights in the model town. Each send data back to the Processing GUI for data logging and plotting purposes.

The Arduino Dues each have a number of components they communicate with through various protocols(PWM, SPI, Analog). These perform tasks like encoder buffering, motor control, and signal generation. The connections can be seen in Figure 3, but which protocols each individual component use are most easily discerned from the Arduino source code.

### 2.2 Graphical User Interface

This GUI is intended to be used with a touchscreen interface, but it is also fully functional with a mouse. A screen shot of the GUI is shown in Figure 4. It is divided into three sections: The left instructional side, “Mission Control”, and “System Status”.

The left side of the “Mission Control” section of the GUI pertains to control of the wave maker, which allows the user to switch between operational modes (“jog,” “function,” “sea state,” and “off”) and set the relevant parameters. If, for example, the system is in “sea state” mode, the user can set the significant wave height ( $H_s$ ), peak frequency ( $f_p$ ), and peakedness factor ( $\gamma$ ) for a JONSWAP wave spectrum. The “function” mode commands a simple sine wave, and so there parameters are amplitude and frequency. The ‘jog” mode simply commands a static position for the plunger to go to, so the only input parameter is that command position. There are only as many input sliders displayed as there are inputs to the active control mode. For example, if the selected mode was “jog”, only one slider would be present in that section of the GUI for the user to interact with.

The right side of the “Mission Control” section of the GUI contains controls for the WEC, which can be set into “torque” mode; in which the user directly sets a commanded torque, “feedback” mode; where proportional and integral feedback factors can be set by the user; “SID” mode, which

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<sup>1</sup><https://processing.org>

<sup>2</sup><http://www.sojamo.de/libraries/controlP5/>

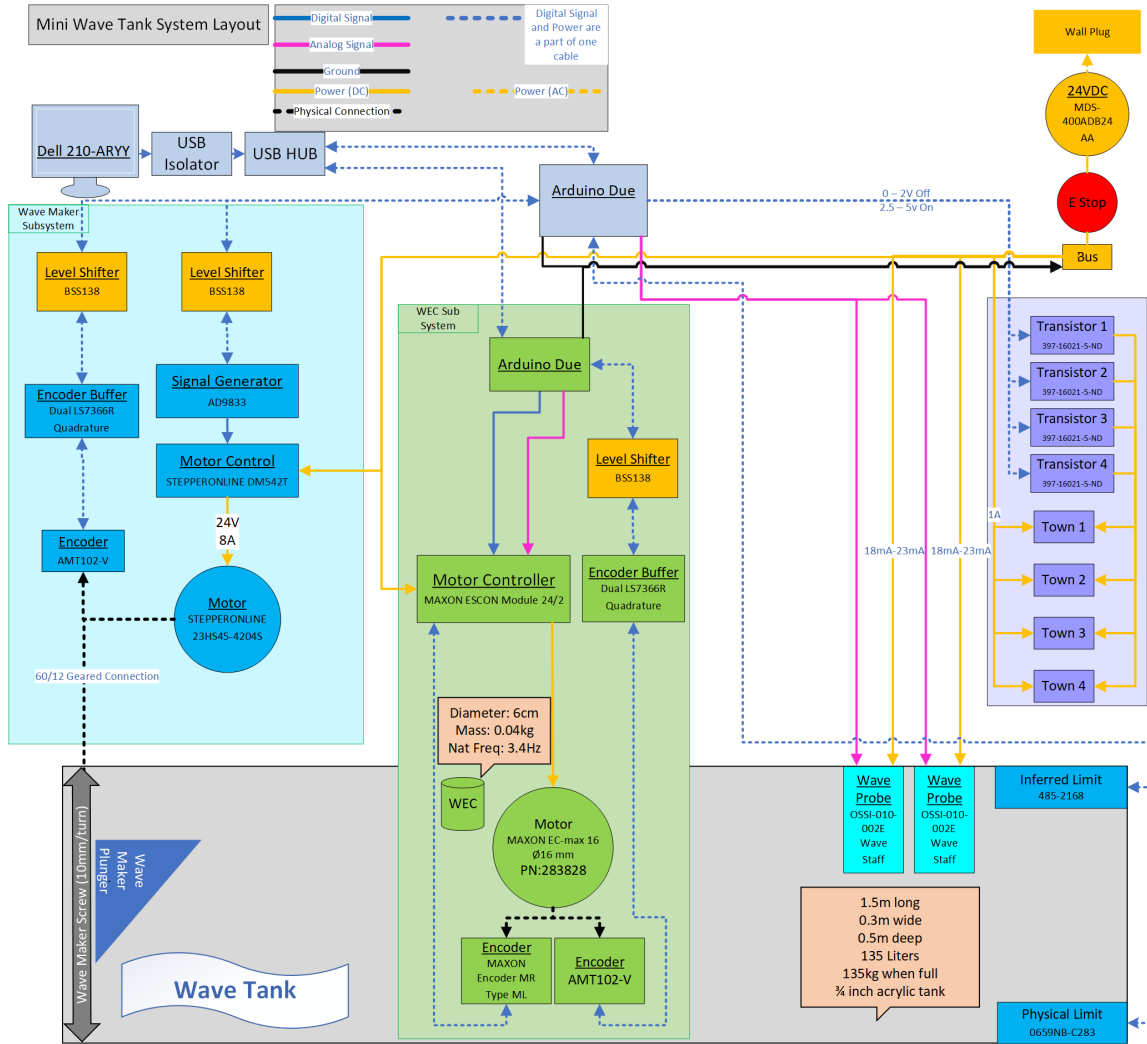


Figure 3: System layout diagram.

represents system identification and allows for open-loop multi-sine signals to be set by the user; and “off.” The “SID” works with the same inputs and JONSWAP control method as the “Sea State” mode for the wave maker, but commanding torque instead of position. Where the purpose of the JONSWAP in the wave maker controls is to replicate a natural wave state, as a torque controller for the WEC its purpose is only to provide a wide variety of torque inputs. This is useful when characterizing the hardware using recorded data in post-analysis.

The “System Status” section shows two plots, one for the WEC and one for the wave maker, with each allowing the user to choose what data is plotted. There are multiple options for the data included in each of these plots, with the ability to plot all any combination of variables simultaneously. Each is plotted in a different color, allowing the user to differentiate the various variables on each plot. The available variables in the wave maker plot(left side) are “Wave Maker Position”(as measured by the encoder) and “Wave Elevation”(As measured from one of the submerged probes). The WEC plot variables are “Position”(measured from an encoder), “Velocity”(differentiated from position), “Torque”(derived from a torque constant and motor current), and “Power”(as derived below). Below the plots are an FFT of the generated waves(measured from the encoder), and a

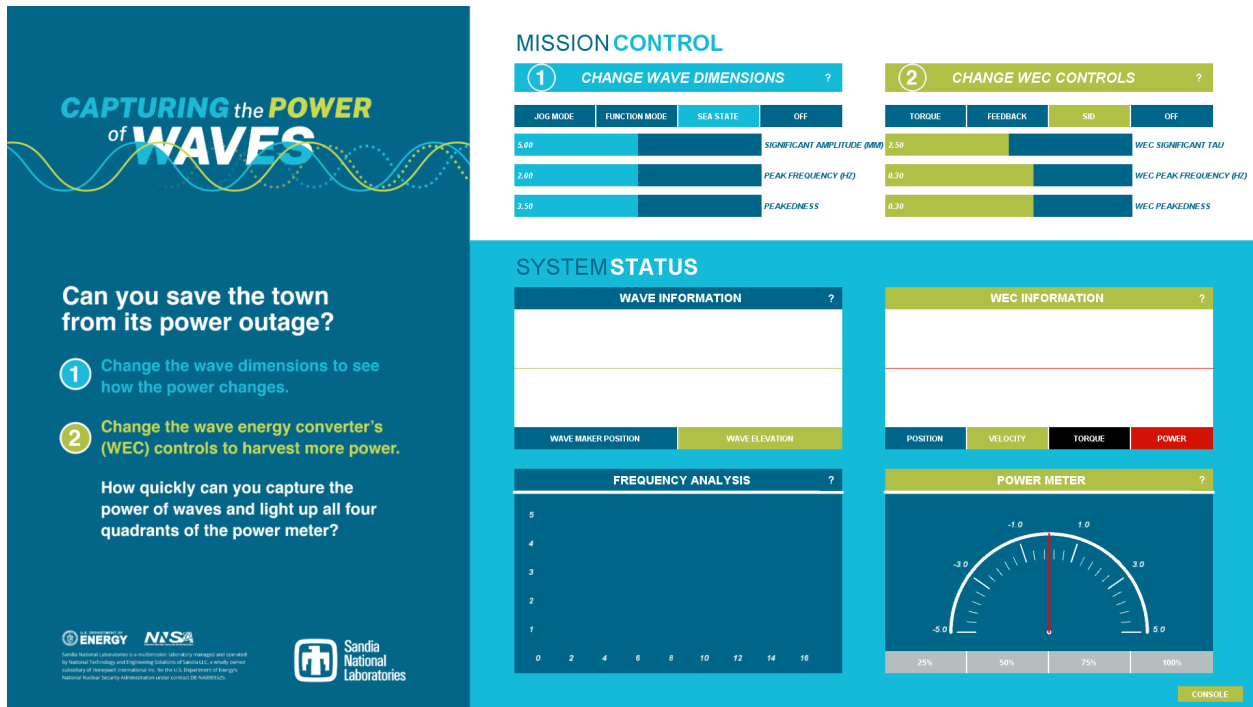


Figure 4: Graphical user interface (GUI) screenshot.

radial meter that displays the hypothetical generated power of the WEC. That hypothetically generated power meter is driven by the same variable as the “Power” variable in the WEC information plot above the meter, given by the following formula:

$$Power = -CommandedTorque \cdot Velocity \quad (1)$$

A number of key factors of SIWEED are:

- **Open-source and documented design:** To our knowledge, the SIWEED is the first educational wave tank and WEC system to be fully documented with an open-source design and software package. This will enabled interested researchers and students to efficiently develop replicates and variations of the SIWEED design for their own purposes.
- **Portability:** To allow for transport to conferences and outreach events, the SIWEED has been specifically designed to allow for easy transportation.
- **WEC control:** In addition to demonstrating the physics of ocean waves, the SIWEED allows users to interact with a WEC control system to better understand the principles of reactive feedback control to maximize power absorption for the waves.
- **Student-led design:** The SIWEED project has been a student-led design project involving undergraduate engineering students.
- **Curriculum:** The SIWEED repository includes a curriculum for students K-12 based on the Next Generation Science Standards [6]. The repository contains a presentation and a document intended to be given to the teacher beforehand. The presentation explains water power and Sandia National Labs’ role within it, and then goes into more detail about wave energy

converters and how the SIWEED demonstration works. The teacher resources document contains general information about the project, and a multitude of resources surrounding wave energy education, including videos, worksheets, vocabulary words, general topics, and Next Generation Science standards for each grade level.

### 3. Design files

Design file-name	File type	Open source license	Location of the file(s)
Final SIWEED Town	.SLDASM	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>
Hardware Hat	.SLDPRT	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>
WEC_Controller/interrupts.ino	.ino	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>
WEC_Controller/Serial.ino	.ino	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>
WEC_Controller/WEC_Controller.ino	.ino	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>
WaveMaker_Controller/interrupts.ino	.ino	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>
WaveMaker_Controller/Serial.ino	.ino	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>
WaveMaker_Controller/WaveMaker_Controller.ino	.ino	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>
dataLogging.pde	.pde	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>
Meter.pde	.pde	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>
Serial.pde	.pde	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>
siweedGUI.pde	.pde	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>
UI.pde	.pde	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>
UnitTests.pde	.pde	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>
fft.java	.java	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>
Complex.java	.java	GNU GENERAL PUBLIC LICENSE	<i>online repository</i>

The referenced online repository is here: <https://zenodo.org/record/7502670>.

**CAD Model:** The CAD assembly includes all functional physical parts of the SIWEED system, with accurate dimensions that can be referenced during fabrication and assembly. Aesthetic details, like the town are intentionally vague in the CAD model. Physical implementation of artistic aspects are not important for functionality, but are thought to add significantly to audience engagement. The files in the repository are Solidworks models, with all dependencies included in a compressed archive. There is an additional part labeled “Hardware Hat”. This was a late addition that was 3D printed to cover potential pinch points on the model, and prevent sunlight from interfering with the infrared limit switches. Because it’s a late addition, the part is included in the repository, but not in the final assembly.

**Processing Sketches:** The Processing sketch is made up of multiple files combined in the processing IDE as separate tabs. This includes the .pde files and the .java files. This is done mostly for organization purposes, but all files are necessary for the sketch to run properly. It is important to note that the sketch is also dependent on the Console library and ControlP5 library, and various graphics and text files that support the GUI. These files are not listed here but are all included in the online repository.

**Arduino Sketches:** Similarly to the Processing sketch, the two Arduino sketches are broken into multiple files for organization. Once again, all files are required for the sketch to function. It is important to note that the sketches are also dependent on various imported libraries, which are included in the online repository, but not listed here. Some of these libraries are modified from their original versions, so it is important that they are pulled from this project repository, and not the libraries’ original sources.

#### 4. Bill of materials

The complete Bill of Materials can be found here: <https://zenodo.org/record/7502670>. Note that a SIWEED system can be assembled with any tank on hand (e.g., a fish tank) and any Windows PC capable of running the Processing IDE; as these components can contribute significantly to system cost, the BOM lists the tank and computer separately from the remainder of the components.

#### 5. Build instructions

Using the System Layout diagram in Figure 3, the bill of materials, and other dimensions listed in this document, a functionally similar version of this wavetank can be reconstructed. Many parts can be substituted with similar ones, such as the laptop, transistors, power supply, or the tank itself. Software specific hardware, such as the Arduinos or Encoder Buffers should not be substituted. It is important to consider safety during reconstruction: Electrical isolation and grounding, as well as guarding pinch points, is essential for safe usage.

Software setup:

- Download the latest version of Arduino IDE and Processing IDE.
- Download the Master SIWEED Repository.
- Change the Sketchbook Location for the Arduino IDE to `\siweed\Arduino`.
- Change Sketchbook Location for the Processing IDE to `\siweed\Processing`.
- Change Arduino IDE board to “Arduino Due Programming Port”.
- Upload the sketches to the Arduinos.

- A more detailed version of these instructions can be found in the README file of the repository.

## 6. Operation instructions

After performing the setup described in the build instructions, the project can be operated as follows:

- Power on the wavetank, ensuring any kill switches are closed, and any pinch points are clear.
- Open processing.exe.
- File > Open > siweedGUI.pde (Ex: C:\Users\user\Documents\GitHub\siweed\Processing\siWeedGUI\siweedGUI.pde)
- (optional)Edit modifiers. These are booleans at the top of the code that will do things like enable basic mode, debugging, or data logging.
- Click “Run”.
- The GUI will open, allow some time for it to load.
- In the console, which will either be in the GUI, made visible by pressing the console button in the bottom right corner, or in the Processing console, depending on your boolean modifiers, unit tests should be visible that can be used to verify that everything is functioning properly. Note that the color of the console button in the GUI is representative of the serial checksum status. When the received checksum matches the calculated checksum(functioning nominally), the button will be a green/yellow. Otherwise it will be gray, indicating one of the Arduinos’ checksum does not match, and the system is out of sync. This will result in the state of the GUI not accurately representing the state of the physical system.

## 7. Validation and characterization

- **Torque constant verification:** The factory torque constant was verified by logging the position and current of the free floating WEC while commanding a slow sinusoidal current. The position displacement time series was converted to a time series of the applied physical torque with the following equation:

$$\tau = \sigma \cdot \gamma \cdot d \cdot \pi \cdot r^2 \quad (2)$$

Where  $\tau$  is torque,  $\sigma$  is the radius of the pinion gear,  $\gamma$  is the specific weight of water,  $d$  is the displacement of the buoy in the water, and  $r$  is the radius of the buoy. It is important to note that the torque values at this point did not account for friction or hysteresis. Plotting this torque data against the recorded commanded current values gives Figure 5. The “fit1” line represents the best linear fit of the entire data set, but the data points at the highest and lowest currents are affected more significantly by static friction, so omitting them from the data set improves the torque constant estimation, as shown with the “fit2” line in Figure 5. This provides an estimated torque constant of about 7.52 mNm/A, which is within 4% of the factory stated constant of 7.8 mNm/A.



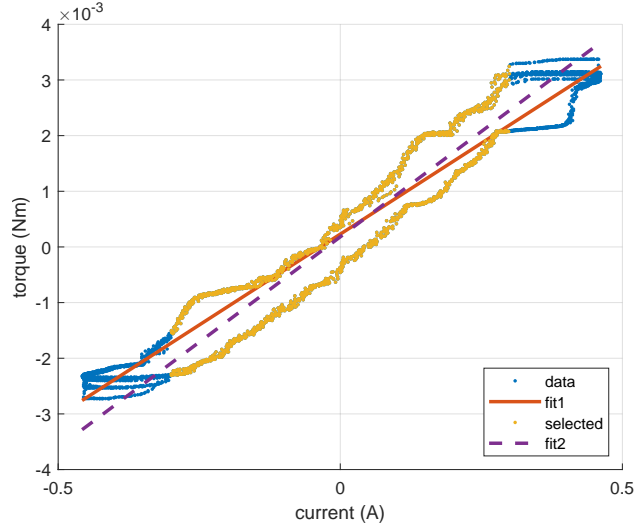


Figure 5: Torque vs commanded current, with linear fits of the entire and partial data set.

Since torque is being estimated from displacement and the frequency is low (inertial and viscous effects are small), the friction shows up as a “constant” offset from the ideal torque constant and doesn’t affect the slope. This allows the friction to be seen as half the offset between the data points as the wave maker moves up, and the points as it moves down. Plotting the torque error using the calculated torque constant against the current gives Figure 6.

The average offset shows that the friction is about 0.45 mNm in this operational envelope.

- **Wave Probes:** The readings from the wave probes could be verified by attaching them to the wave maker, which has a very precise encoder that allows for accurate changes in displacement. Moving the wave maker with the wave probe attached and comparing the displacement data from both of them was used to make sure the wave probe was providing accurate readings.

It was found having two wave probes as close as they are, roughly 1ft apart, was problematic. Changing the depth of one probe seemed to also adjust the reading of the nearby, stationary probe. It is believed this is caused by a sort of capacitive coupling, but a solution was never pursued. Known work-arounds are only using one probe, or powering the second probe off during operation.

- **WEC feedback control** The PD controller functions on the following formula:

$$\tau = kp \cdot p + -kd \cdot v \quad (3)$$

Here,  $\tau$  is the calculated torque,  $kp$  is the user defined proportional gain,  $p$  is the position in meters,  $kd$  is the user defined derivative gain, and  $v$  is the velocity, in meters per second, calculated by the change in position over the last 10 milliseconds. Using this control method allows the WEC to be controlled as a spring and damper, with the proportional gain  $kp$  adjusting the strength of the spring, and the derivative gain  $kd$  adjusting the strength of the damper. Unlike a physical spring, this “spring” can both push device towards center, or push it away, depending on the sign of the gain. A positive  $kp$  will act as a decentering force, whereas a negative  $kp$  will center the WEC to the waterline, similarly to a physical spring.

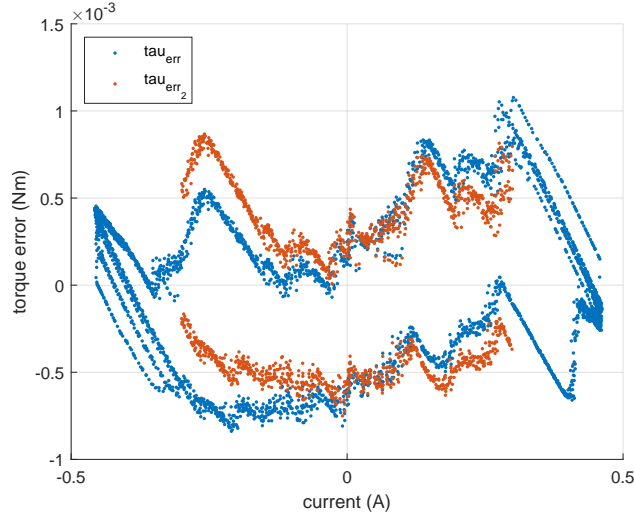


Figure 6: Torque error vs commanded current.

This calculation is done on the Arduino Due micro controller responsible for controlling the WEC, which commands an output torque through PWM to the WEC motor controller. The position and velocity are determined with an encoder, while the  $kp$  and  $kd$  inputs are set by the user in the GUI, which the Arduino receives through USB serial.

By logging the inputs and output of the control system through a range of user inputs, its performance can be verified. Initial tests showed a delay of three samples (100 ms) in the control loop. This was found to be an error with the serial communication checksum function, and has since been fixed. Control loop response times can now be verified as less than 33 ms, as the data logging control loop runs at 30 hz and shows a delay of one sample or less.

Figure 7 shows the controller during typical operation. The commanded torque was calculated as per above formula, while the measured torque was taken from an analog output on the WEC motor controller that measures current, then multiplying it by the known torque constant. This shows us how the PD control algorithm and motor controller react to our given inputs. As the linearity of the plot shows, the measured output torque closely matches the expected torque. The standard deviation of the torque during user testing showed to be  $3.8286e-4$  Nm.

There is a theoretical possibility to experience saturation near the limits of our torque output. This is the result of a protection written into the WEC motor controller, and can be adjusted by what is referred to as the “Thermal Time Constant”. When commanded to apply a torque over what the controller deems as nominal, the motor controller will apply this torque for only some time before saturating at the maximum nominal torque. This was seen during lab limit testing, occurring around  $3.5e-3$  Nm, but not during any user tests, as the commanded torque was never that high. If it were to become an issue, the range of possible  $kp$  and  $kd$  commands and torque jog commands could be made more limiting in the GUI to avoid any saturation triggers.

While fitting closely, there is still error present in this control loop. Figure 8 Shows a histogram of the measured torque subtracted from the expected torque, giving us the error. In these particular user tests, the RMS error was  $9.84e-5$  Nm, while the standard deviation of the torque measurement was  $3.82e-4$  Nm.

Part of what has to be considered with this error is noise in the analog signal that is used

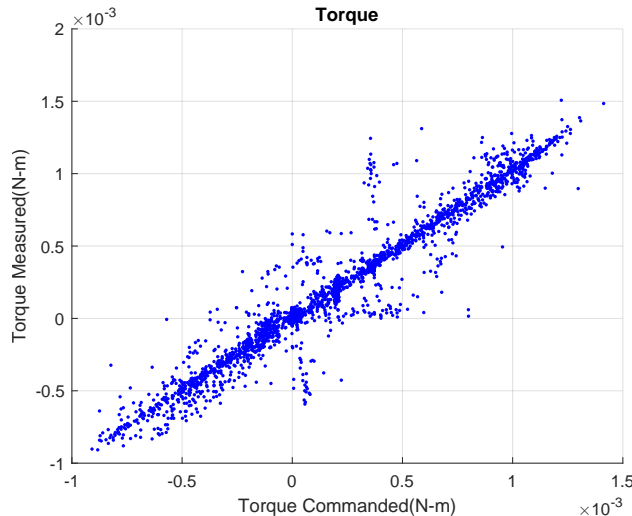


Figure 7: Torque Measured vs Torque Commanded

to read amperage and calculate measured torque. To characterize this, zero torque can be commanded, and then the measurement analyzed. Figure 9 shows a histogram of the torque when a zero command is sent. It can be easily seen that there is a slight positive offset in the noise, which is assumed to come from inaccuracy in the analog reporting on the motor controller, or the analog reading on the Arduino Due. This offset varies from test to test, and can be negative. Using this method of analyzing only data points where the torque command is zero over multiple tests gives a noise band of about  $8e-5$  Nm, where 90% of samples lie between  $-4e-5$  Nm and  $4e-5$  Nm.

## 8. Declaration of interest

Declarations of interest: none

## Acknowledgment

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## References

- [1] Giorgio Bacelli and Ryan G. Coe. Comments on control of wave energy converters. *IEEE Transactions on Control Systems Technology*, 29(1):478–481, Jan 2021. doi: 10.1109/TCST.2020.2965916. URL <https://ieeexplore.ieee.org/document/9005201>.
- [2] Ryan G. Coe, Giorgio Bacelli, David Patterson, and David G. Wilson. Advanced WEC Dynamics & Controls FY16 testing report. Technical Report SAND2016-10094, Sandia National Labs, Albuquerque, NM, October 2016. URL <https://mhkdr.openei.org/submissions/151>.

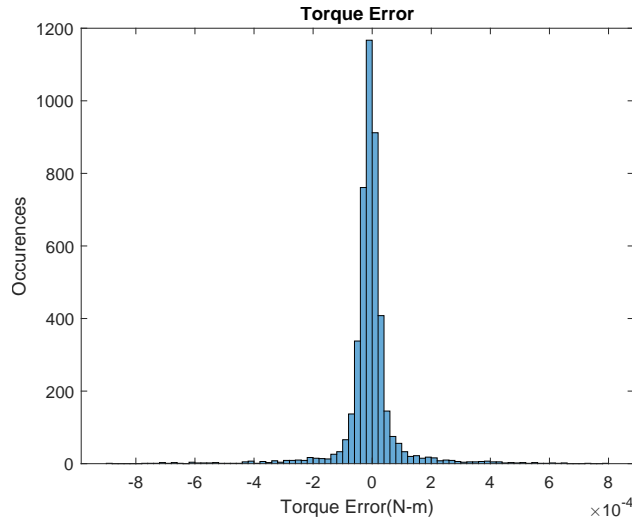


Figure 8: Error Histogram

- [3] Ryan G. Coe, Giorgio Bacelli, and Dominic Forbush. A practical approach to wave energy modeling and control. *Renewable and Sustainable Energy Reviews*, 142:110791, 2021. ISSN 1364-0321. doi: 10.1016/j.rser.2021.110791. URL <https://www.sciencedirect.com/science/article/pii/S1364032121000861>.
- [4] Jae Min Hyun. Simplified analysis of a plunger-type wavemaker performance. *Journal of Hydronautics*, 10(3):89–94, 1976.
- [5] Ivan. New educational tank in the national museum of scotland’s energy laboratory. URL <http://www4.edesign.co.uk/2016/07/new-tank-at-the-national-museum-of-scotlands-new-energy-laboratory/>.
- [6] NextGenScience. Next generation science standards. URL <https://www.nextgenscience.org/>.
- [7] JBA Trust. Wave tank. URL <https://www.jbatrust.org/how-we-help/physical-models/wave-tank/>.
- [8] Matthew Lawrence Unger. *Creating a flexible, Web-enabled learning and research facility at the MIT Towing Tank*. PhD thesis, Massachusetts Institute of Technology, 2006.

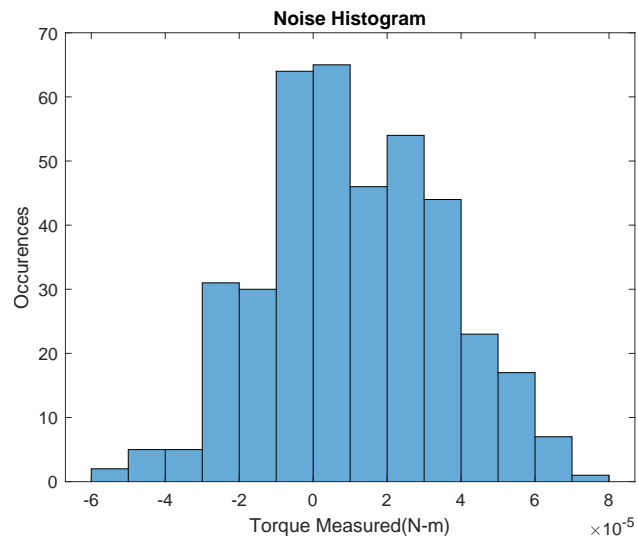


Figure 9: Noise Histogram