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Lab 1 – Part 2: Load Cell Project

Introduction

Olympic diving, while conceptually straightforward, demands meticulous attention to detail and extensive training to achieve perfection, especially on the grand stage of the Olympics, held every four years. Elite athletes in this sport dedicate the majority of their lives honing their skills for just a handful of dives in front of the global audience. Consequently, scientific analysis of athletes' techniques becomes imperative to ensure consistency and precision in their release points from the diving board for their chosen dives. Particularly, analyzing the deflection from the release point becomes crucial to optimize the diver's aerial performance. Furthermore, examining the strain energy of the diving board provides insights into the energy output of the dive, aiding divers in understanding their performance better.

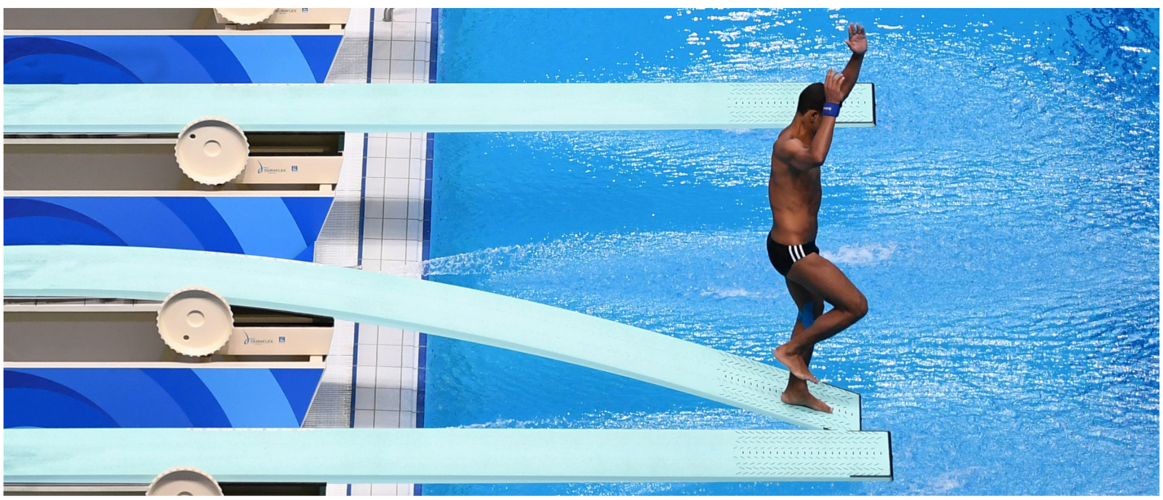

Figure 1: Olympic Diver Photograph

Calculations

The design team constructed a miniature diving board comprising a plywood base, elevation stands created from 2x4 and 4x4 wood planks, and a diving board fabricated from an acrylic sheet. A typical diving board measures 3 m (9 feet, 10 inches) in height, 0.5 m (1 foot, 10 inches) in width, and 4.8 m (15 feet, 7 inches) in length. In contrast, our acrylic micro-replica stands at 4.159 inches in height, 12 inches in width, and 24 inches in length. Utilizing area ratios, as exemplified in Equation 1, our micro-replica corresponds to an approximate scale factor of 15.

$$\frac{Olympic\ Board\ Surface\ Area}{Scaled\ Down\ Model\ Surface\ Area} = \frac{(15'7" \times 1'10")}{(12" \times 24")} \approx 15 \tag{1}$$

Moreover, the typical weight of an Olympic diver is 59.8 kg (132 lbs). When positioned on a 3 m high diving board, their muscles exert an applied force typically equivalent to half their body weight, as outlined in Equation 2:

$$F_{total} = F_{body} + F_{applied} = 1.5F_{body} = 198\ lb \quad (2)$$

[1]

$$F_{test} = \frac{F_{total}}{Scale\ Factor} = \frac{198}{15} = 13.2\ lb \quad (3)$$

Hence, based on the calculated scale factor, the masses we will test will be distributed around 13.2 lbf, chosen for the sake of testing convenience.

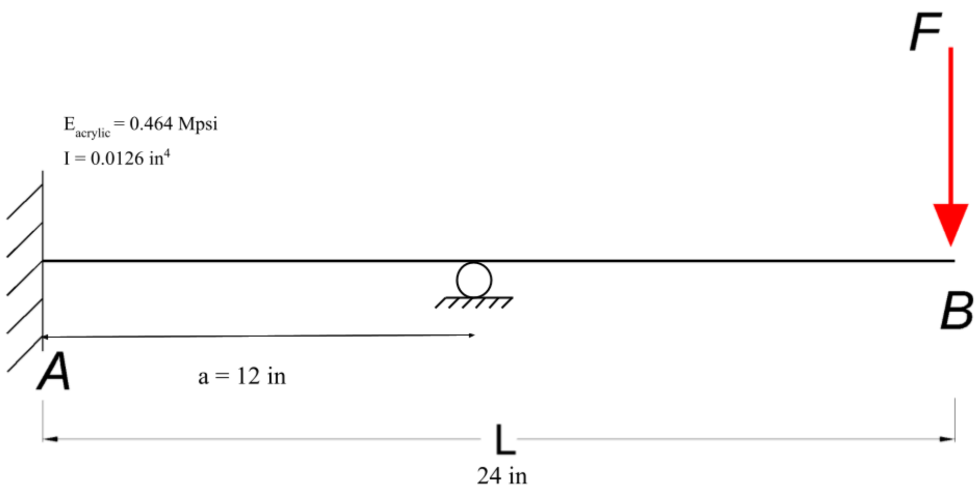

Figure 2: System Modeled as Cantilever Beam

Variable (Units)	Description	Value
F	Force Applied to End of Board	$15\ lb$
L	Length of Board	$24\ in$
$E_{acrylic}$ (see footnote[2])	Young's Modulus of Acrylic	$0.464\ Mpsi = 464,000\ lbf/in^2$
b	Width of Board	$12\ in$
h	Thickness of Board	$0.233\ in$
a	Distance from Hinge to Pivot of Board	$12\ in$

Table 1: System Variables

[1] Wired, Olympic Physics: Diving and the Moment of Inertia by Rhett Allain. August 11, 2012. https://www.wired.com/2012/08/diving-and-the-moment-of-inertia/

[2] *Young's modulus, tensile strength and yield strength values for some materials*. Engineering ToolBox. (n.d.). https://www.engineeringtoolbox.com/young-modulus-d_417.html

The deflection of a beam is of the form of Equation 4.

$$\delta = \frac{FL^3}{3EI} \tag{4}$$

where δ is deflection, *E* is Young's Modulus, and *I* is the area moment of inertia of the cross-section of the beam.

The area moment of inertia for a rectangular cross section of width *b* and height *h* is as follows in Equation 5.

$$I = \frac{1}{12}bh^3 = 0.0126\ in^4 \tag{5}$$

Considering that the diving board bends solely beyond the pivot point marked by the PVC pipe, we concluded that modeling our diving board as a straightforward cantilever beam with the "wall" positioned at the PVC pipe would suffice. Consequently, the deflection of the beam's end under a 15 lbs load can be calculated as follows in Equation 6.

$$\delta = \frac{F(L-a)^3}{3EI} = \frac{(15)(12)^3}{3(464000)(0.0126)} = 1.478\ in \tag{6}$$

The strain energy can be determined from the applied force on the end of the diving board, as depicted in Equation 7. Here, *l* for our computations is represented as (L-a), as illustrated in Equation 8.

$$U = \frac{1}{2}\frac{M^2 l}{EI} \tag{7}$$

$$U = \frac{1}{2}\frac{M^2(L-a)}{EI} = \frac{1}{2}\frac{F^2(L-a)^3}{EI} = \frac{1}{2}\frac{15^2(12)^3}{(464000)(0.0126)} = 33.25\ lbf.in \tag{8}$$

Experimental Setup

After extensive testing with the load cell, we found it to be considerably more accurate when measuring load values within the range of 10-20 lbs. According to the load cell datasheet, it's capable of measuring values ranging from 6.6 to 440.9 lbs.

The diving board-strain gauge system was created specifically to measure a single force applied at the end of the board. Picture a scenario where you have a long diving board with a weight placed at one end. To support this setup, there's a roller in the middle of the board. The strain gauge is attached just before this roller, built into the wooden stand at the front. It detects the pressure applied and indicates the resulting strain. See Figure 3 below to get a better idea of how this strain gauge fits into the entire system.

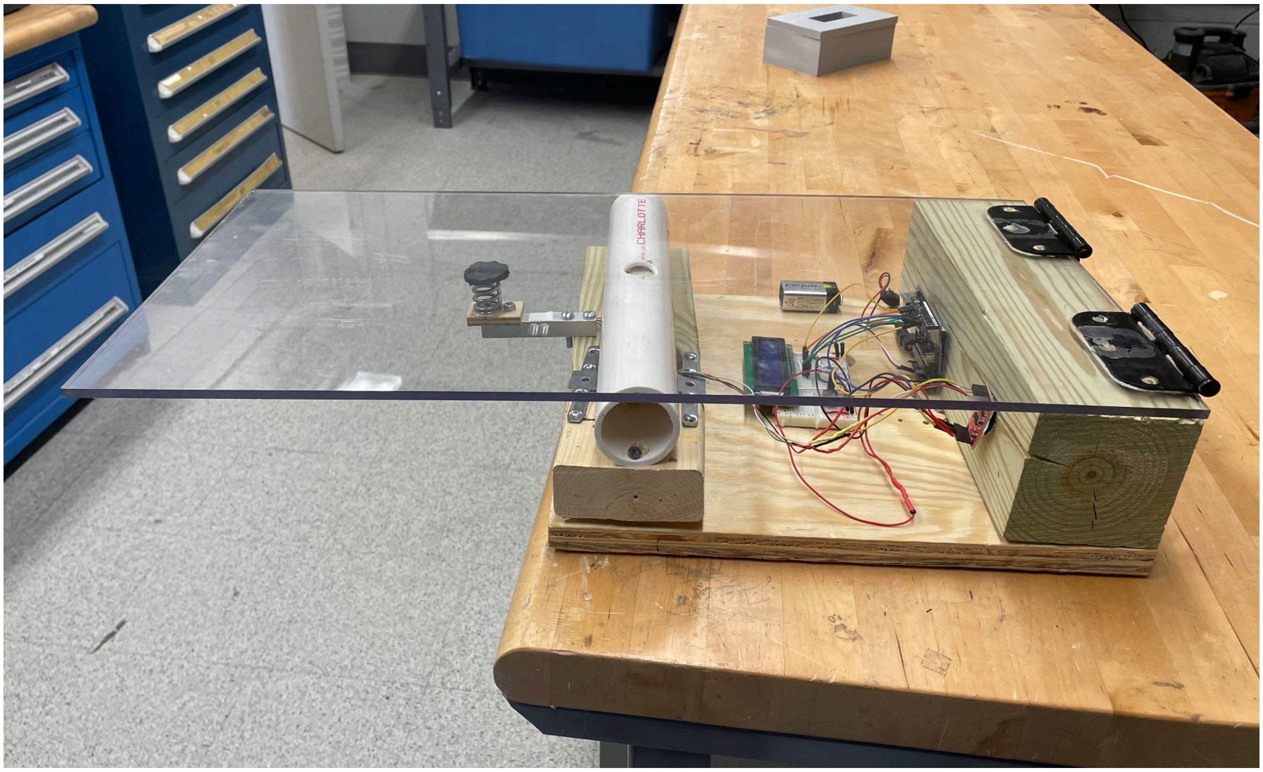

Figure 3: Fully Engineered System

To translate the voltage measurements obtained from the load cell into force readings on the diving board, we utilized a load cell amplifier (Figure 4). This step was essential because the load cell generates small electrical signals in response to mechanical force, usually in the millivolt range, which can be prone to interference or noise. The load cell amplifier helps by conditioning these weak signals, amplifying them to levels more suitable for accurate processing by the Arduino. Additionally, it filters out noise and unwanted signals, thereby enhancing the precision and reliability of the measurements.

Once the load cell amplifier was connected to the load cell, it was then linked to the Arduino, allowing the Arduino to capture the voltage measurements and convert them into force readings. This process included calibrating the load cell using known masses. Subsequently, the Arduino was programmed to display the recorded force and strain energy values from the load cell on an LCD screen (Figure 5). The Arduino code pertaining to this process is available in the Appendix for further examination.

Furthermore, Figure 6 below illustrates all of the electrical components integrated into the system, along with the operational strain gauge providing a reading.

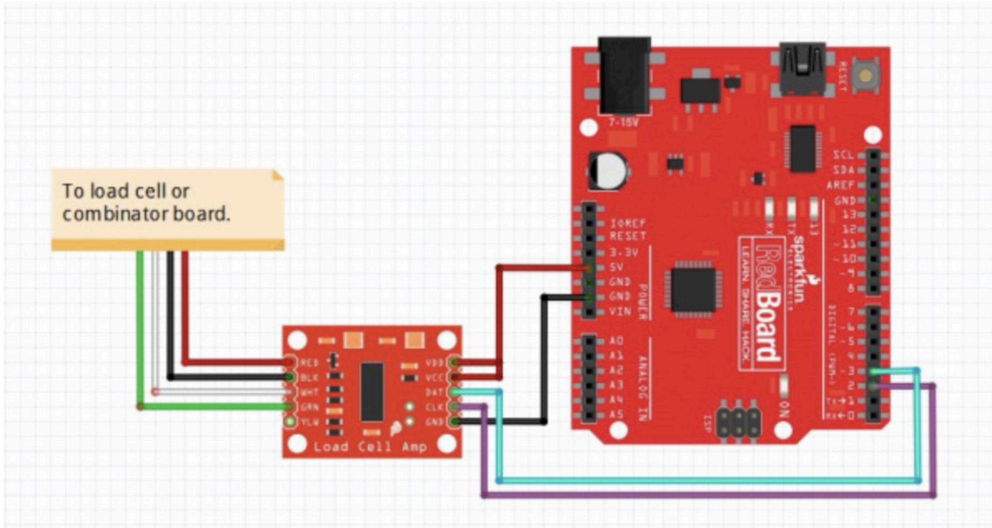

Figure 4: Schematic of the Connection of the Load Cell to the Arduino [3]

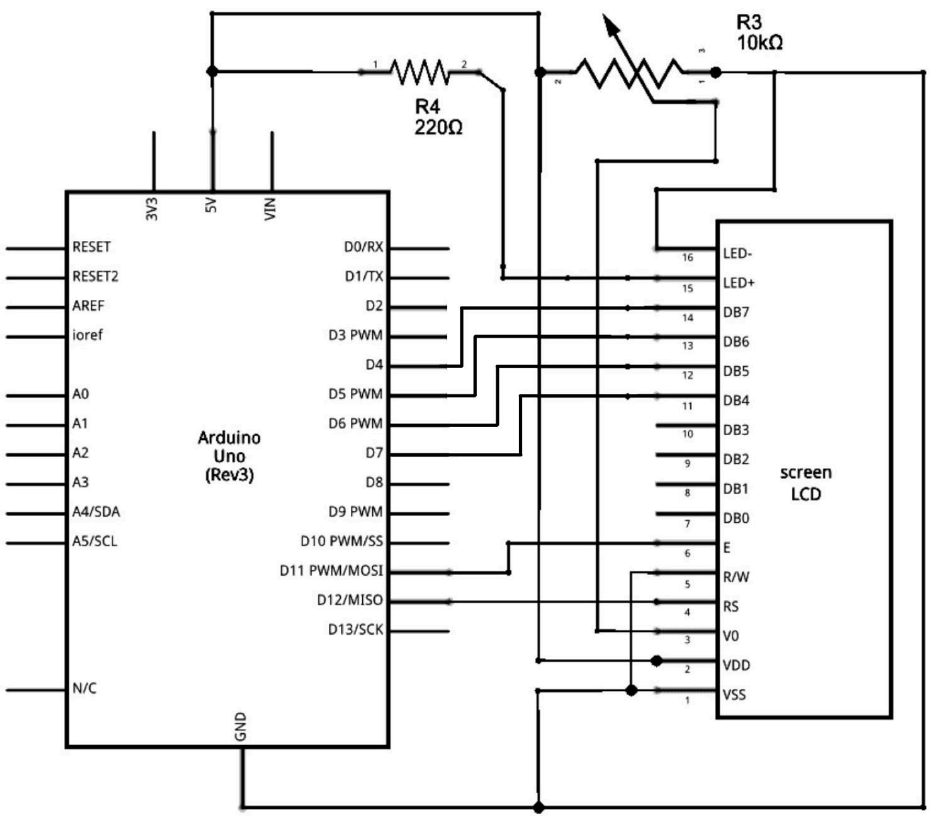

Figure 5: Schematic of Connections of LCD Screen to Arduino, Adapted from Arduino Docs [4]

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[3] "Load Cell Amplifier HX711 Breakout Hookup Guide - Learn.sparkfun.com." *Sparkfun.com*, 2014, learn.sparkfun.com/tutorials/load-cell-amplifier-hx711-breakout-hookup-guide/all.

[4] "Liquid Crystal Displays (LCD) with Arduino | Arduino Documentation." https://docs.arduino.cc/learn/electronics/lcd-displays/.

Figure 6: Engineered Electrical Components

The system exhibits high accuracy in determining loads applied at a specific point on the beam within the range of 10 lbs, with an approximate deviation of ±2 lbs. However, values lower than this threshold were influenced by the rubber connector between the board and the load cell/spring system, as it compressed and absorbed components of the force that would have otherwise been measured by the load cell. Conversely, values exceeding this range became inaccurate due to the physical compression of the spring. While the spring remained nearly uncompressed for loads less than 12 lbs, heavier loads compressed the spring, absorbing components of the load, resulting in a larger percent error.

Although the load cell itself is rated with a load capacity of 3 - 200 kg (approximately 6.6 lbs - 440.9 lbs), the inaccurate readings observed in the 1, 2, and 5 lb ranges could potentially be attributed to these loads falling outside the specified accuracy range of the parallel beam load cell. Additionally, the team's testing and experimentation did not involve masses exceeding 20 lbs due to concerns regarding the acrylic beam's structural integrity. Specifically, the deflection observed at the maximum weight tested was deemed the highest acceptable value without risking catastrophic failure of the system. Moreover, in our system, a 20 lb mass equated to a 200 lb diver, significantly surpassing both the average diver weight of 130 lbs and the average male diver weight of 146 lbs.

When designing the test stand for the diving board, it became evident that the material chosen needed to flex and bend without risking cracks, while also swiftly regaining its original shape to provide the necessary force during a dive. Research indicated that standard diving boards are commonly crafted from fiberglass, though alternatives such as wood or metal are also feasible as long as they offer a non-slip surface.[5] Upon exploration of materials in the Husdon material room, the team discovered a sheet of acrylic that possessed the desired characteristics.

The design of the test stand remained unchanged from the project's beginning, comprising a wooden baseboard, two wooden supports, and a PVC pipe as the pivot support for the diving board. These components were firmly secured using screws, while the acrylic sheet was attached using a hinge bonded with epoxy glue. Additionally, for a comprehensive view of the model, refer to Figure 7, which provides a detailed sketch of the entire setup. For further clarity, please refer back to Figure 3 for the fully assembled system with all these components in place.

Initially, the team planned to utilize the Circular Compact Compression Load cell to gauge the strain on the diving board. However, during the construction of the test stand, it became apparent that integrating this load cell into the design would pose challenges. The load cell measures force through a small center area, making it exceedingly difficult to translate the force exerted on the diving board to such a confined region. Despite efforts to embed the load cell within a small hole cut into the PVC pipe, ensuring consistent contact with the load cell's center proved problematic, especially as the angle of contact between the board and the pipe altered with the diving board's flexing. Additionally, extensive testing with this load cell connected to the Arduino and code revealed inconsistent readings even when known masses were placed consistently.

As a result, the team opted to use the Straight Bar load cell instead. The design of the test stand was modified to position the load cell off the edge of the wooden structure, accompanied by a system that ensured the diving board maintained contact and alignment with the load cell when stationary, yet allowed for compression without damaging the board. This revised design effectively facilitated the diving board's movement while accurately translating the force to the load cell. Subsequent testing with this load cell yielded consistent readings when known masses were applied to the diving board. Calibration of the load cell using known masses was imperative to ensure that voltage readings accurately corresponded to force and strain energy values. Following calibration, the structure underwent testing to confirm its ability to consistently display the correct force and strain values.

[5] "Diving Boards - What Are They & Should I Get One?" Premier Pools & Spas | The World's Largest Pool Builder!, 17 Aug. 2022, https://premierpoolsandspas.com/diving-boards/#:~:text=Diving%20boards%20are%20mostly%20made,that%20divers%20can%20land%20safely.

Once the load cell was functioning effectively, the team proceeded to solder all connections to provide greater permanence. Additionally, an LCD screen was incorporated into the circuit to enable the load cell to display the measured force and strain energy values.

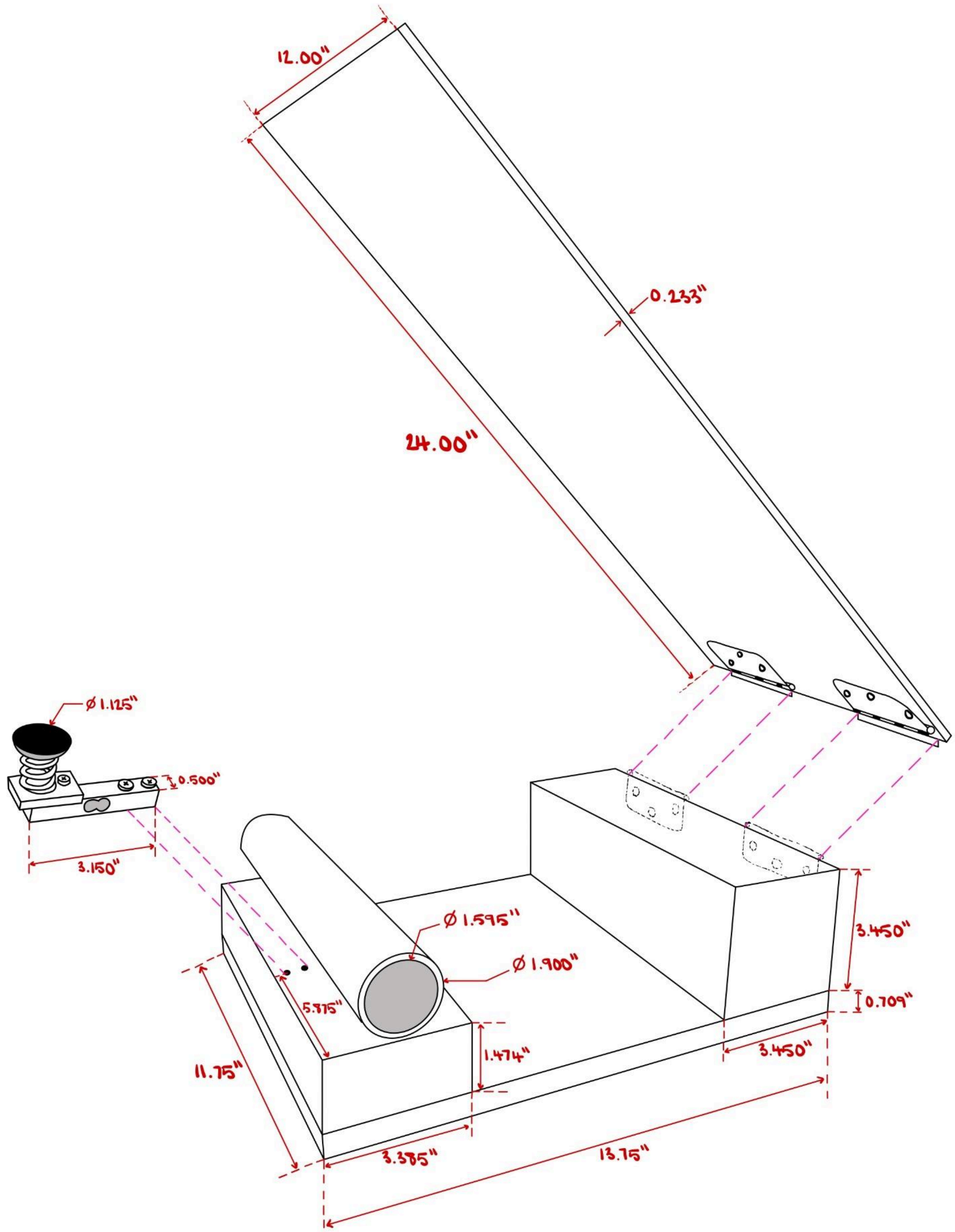

Figure 7: Sketch of Model

Results

Theoretical Force (lb)	Average Experimental Force (lb)	Percentage Error	Theoretical Theoretical Deflection (in)	Average Experimental Deflection (in)	Percentage Error
1	0.730	26.70%	0.099	0.127	28.28%
2	1.733	13.35%	0.197	0.257	30.46%
5	4.930	1.40%	0.493	0.523	6.09%
10	9.660	3.40%	0.985	1.017	3.25%
12	12.100	0.83%	1.182	1.127	4.65%
15	15.670	4.47%	1.478	1.267	14.27%
20	21.733	8.67%	1.970	1.742	11.57%

Table 2: Average Results of Testing

Theoretical Force (lb)	Theoretical Strain Energy (lbf-in)	Experimental Strain Energy (lbf-in)	Percentage Error
1	0.148	0.079	46.62%
2	0.591	0.444	24.87%
5	3.695	3.591	2.81%
10	14.778	13.790	6.68%
12	21.281	21.637	1.67%
15	33.251	36.288	9.13%
20	59.113	69.801	18.08%

Table 3: Strain Energy Calculated Values from Theoretical and Experimental Load Values

The prototype successfully fulfilled its purpose of measuring the force on the end of the diving board, converting it into strain values, and displaying these results. Analysis of the results, as can be seen in Table 2 and Table 3, revealed that the load cell exhibited high accuracy at higher force values, with a minimal deviation of 0.83% observed at 12 lbs. However, its accuracy diminished when testing lower loading values, reaching a maximum deviation of 26.7% at 1 lb. This discrepancy may stem from the load cell's sensitivity range, which spans from 6.6 lbs to

440.9 lbs, rendering it less accurate for measurements below this threshold. Notably, the percentage error for deflection, force, and strain energy was lowest at a load of 12 lbs. Since this load closely resembles the scaled-down weight of a diver, it can be inferred that the diving board would effectively measure force, deflection, and strain energy when in use by a diver.

For future iterations, enhancements to the design could include developing an enclosure for the electronics with a side-mounted display for easier readability. Additionally, waterproofing the enclosure would safeguard the electronics from any splashes generated when the diver enters the water, ensuring the longevity and reliability of the system.

Our design holds the potential for seamless integration into professional diving settings. In practical applications, both professional and amateur divers can utilize the data gathered from our product, the diving board, to gauge the force exerted during a skill. Moreover, the strain energy value serves as a valuable indicator, eliminating the need for complex calculations, and offering insights to the divers about the energy they possess, which can be converted into kinetic and potential energy during dives.

In the realm of diving, precise control over height and execution is paramount for successful skill performance. Each skill necessitates a specific degree of bounce or "jump," which can be inferred from the force measurements. Coaches can collaborate with divers, leveraging force data to optimize their jumping technique and refine their skill execution.

Even amateur divers stand to benefit significantly from access to force data, enriching their training experiences. By monitoring their progress and correlating force measurements with performance outcomes, divers can identify areas for improvement and track their growth more effectively. Integrating force data from the test stand into diving training and coaching programs promises more informed and tailored approaches to training, ultimately enhancing performance and safety within the diving community.

Cost

Part	Cost ÷ Quantity	Quantity	Total Cost of Part	Cost Sourcing
4x4 Wood Plank	\$8.68 / 8 ft = \$1.085 / ft	1 ft	\$1.085	Home Depot
2x4 Wood Plank	\$3.34 / 8 ft = \$0.4175 / ft	1 ft	\$0.4175	Home Depot
Plywood	\$14.35 / 32 ft^2 = \$0.4484 / ft^2	1.1667 ft^2	\$0.5232	Home Depot
Acrylic Board	\$87.96 / 24"x48" = \$0.08 / in^2	(12"x24") = 288 in^2	\$22.00	Home Depot
2 inch (nominal) PVC Piping	\$17.74 / 10 ft = \$1.774/ft	1 ft	\$1.774	Home Depot
#8 2" Wooden Screws	\$9.97 / 129 screws = \$0.077/screw	8 screws	\$0.618	Home Depot
#10 1" Zinc Plated Wood Screws	\$1.38 / 4 screws =	8 screws	\$2.76	Home Depot
Hinges + Screws	\$3.27 / hinge	2 hinges	\$6.54	Home Depot
SparkFun Load Cell Amplifier	\$10.95	\$10.95	\$10.95	Amazon.com
Arduino	\$27.60	\$27.60	\$27.60	Amazon.com
Wires	\$3 / 25 ft = \$0.01/inch	60 inches	\$0.60	McMaster-Carr
Load Cell	\$9.50	\$9.50	\$9.50	SparkFun
Total	**\$84.37**			

Table 4: Cost Breakdown of Mini Diving Board Components

Appendix

Theoretical Force (lb)			**Experimental Force (lb)**			**Theoretical Deflection (in)**			**Experimental Deflection (in)**		
Trial											
1	2	3	1	2	3	1	2	3	1	2	3
1	1	1	0.7	0.7	0.8	0.122	0.132	0.127	0.125	0.130	0.125
2	2	2	1.8	1.7	1.7	0.250	0.249	0.272	0.250	0.260	0.260
5	5	5	4.6	5.1	5.1	0.519	0.522	0.528	0.500	0.520	0.550
10	10	10	9.6	9.8	9.6	1.018	1.017	1.017	1.000	1.000	1.050
12	12	12	12.1	12.2	12.0	1.126	1.127	1.126	1.125	1.125	1.130
15	15	15	15.7	15.7	15.6	1.260	1.261	1.281	1.250	1.300	1.250
20	20	20	21.8	21.7	21.7	1.758	1.727	1.741	1.750	1.700	1.775

Table A1: Results of Testing from Three Trials

Arduino Code

```
#include "HX711.h"
#define calibration_factor -116900
#define DOUT 3
#define CLK 2
HX711 scale;
#include <LiquidCrystal.h>
// initialize the library by associating any needed LCD interface pin
// with the arduino pin number it is connected to
const int rs = 12, en = 11, d4 = 7, d5 = 6, d6 = 5, d7 = 4;
LiquidCrystal lcd(rs, en, d4, d5, d6, d7);
float strain_energy(float force) {
float len = 12;
float youngs_mod = 464000;
float moment_of_inertia = 0.0126;
return (1/2) * ( (force * force) * (len * len * len) ) / (moment_of_inertia* youngs_mod);
}
void setup() {
Serial.begin(9600);
Serial.println("HX711 scale demo");
scale.begin(DOUT, CLK);
scale.set_scale(calibration_factor);
scale.tare();
Serial.println("Readings:");
// set up the LCD's number of columns and rows:
lcd.begin(16, 2);
// Print a message to the LCD.
lcd.print("F(lbs) U(lbs-in)");
}
void loop() {
Serial.print("Reading: ");
force = scale.get_units();
strain = strain_energy(force);
Serial.print(force, 1); //scale.get_units() returns a float
Serial.print(" lbs"); //You can change this to kg but you'll need to
refactor the calibration_factor
Serial.println();
lcd.setCursor(0, 1);
lcd.print(force, 2);
lcd.setCursor(7, 1);
lcd.print(strain, 2);
}
```

Figures A1-A4: Supplemental Design Process Images