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Article

Experimental characterization of thrust for ≤20 N-s impulse solid rocket motors

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SUMMARY

The rocket launch industry is booming as the desire to explore new horizons rapidly increases. Launching observation and telecommunication satellites into orbit has normalized weekly launch cadences. As such, research on rocket motors has skyrocketed as well. Small-scale solid rocket motors are cheaper (a few hundred dollars vs. millions of dollars) and cleaner (less fuel consumption and emitted greenhouse gases) proxies for full-scale rocket engines, but they are not as widely studied. This work has provided insight into the benefits of small-scale solid rocket motors using a novel load cell test stand to measure thrust, a key measure of performance. To provide guidance for the use of larger-scale rocket engines, this study hypothesized that the motor with the most propellant would be the most effective in producing high magnitude and long duration thrust. Using Estes motors A8-0, B6-0, C11-0, and D12-0, this work found this to largely be true. Additional findings include that larger motors like the D12-0 tend to have higher total thrust per mass and higher propellant-to-total-mass ratio.

INTRODUCTION

Orbital rockets have become an integral part of science, allowing researchers to analyze and observe where they could not before through communications, observation, weather, and GPS satellites they launch into orbit (1). However, building and launching modern-day rockets is not cost-effective, mainly because rocket fuel is expensive and most are not reused. As large motors cost more to construct and operate, it is more economic to study smaller motors and scale findings to larger ones. In fact, the recent Artemis I mission that flew around the moon on the Space Launch System (SLS) rocket had a price tag of $4.2 billion (2). Furthermore, it was part of a program that was $6 billion dollars over budget (2). SpaceX, the leader in commercial space access, still charges $67 million per launch with its Falcon 9 rocket (3). In order to minimize initial research and development costs, SpaceX opted to test their Merlin engines and booster landing system on a much smaller platform named Grasshopper (4). For theoretical orbital launch vehicles, lower total mass and higher launch frequency decreases cost for reusable launch vehicles like the Falcon 9 (5). No relationships have yet been drawn connecting model rocket motors and orbital boosters to utilize the low-cost alternative of model rockets, prompting this study of model rocket motor thrust and performance across a range of sizes.

Previous studies like that of Penn et al. have focused on model rocket motor thrust in small-scale (<100 N) model rocket motors as this study does (6). Penn et al. detailed how they measured thrust and how their thrust values compared to the supplier's motor thrust data on motors up to class E (6). The motor's class denotes its propulsive power in terms of total impulse, with Class A being the least powerful and higher alphabet letters indicating greater power. Each class is approximately twice as powerful as the last, which means testing motors from classes A through E encompasses a variety of motors and provides a spectrum of data. However, no attempt has been made to draw a relationship between the performance of these small model rocket motors and their larger orbital booster counterparts.

Small rocket motors are the focus of this work because they are cheaper and more commercially available than orbital-class motors. These smaller motors can provide insight into the inner workings of large engines and experimental propellants without the excessive costs associated with fabrication and operation. The largest solid rocket motor available to consumers without added fees like hazmat shipping and handling is a class D motor, which is limited to 20 N-s of total impulse (10). This work investigated the effectiveness of commercially available model rocket motors under 20 N-s of total impulse by measuring each motor's thrust, collecting data on thrust versus time for Estes motors A8-0, B6-0, C11-0, and D12-0. Each of these motors is fairly similar except for their propulsive power, leading us to our hypothesis that the motor with the most propellant will be the most effective. This work found this to be true, with the largest motor we tested, the D12-0, at the top of many of the measures used to analyze each motor. In short, this study found that model rocket motors have many advantages for research over orbital boosters, and that certain measures like maximum thrust are heavily correlated to the size of the motor.

RESULTS

To evaluate model rocket motors and compare their thrust characteristics to one another, we collected data on thrust versus time for Estes motors A8-0, B6-0, C11-0, and D12-0. This data indicates how much propulsive force the motor can produce over time, key to the rocket's ability to escape gravity and complete different flight patterns. These motors were chosen for their 0-second delay or 'booster' configuration which made them easier to use in conjunction with the novel test stand. For each motor, we calculated the maximum thrust, duration, total thrust, propellant mass, total mass, maximum thrust per mass, total thrust per mass, and percentage of propellant. For maximum thrust, propellant mass, maximum thrust per mass, and percent propellant, we excluded C11-0 motor data since only half of the thrust curve was obtained

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due to combustion chamber overpressure during testing (**Figure 1**).

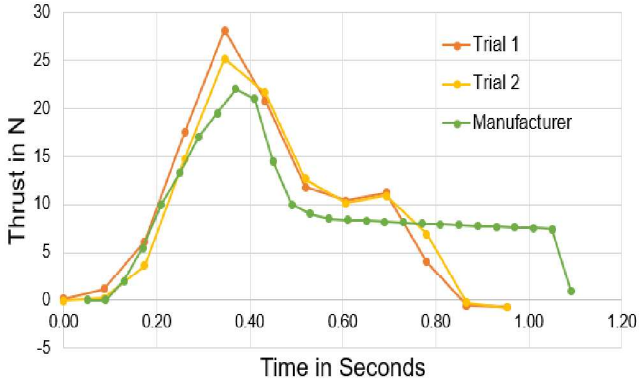

Figure 1. C11-0 motor thrust. Manufacturer data graph and plots of both experimental static fires for Estes C11-0 motors. The manufacturer data comes from the official Estes Rockets website and the experimental data was gathered using the test stand described in the Materials and Methods section (10).

The A8-0 motor is not the best in any category, as it is the smallest and has the least propellant mass with 4.2 g (**Figure 2**). The maximum and total thrust per mass measures were introduced to consider overall efficiency, but the higher casing-mass-to-propellant-mass ratio in A8-0 motors means they are worse-performing in these measures as well, with 0.46 N/g and 0.18 N/g, respectively (**Table 1**).

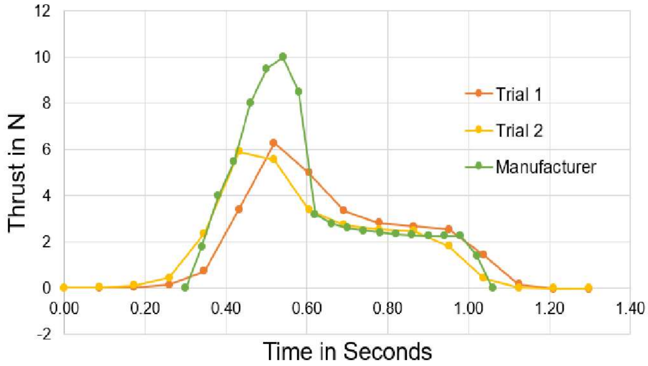

Figure 2. A8-0 motor thrust. Manufacturer data graph and plots of both experimental static fires for Estes A8-0 motors. The manufacturer data comes from the official Estes Rockets website and the experimental data was gathered using the test stand described in the Materials and Methods section (10).

Surprisingly, experimental data shows the B6-0 motor is the best motor for maximum thrust per mass at 0.63 N/g (**Figure 3**, **Table 1**). However, Manufacturer data suggests the D12-0 motor should be better in this category, with 0.81 N/g (**Table 1**). The C11-0 motor's manufacturer data suggests it should also be in the same ballpark with 0.76 N/g, but since most of the C11-0 data was discarded we were unable to compare them with experimental data.

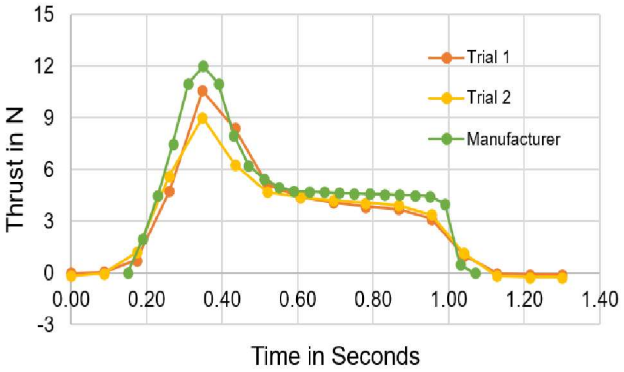

Figure 3. B6-0 motor thrust. Manufacturer data graph and plots of both experimental static fires for Estes B6-0 motors. The manufacturer data comes from the official Estes Rockets website and the experimental data was gathered using the test stand described in the Materials and Methods section (10).

C11-0 experimental thrust curves show first the motor running hot with a higher peak, then the overpressure event with an early end to the burn (**Figure 1**). Since only half of the C11-0 thrust profile was obtained before overpressure, it is not possible to analyze the relative performance of this motor to a high standard at this time; in the measures where data could be recovered, it was outperformed by another motor.

Among the motors we tested, the D12-0 motor is the best motor in maximum thrust (20.6 N), duration (2.0 s), total thrust (16.54 N-s), and propellant mass (21.9 g) (**Figure 4**, **Table 1**). This makes sense because the D12-0 has the most propellant of any of the tested motors. It is also the best motor in total thrust per mass (0.41 N-s/g) and percent propellant (54.1%) because less of the total mass is from the case and more is from the propellant.

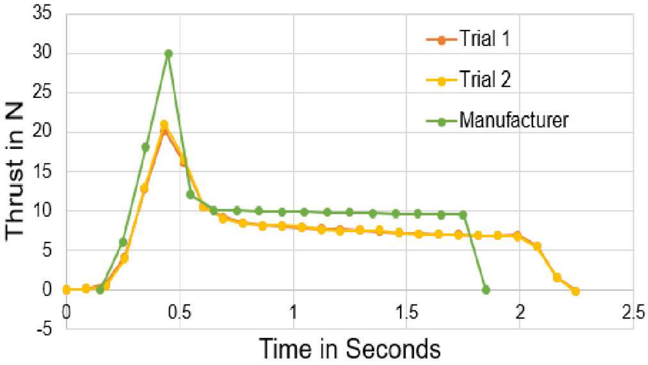

Figure 4. D12-0 motor thrust. Manufacturer data graph and plots of both experimental static fires for Estes D12-0 motors. The manufacturer data comes from the official Estes Rockets website and the experimental data was gathered using the test stand described in the Materials and Methods section (10).

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Motor	A8-0		B6-0		C11-0		D12-0	
Source	Experimental	Manufacturer	Experimental	Manufacturer	Experimental	Manufacturer	Experimental	Manufacturer
Max Thrust (N)	6.1	10.0	9.8	12.0	26.6	22.1	20.6	32.9
Duration (s)	0.7	0.7	0.8	0.8	0.7	0.8	2.0	1.6
Total Thrust (N-s)	2.43	2.50	4.25	5.00	9.38	10.00	16.54	20.00
Propellant Mass (g)	4.2	4.1	8.3	6.5	79.4	12.4	21.9	23.8
Total Mass (g)	N/A	13.3	N/A	15.6	N/A	29.2	N/A	40.5
Max Thrust / Mass (N/g)	0.46	0.75	0.63	0.77	0.91	0.76	0.51	0.81
Total Thrust / Mass (N-s/g)	0.18	0.19	0.27	0.32	0.32	0.34	0.41	0.49
% Propellant	31.6	30.8	47.0	41.7	271.8	42.5	54.1	58.8

Table 1. Collected experimental and manufacturer data. Total thrust was calculated using a trapezoidal Riemann sum integration of the thrust curve. Propellant mass is the difference in motor mass before and after the test, and percent of propellant is propellant mass divided by total mass. Experimental total mass is not included because it was not measured during the data collection phase of this study; measures based on motor mass use the manufacturer mass data. As mentioned, the incorrect percent propellant measure for experimental C motor data is simply a result of the overpressure that occurred and was kept in the table to illustrate the effects of combustion chamber overpressure.

DISCUSSION

Overall, the D12-0 motor is the best performing in the greatest number of measures. Most of the C11-0 motor data has been excluded due to combustion chamber overpressure during testing, while the B6-0 motor shows the best maximum thrust per mass experimentally but not analytically. The smallest and lightest motor, the A8-0, surprisingly was not the best in any of the measures, even the ones that look for overall efficiency.

For rocket motors in launch vehicles, maximum thrust is the most important metric, as it determines how fast the rocket exits a planet's atmosphere and therefore its overall efficiency. On the other hand, some rocket engines are designed to operate in the vacuum of space, where maximum thrust is less important, and efficiency (or specific impulse) becomes much more important. Whichever the case, most of the measures of a motor's performance can be improved independently, and companies can optimize their motors to fit their mission needs.

The maximum thrust per mass is similar between all four motors in both experimental and manufacturer data (C11-0 motor experimental data excluded). If this correlation only appeared in experimental data, it could be due to test variability, but data from the manufacturer affirms this trend is accurate. However, manufacturer data for bigger motors (Estes E16-0 and F15-0) do not show this correlation, which means it may not apply for larger scale rocket motors (10). This could be due to a slightly more powerful propellant or differences in casing material and geometry. Further studies into the relationship between different sizes of rocket motors should use available or collected data to estimate the performance of a motor and subsequently test the motor to determine the accuracy of the estimation.

The C motor data was excluded from consideration for the best motor due to combustion chamber overpressure during testing. In future iterations of this study, this could be fixed by adding more epoxy to the plug to make sure the hot exhaust gas stays in place or looking at a different adhesive that is better equipped to handle high amounts of force and heat. Further studies could also gather more data from each motor type to collect a more accurate data set. Investing in higher sample rate data collection could also slightly improve data on the smaller motors, as they burn through quickly. The larger, more accurate data sets with higher sample rates would also reduce discrepancies between experimental and manufacturer data like how the B6-0 experimentally shows the highest maximum thrust per mass when manufacturer data suggests the D12-0 should perform better in this measure.

There are two things that differ between this analysis of model rocket motor thrust curves and that of Penn et al. in addition to the range of motors tested (6). The first difference is their static fire stand, which uses a force meter designed for lab use to collect thrust data at 250 Hz, where the load cell and HX711 chip in this study's static fire stand run at 10 Hz (6). Despite the large difference in sample rate, no major differences were seen, and good agreement was shown between experimental thrust profiles from this work, the manufacturer, and Penn et al., providing confidence in the novel test set-up. Specifically, each motor type exhibits performance similar to manufacturer data, and the experimental graphs show the same thrust curve shape as the manufacturer graphs (6). Also, their static fire stand allows for the testing of motors with ejection charges since the hot gases can easily escape without impacting the thrust measurement. This differs from this study's setup because we exclusively used 'booster' motors (no delay or ejection charge) that were plugged with epoxy to prevent hot gases from escaping out the wrong end of the motor. Addition of the epoxy may have slightly affected the data since some measures consider motor weight, but even for the smaller motor the epoxy is expected to be less than 5% of the total mass. Secondly, Penn et al. focused solely on maximum thrust and duration, while this study includes more measurements such as total thrust and percent propellant (6). By including more parameters in the data, this study provides an analysis of these motors with a more complete interpretation of performance.

Researching large-scale motors is expensive and time-consuming, encouraging research on smaller motors.

Data from this study and others can be used to determine correlations between size and performance. These trends would inform research on large-scale motors that could be done through small scale mock-ups, requiring less time and money while still providing the data needed from a static fire.

Full scale rocket motors, even solid fuel ones, are expensive considering their short lifetimes. Solid rocket motors, which have lifetimes of only a few minutes, require custom tools to form the massive grains and take weeks to cure (7). In total, the NASA Space Shuttle's solid rocket boosters cost around $2.5 billion to develop, putting them far out of reach for the average U.S. citizen or even many researchers (8). Model rocketry offers an alternative, providing solid fuel motors and casings for less than $100.

When we purchased these four motors online, we also noted the price differences between them. The D12-0 motor was the most expensive at $13.49, followed by the B6-0 motors at $11.99, the A8-0 motors at $11.29, and the C11-0 motors at $9.99. As these prices are similar and each motor is quite different, we conjecture that consumers interested in these products would choose the right motor for their needs despite the price differences. As such, motor prices were excluded from the main portion of this study.

In addition, orbital-class solid-fuel boosters put out around 200 metric tons of carbon dioxide every launch, which contributes to climate change caused by greenhouse gas pollution (9). Since model rocket motors are much smaller, pollution is greatly reduced. Orbital rockets are still necessary for launching satellites into orbit, but model rocket motors are much cheaper and better for the environment than orbital-class solid fuel boosters for research purposes, such as studying their characteristic thrust curve that all sizes of rockets share.

The benefits of model rocket motors extend beyond cost and environmental impact. Hobbyists around the world have access to model rockets and can purchase them at local hobby shops or online. This makes research on model rocket motors much more convenient than on orbital rocket motors, one reason why Penn et al. and this study employ model rocket motors (6). Another advantage of model rocket motors is that anyone with proper certification can fire them. An approved launch site, clear weather, and an off-the-shelf launch stand and controller is all that is needed. For hobby purposes, A8-0 motors are still useful for launching small recreational rockets despite not being the best motor in any category since bigger, heavier motors would cause instability in the rocket as it flies. Orbital rocket motors, on the other hand, can only be launched after receiving lengthy and costly Federal Aviation Administration (FAA) certification. The final advantage of model rocket motors is they come with their own igniters, which easily hook up to the launch controller when it is time for ignition. Orbital rocket motors are custom-made and therefore companies must design their own igniters and integrate them into their launch systems. From their availability to their ease of use to their simple ignition system, model rocket motors have many advantages for research over orbital rocket motors.

MATERIALS AND METHODS

Instruments and Motor Set Up

Experimental thrust curve data was collected before any analysis on model rocket motor thrust curves was completed. To collect this data, a novel static fire test stand was built with a load cell to measure the thrust of rocket motors from classes A-D, specifically Estes motors A8-0, B6-0, C11-0, and D12-0 (**Appendix A**). Each motor was fired twice from the same stand in the same conditions to collect more data and ensure consistency.

The short height and the heavy (11.4 lb.) base enable the test stand to remain stable without using stakes or other methods of ground attachment. The model rocket motor is secured in the white PVC tube and fires upside down, pushing down on the load cell and the test stand. This removes as much risk as possible by directing the fire upward, away from people and equipment, while still allowing ignition to be visually confirmed. The force from the motor registers in the load cell, which sends a weak signal to the small HX711 load cell amplifier chip to boost the signal. A Raspberry Pi reads this signal, then logs it to a file along with the timestamp for later analysis. All electronics are separated from the test stand to dampen the effect of vibrational noise from the motor firing (**Appendix B**).

Data Collection

We collected data using a novel test stand which relies on an HX711 load cell amplifier chip. In its default configuration, the HX711 runs at a 10 Hz sample rate, which means that for every second the motor fires, the chip will log 10 load cell readings. This is more than adequate resolution to capture the shape of each motor's thrust curve over the ~1 second it fires. We used a load cell rated for the expected thrust from the rocket motors, which for our range of motors was a maximum capacity of 20 kg.

In preparation to fire the motors, we plugged all the motors with epoxy to prevent hot gas escaping out the wrong end of the motor. The unwanted escape of mass would otherwise lead to unpredictable thrust effects and render the corresponding data useless. For each motor type, we plugged and fired two motors, averaged the resulting two data sets, and collected manufacturer data from the official Estes Rockets website (10).

Data from these thrust experiments were then compared to the manufacturer-provided thrust curves. From these comparisons, the best model rocket motor was quantitatively determined based on thrust, thrust-to-weight ratio, and other performance metrics. Total thrust was calculated using a trapezoidal Riemann sum integration of the thrust curve. Propellant mass is the difference in motor mass before and after the test, and percent of propellant is propellant mass divided by total mass. Experimental total mass is not included because it was not measured during the data collection phase of this study; measures based on motor mass use the manufacturer mass data.

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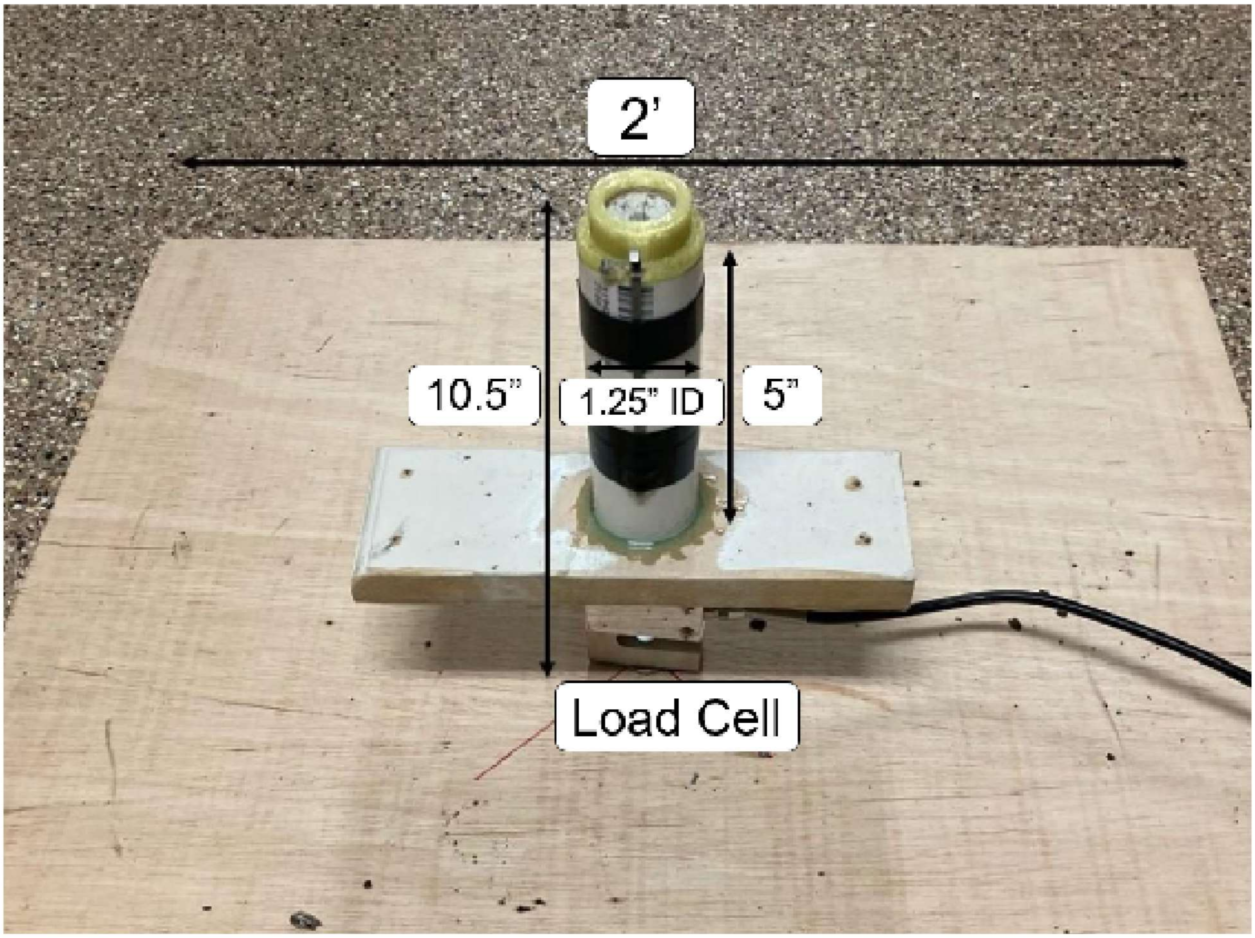
APPENDIX



Appendix A. Test stand build. The completed static fire test stand build, including a motor. The motor is inserted into the tube with the flame end up, along with spacers to hold it in place during the static fire. Missing from this photo is the igniter and wires from the launch controller needed to ignite the motor.

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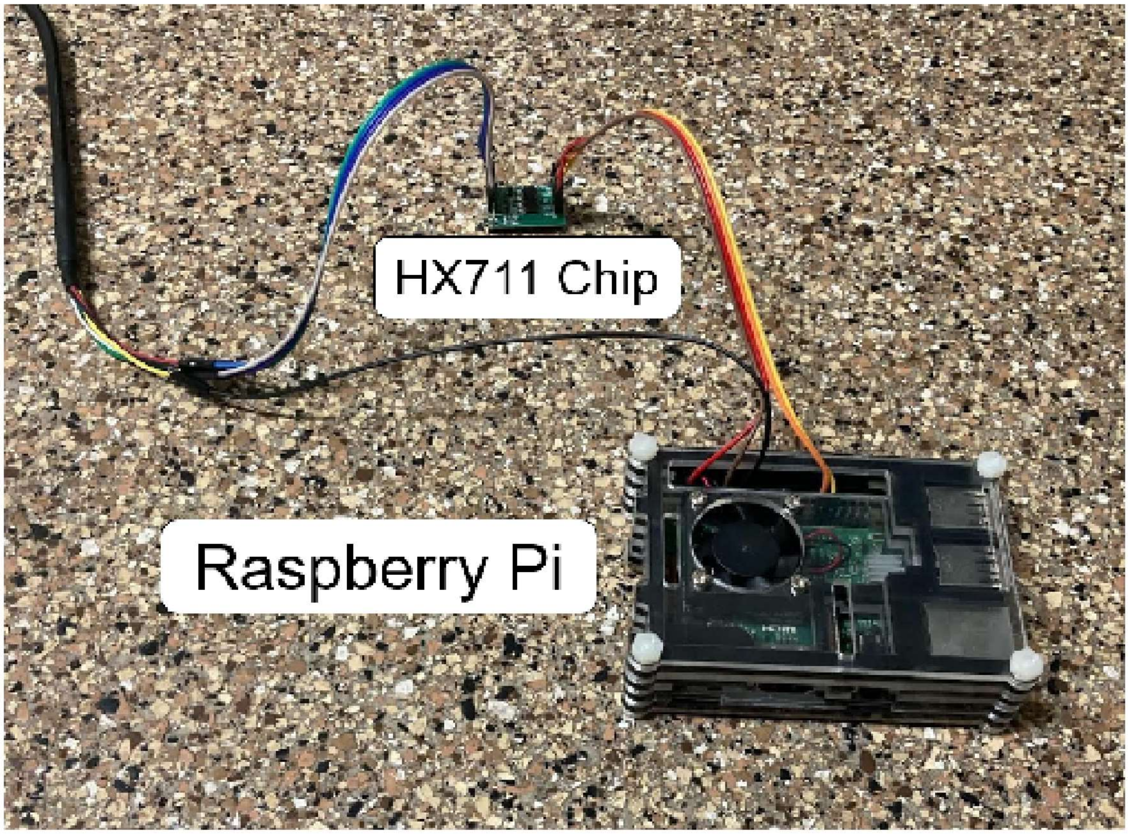

Appendix B. Test stand electronics. The electronics for the test stand. The black wire bypassing the HX711 chip is to ground external noise from the load cell. Not shown are power, display, and keyboard and mouse cables connected to the Raspberry Pi to run the data collection program.