Design of a Two-Axis Shaking Table to Simulate Earthquakes in an Educational Setting

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Introduction

Earthquake strikes are a destructive, costly, and deadly force. High magnitude earthquakes in heavily populated areas historically cause thousands of deaths that could be prevented if buildings were better made to resist such strong forces. The cost of repair and clean up cost often extends into the tens of millions[7].

The design of an earthquake simulation table that can be used in educational settings has been assigned as an undergraduate senior capstone project. The table will be used to analyze the effect of earthquake forces on smart structures to help develop an understanding of the effect of earthquake forces and design earthquake-resistant designs in architecture. Our client has requested that the simulation table be able to emulate real-time earthquake data in two horizontal directions (X,Y) in a strict budget. We have defined the problem, gathered information, generated alternatives, evaluated potential solutions, and have a proposed design for the machine.

Problem Definition

According to the Center for Research on the Epidemiology of Natural Disasters, approximately 121 million people are affected by earthquake strikes, and caused as many as 750,000 deaths between 1994 to 2013. About 55% of people are killed by earthquakes, more than any other types of natural disaster, and cost more than $700 billion in damages. The National Earthquake Information Center locates about 30,000 earthquakes each year. A system is needed to study the stability of structures during the earthquake strikes to minimize damages.

The machine created by our team is to be used as an educational tool in earthquake science. An affordable shaking table that accurately emulates earthquake forces could be valuable to children's science museums, primary and secondary schools, and universities.

Our senior design team first established what the design must satisfy to be a viable solution and determine what factors would be used to evaluate the performance of competing solutions. Table 1 is the list of constraints and evaluation metrics.

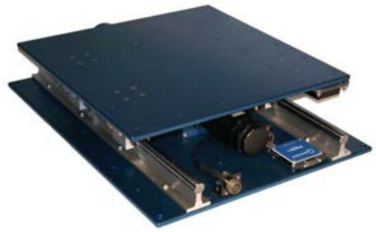
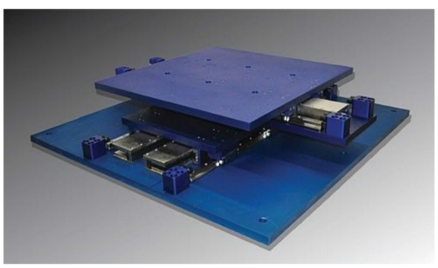
Table 1: Requirements, Constraints and Evaluation Metrics

Requirements	- Emulate the acceleration data from past earthquakes when input into software - Must be easy to use - Must be easy and inexpensive to maintain - Software must at least simulate sine and cosine waves - Must support a structure and have a method to attach the structure to the table - Must have a way to measure the table/structure's results during simulation - Must include comprehensive user manual
Constraints	- Must simulate 2 components of 3 possible – horizontal components (x,y) - Motion in multiple axis is able to strain a building in unique ways that is not possible with only a single direction of force - A third axis (Z) would be a large step up in complexity and price - Must be $1500 or less - Must be able to operate without requiring extensive training - User interface should be intuitive enough for basic operation - User manual should contain all information required to operate and maintain the table
Evaluation Metrics	- Less expensive is better - Higher positional and accelerational accuracy in emulation is better - Parts with easy and inexpensive maintenance plans are better - Longer lifespan is better

Background

Upon researching potential solutions for building an earthquake table, multiple competitive products were discovered. These ranged from cheap classroom inventions for towers of straws and marshmallows to industrial sized tables meant to hold a three story building. These varied in their size, power and repeatability, and so the most reliable designs were selected for further research and study. Table 2 provides a few visuals and specifications for other products of this kind.

Table 2: Competitive Products

Competitor	Visual	Specifications
Quanser Shake Table II[13]		Stage Size: 0.46 m x 0.46 m Motor: Servo with lead screw Power: 4.5kW Max payload: 7.5 kg Max Acceleration: 2.5g Travel: ± 7.6cm (x), ± 7.6cm (y) Price: $$
Quanser Shake Table III X-Y[14]		Stage Size: 0.7 m x 0.7 m Motor: Linear Power: 4.5kW Max payload: 100 kg Max Acceleration: 1g x 1g Travel: ± 10.8cm (x), ± 10.8cm (y) Price: $$$
H2W Technologies XY Shake Table[15]		Motor: Linear Travel: ± 3.2cm (x), ± 3.2cm (y) Price: $$
3-Axis Hydraulic Vibration Shaker[4]		Stage Size: 0.8 m x 0.8 m (largest) Motor: Servo-Hydraulic Max Acceleration: 150 m/s^2 Max Velocity: 1 m/s Price: $$$$ http://www.econ-group.com/product/?id=49

Methodology

Multiple earthquake tables have been designed for the same need by competitors. These designs consist of state of the art motors and materials and are sold at high prices in comparison with our own budget. We studied these designs to determine four potential solutions for the primary component of the earthquake table, the motor. These are hydraulic, pneumatic, linear, servo motor and ball screw, and servo motor with belt. We evaluated the solutions with four evaluation metrics in mind: cost (40%), emulation accuracy (30%), lifespan (20%), and ease of maintenance (10%). We determined that using a servo motor with a ball screw was the best option for the given requirements.

Motor Selection

The competitive products helped our team develop a list of the required materials and components that are required to fulfill the purpose of our table. What we learned is the primary component in a table that can move in both horizontal directions is the method to convert rotational motion into linear motion. We looked extensively into four different possibilities.

The linear motor requires the most additional electrical components, but also allows for the most compact, high speed and high acceleration motion of the four. This type of motor utilizes coils of wire (the rotor), moving inside a magnetic track (the stator). Currents passed through the rotor cause force to be exerted upon the stator, causing the rotor to move. Shown below in Figure 1 is a typical design of these coreless motors. These motors also require a large drive system to provide current into the coils, which makes their cost higher than that of a traditional motor[9].

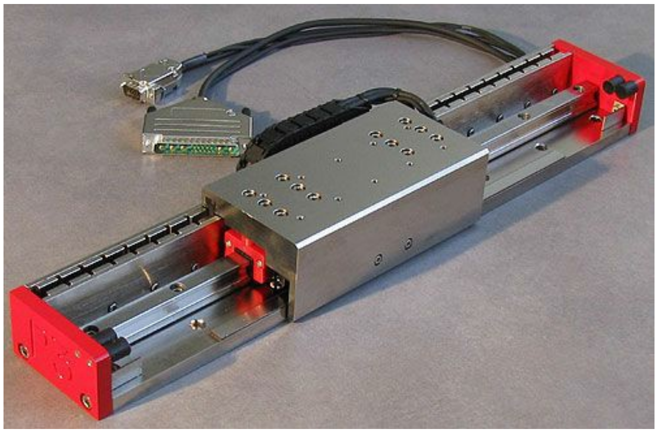


Figure 1: Linear Motor[11]

The servo and screw is a moderately priced and moderately powered option, utilizing a stepper or servo motor and a ball screw. The motor contains an internal drive, which receives input signals from the control module, and converts it into the AC power required by the motor.

A ball screw is used to translate the servo motor's rotational motion into linear motion. This has the additional benefit of simultaneously increasing the force that is applied to the object in motion, allowing for higher accelerations with less strain on the motor.

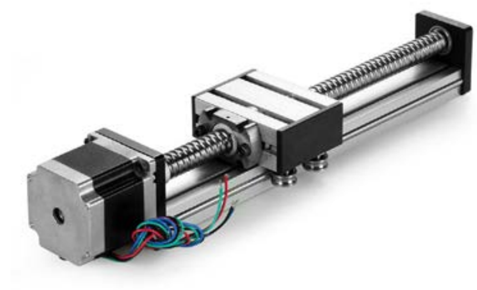


Figure 2: Stepper Motor and Rail[1]

A hydraulic system applies pressure to a hydraulic cylinder using a fluid. Because of the incompressible nature of fluids, a higher pressure is able to be created than by a pneumatic system. This pressure is supplied using hydraulic pumps, and controlled with hydraulic valves. Due to the large number of additional parts required, hydraulic systems are the most expensive to create and maintain. Many parts wear due to motion, and the high pressure created by the fluid can lead to failure of hoses and other parts. However due to the high pressures able to be created using these systems, they are the most prevalent sources of motion in extremely large earthquake tables[8].

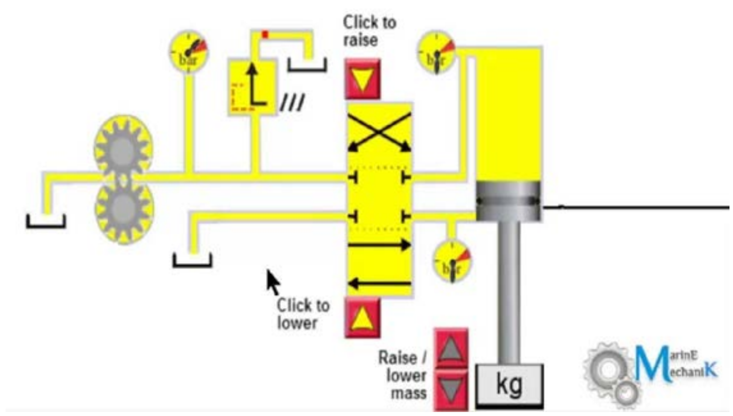


Figure 3: Hydraulic System[12]

Servo and belt systems are commonly used in manufacturing as a cheap way to achieve linear motion from a stepper or servo motor. These systems have the advantage of low cost due to a low amount of components used. Additionally, because of their few moving parts, there are not many places that can fail. Unfortunately for this application, the high changes in acceleration would put high strain on belts, causing them to wear and fail prematurely[2].

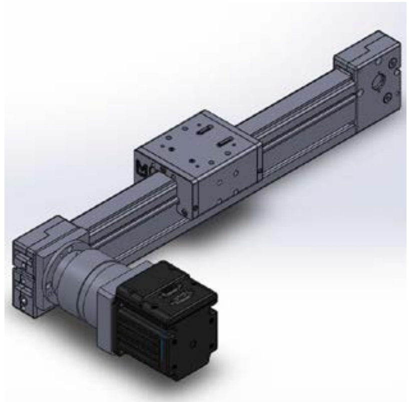


Figure 4: Servo and Belt System[3]

Table 3 provides a list of the different motor and the specialized components that are associated with them. As the primary constraint is cost, we put an approximate cost on each different motor and its components. Much of this information was not available on the internet, so we contacted multiple supply companies that could provide a quote. A linear motor supplier was able to quote a cost half of what is usual in support of the purpose of the project.

Table 3: Specialized Components Required and Approximate Cost for a Single Axis

Linear Motor	Stator	Rotor	Linear Motor Drive	Power Supply
$1648	$470.90	531.45	$316.80	$328.89
Servo & Screw	Servo	Ballscrew	Power Supply	
$748	$349	$200	$199	
Hydraulic	Hydraulic Pump	Hydraulic Valve	Hydraulic Cylinder	Pressure Gauges
$2496	$725	$249	$1322	$200
Servo & Belt	Servo	Belt & Pulley	Power Supply	
$698	$349	$150	$199	

Once the drive type was selected, the specific type of motor used needed to be selected. These motors had to meet several requirements. The motors needed to be somewhat low cost, as they would be a large portion of the overall project's final total. Additionally, to keep the control system from requiring to do a great deal of extra computation the motors should have a simple to interface drive. Finally the motors needed to have the most possible output power to allow the table to move with the required velocity.

The motors selected were Clearpath motors from Teknix, and were chosen due to their integrated drive mechanism. This would allow the group to reduce the number of components used. A power supply from Teknix was also selected to help improve the reliability of the system due to the design of the motors. The power supply allows the motors to backfeed power from braking, enabling faster direction changes. The motors are able to be powered from 24-75 volts, and the Teknix power supply uses the highest 75 volt option, which causes the motor to allow itself to move with maximum possible torque[5].

In order to drive the motors, the group chose to make custom cables by purchasing molex connectors and using spare wire from the university's spare parts. This was done as cables from the motor manufacturer were much more expensive, and making cables ourselves would allow for the length to be selected to minimize excess cabling. To use the motors, an arduino was connected to the cables, using a custom circuit board.

Material Selection

For the design in question, the materials that would be used to construct and support the table would need to be able to withstand the force of earthquake like movements without causing the ball screws to break. The ball screws are not made to handle weight as a normal stress and are just meant to move the different platforms on their axis. This means that the support rails need to take most of the weight and the overall weight of the parts should not be too heavy.

Wood is not strong enough to handle the quake movements and the weight of the mechanical systems as a base. Wood is strong enough to serve as the top-most shaking stage as wooden boards are easy to keep flat, easy to alter to affix structures to it, and light enough to not cause undue stress on the rest of the table. Steel and aluminum are the next best materials to use as their weight to cost and weight to strength ratios are more reasonable than some plastics. Steel is usually less expensive than aluminum and is strong enough to handle the vigorous movement of a small quake and the weight of heavier objects. Aluminum, on the other hand, is lighter and more malleable making it easier to work with. Because of these factors the final design has both steel and aluminum parts. Steel makes a good base and table material while aluminum is used to alter the heights of specific parts like the guiding rails and ball screws to minimize the overall weight on level of the table as seen in Figure 5 and Table 4 outlines a full list of the parts that are included in the design.

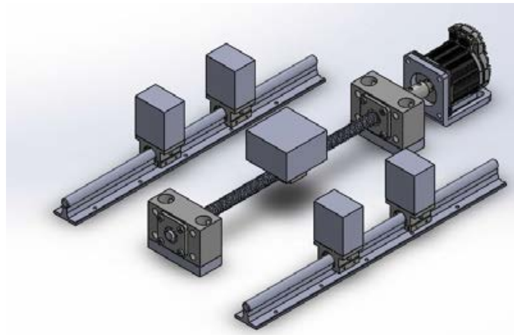


Figure 5: Ball Screw Mechanism and Rail Layout

Table 4: Parts and their roles

Material	Role
Teknic, ClearPath® - Integrated Servo System	Servo/Drive
Heavy mounting bracket for NEMA 34 stepper motor	Servo Mount
Teknic, IPC - 3, 225 W DC Power Supply	Power Supply
Ballscrew (20mm, 550mm), Ballscrew Nut, Mounts (2), Coupler	Linear Motion System
Linear Rail & 2 Linear Bearings, 16mm D, 550mm L	Track System
½" Wood Panel	Top Shaking Stage
1/2" steel plate	Shaking/Inter Stage
⅜" steel plate	Base Stage
Tube aluminum bar stock	Alter component heights
Cold-drawn aluminum bar stock	Alter component height
Motor Cables	Data transfer
Arduino Mega 2560	Controller
Bolts, Screws, Brackets	Fasteners

Mechanical Design

After selecting the motor and materials, the table was then designed in a 3-D modeling program. This helped to determine what the approximate size and dimensions of the table would be. The limiting factor for the table was the ball screw that we had selected for optimum simulation. The ball screw components in conjunction with the motor and the linear shafts do not line up, so the 3-D modeling software was used to determine the size the the appropriate height adjustments that would be needed prior to building the machine. Figures 6 and 7 show the final 3-D depiction of the the table prior to being built.

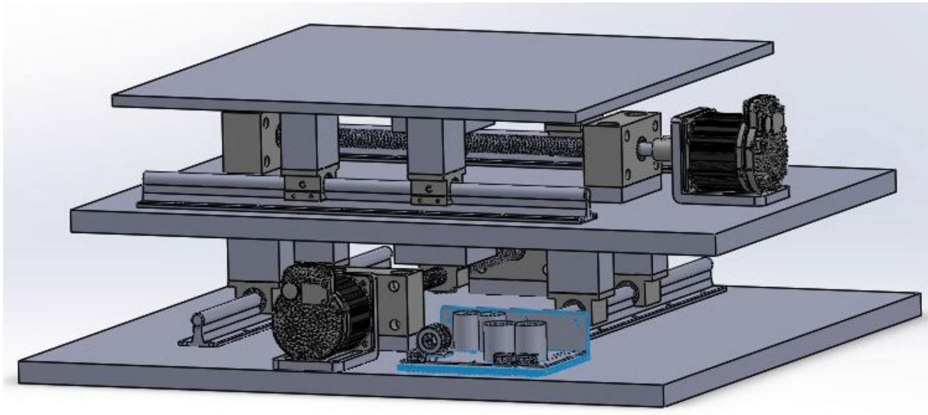


Figure 6: Solidworks depiction of table design

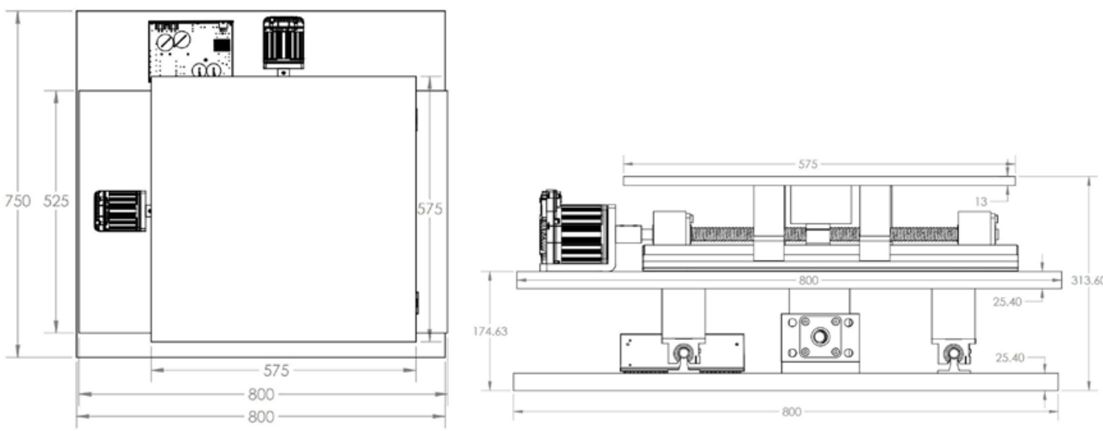


Figure 7: Top and side view of table with dimensions

Controls Design

To control the table, an arduino mega was selected, due to its high memory and large number of I/O pins. This memory was necessary due to the high amount of information required to be transmitted between the arduino and the controlling computer. This data will come from an online database of past earthquake acceleration data, which can be easily converted in a software that we will develop, and consequently input through a controller into the two motors.

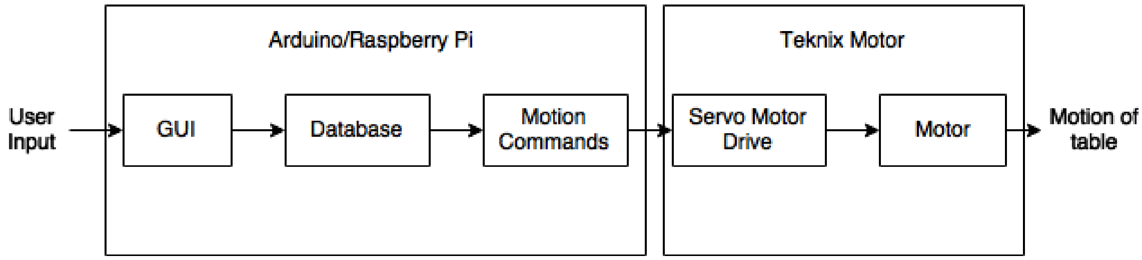


Figure 8: Controller

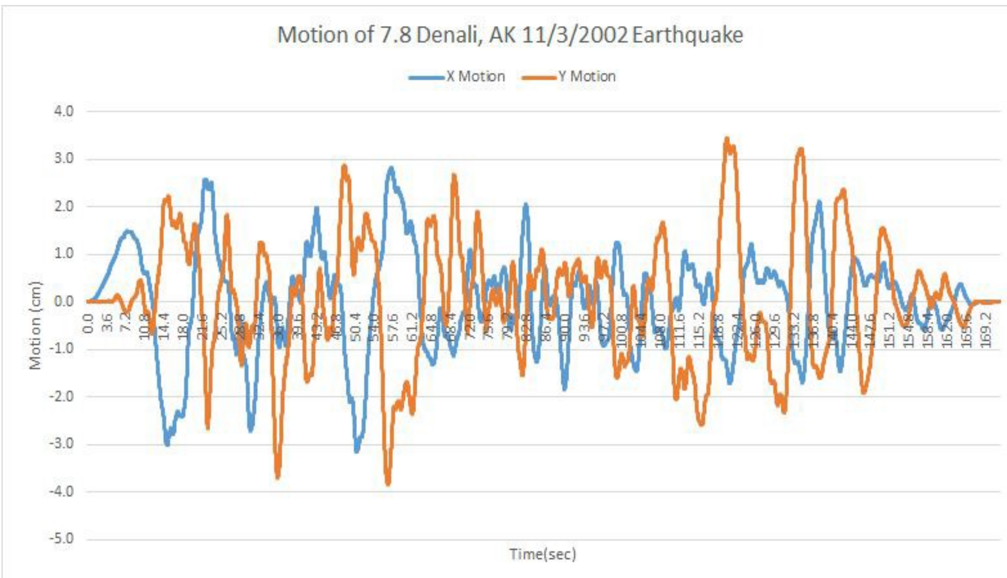


Figure 9: Example of recorded earthquake data that will be simulated[10]

This database, the Ground Motion Database, is produced by the Pacific Earthquake Engineering Research Center. This database has searchable acceleration data for thousands of actual earthquakes, in a wide range of magnitudes[10]. The GUI is used to handle the motion of the table and plot the effect caused by the motion. The GUI that we are designing will allow the user to select whether to simulate past earthquake acceleration recorded data or to generate a sine wave signal. The user will also be able to run the software and see the effect of the motion on the structure. Figure 10 shows a flowchart of the graphical user interface.

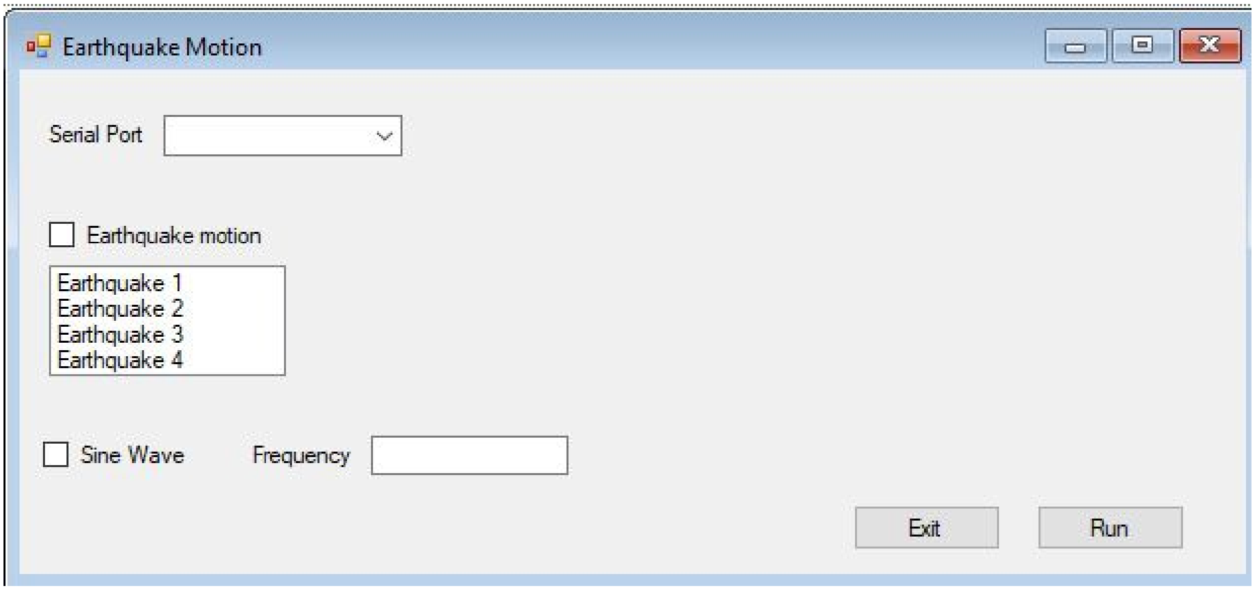


Figure 10: Graphical User Interface

Testing Plan

To test the motors, a series of tests were created. These were to test the motors ability to repeat its motions and to test the speed at which they could move. Finally, a test was done to ensure the motors would not be able to execute a command that would damage the motors themselves.

In order to ensure the motors would be able to move in a predictable and repeatable way, an encoder was used to monitor the rotor angle of the motor shaft. Varying commands were sent, having the motor move in multiple directions, changing speed rapidly to simulate the table in normal operation. In all tests executed, the motor was able to remain in position to the minimum resolution of the encoder (0.056°).

To test the motors self-protection function, a speed that the motors were not rated for was sent to the drive system (1500RPM). This caused the motor to rotate for an instant until it reached its rated maximum speed, and then emergency stop itself. This required a power cycle to allow commands to be responded to. This gave us confidence that any error in our programming would not damage the expensive motors or their drives.

Future Work

The table will be tested with and without a smart structure attached to determine its accuracy and maximum limits of acceleration and payload. The specifications and method for using the machine will be carefully outlined in an instruction manual. The primary goal for this table is to make it as accurate and user-friendly as possible.

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