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FREELOADER: AN OPEN SOURCE UNIVERSAL TESTING MACHINE FOR HIGH-THROUGHPUT EXPERIMENTATION

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ABSTRACT

We present a low cost, desktop size, open source, universal testing machine, designed for inexpensive high-throughput material testing. The tester can apply tensile and compressive loads up to 5 kN at rates ranging from 2 mm/min to 30 mm/min. Force measurements are achieved with ±1.8 N accuracy. The parts list for this machine represents an order of magnitude reduction in the cost per testing unit as compared to commercial systems. We describe the design and construction of the tester and validate its performance. The design, parts list, control software, and user manual are made available freely online under the open source BSD license.

INTRODUCTION

In this paper we present a low cost, desktop size, open source, universal testing machine. Named freeLoader, our machine (shown in Fig. 1) is small, inexpensive, and modular, and it aims to fill the growing need for inexpensive high-throughput material testing methods.

The traditional dog bone tensile testing process is slow and ill suited for parallelization due to the cost and size of the testing machines. Even the smallest universal testing machines (like those sold by Instron, Tinius Olsen, Zwick Roell, Applied Test Systems, MTS Systems, United Testing Systems, ADMET, and

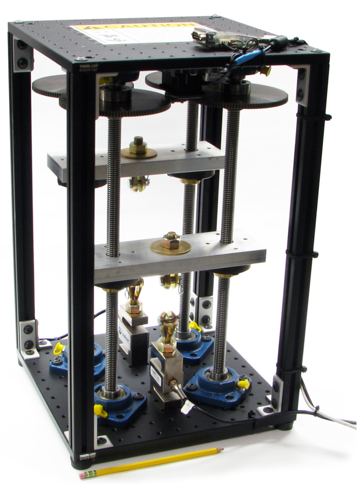

FIGURE 1. PHOTOGRAPH OF THE FREELOADER TESTING MACHINE. A FREELOADER CAN PERFORM TWO SIMULTANEOUS TESTS AND COSTS UNDER US$4,000. PENCIL AT FRONT IS INCLUDED FOR SCALE.

Qualitest) can cost more than US$20,000 for the machine, required calibration, and control software. Such a machine may also require a full desk's worth of space and a dedicated control computer. Devising a high-throughput parallel testing setup

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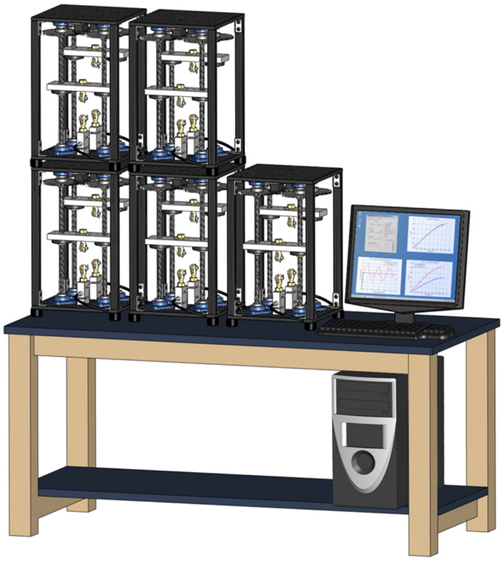

FIGURE 2. CONCEPT IMAGE SHOWING FIVE FREELOADER MACHINES – EACH CAPABLE OF PERFORMING TWO SIMULTANEOUS TESTS. AS SHOWN, THE MACHINES COULD BE STACKED ON ONE DESK AND CONTROLLED FROM A COMMON HOST COMPUTER, YIELDING SUBSTANTIAL SPACE SAVINGS.

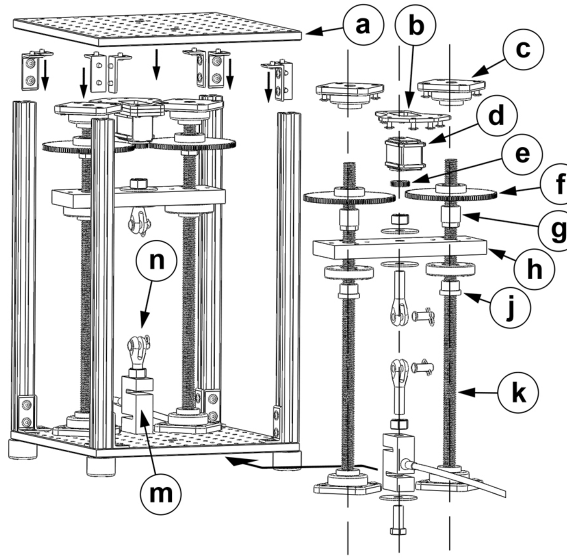

FIGURE 3. EXPLODED VIEW OF THE FREELOADER INCLUDING PARTS: A) OPTICAL BREADBOARD PLATE, B) MOTOR ATTACHMENT PLATE, C) BEARINGS, D) MOTOR, E) SMALL GEAR, F) LARGE GEAR, G) QUICK-GRIP BUSHING, H) CROSSHEAD, J) ACME NUT, K) ACME LEAD SCREW, M) LOAD CELL, N) CLEVIS ROD END.

around these machines is both cost and space prohibitive. However, for approximately the same price and space that one commercial machine requires, five freeLoaders can be built – each capable of performing two simultaneous tests. These five units could be stacked on one desk and controlled from a common host computer, as shown in Fig. 2.

There are many situations where conventional tensile and compression tests are still required. One example is the new family of highly tunable composite materials made possible by recent advances in multi-material 3D printing. It is now possible for a designer to specify not only the freeform geometry of a 3D printed part, but also the material composition and structure – assigning materials ranging from hard plastic to soft rubber at arbitrary locations throughout the part with 42 micron precision [1]. A vast new design space has emerged, where material properties can be tailored to compliment part geometry and function. Unique material properties can be achieved such as auxetic (negative Poisson's ratio) materials [2], anisotropic materials with tunable directional stiffness [2], co-continuous materials that outperform conventional reinforced composites [3], parts with prescribed bending profiles [4], and automatically designed foam structures with desired deformation behavior [5].

In order to take full advantage of this diverse new set of materials and the many opportunities they provide, engineers must be able to predict the structural properties of their designs. Material properties such as Young's modulus and yield stress are key indicators of performance and must be verified with physical tests in order to ground predictions in reality. Unfortunately, existing high-throughput testing methods are ill suited for composite 3D printed materials, which one might purposely design for high heterogeneity, anisotropy, and nonlinearity. Combinatorial methods (where large arrays of vary small samples, each with slightly varying composition, are prepared and measured in parallel) [6, 7]; and, in particular the method of nanoindentation for determining the modulus of a polymer [8], are better suited for more homogeneous materials.

For heterogeneous anisotropic plastics, the traditional dog bone tensile test [9] remains a key evaluation metric. Virtual testing methods that employ finite element analysis, such as recently presented by Kou, Tan, and Lipson [10], may prove to reduce the need for physical tests, but at the moment this method still requires verification from large numbers of tensile tests during the model's training period. High-throughput mechanical testing methods are needed going forward so that candidate designs can be characterized quickly and accurately. In this current age of open source 3D printing and rapidly expanding 3D printing capabilities, inadequate material models and insufficient testing techniques for generating said models are hindering progress.

Here we detail the design, construction, and validation of a prototype freeLoader machine. We also provide addi-

TABLE 1. COMPARISON OF THE FREELOADER AND SEVEN COMMERCIAL TESTING MACHINES.

Machine	Price* (USD)	Load Capacity (kN)	Load Accuracy (% of max)	Size HxWxD (cm)	Machine Weight (kg)	Vertical Test Space (cm)	Position Resolution (mm)	Max Speed (mm/min)	Min Speed (mm/min)
freeLoader	<$4,000†	5	0.02%	50 x 31 x 31	22	27	0.0005	30	2
Vendor 1	~$17,000	2.5	0.5%	154 x 43 x 52	114	124	0.0006	2540	0.005
Vendor 2	~$18,000	22.2	0.1%	152 x 89 x 51	n/a	70	0.001	51	0.5
Vendor 3	~$19,000	5	0.5%	114 x 49 x 45	50	75	0.001	500	0.001
Vendor 4	~$19,000	5	0.5%	126 x 56 x 37	50	73	0.001	1000	0.01
Vendor 5	~$22,000	2.5	n/a	114 x 55 x 46	46	75	0.001	1000	0.1
Vendor 6	~$25,000	5	0.5%	136 x 38 x 50	51	112	n/a	1000	0.05
Vendor 7	~$26,000	5	n/a	114 x 49 x 45	50	75	0.001	500	0.001

**Price includes the machine, load cell, calibration, and control software – it does not include grips*
†Can perform two simultaneous tests on one machine

tional resources including specific build instructions, control software, and a user manual for free online under the open source BSD license (visit `http://creativemachines.cornell.edu/freeloader`). We believe that freely available plans for building freeLoader machines will enable widespread adoption of the high-throughput approaches to material testing that are needed. The simplicity of the freeLoader should enable users to easily alter the design to suit their needs. Users are encouraged to modify the freeLoader design and share their ideas and improvements. Additionally, the low cost and space requirements of the freeLoader make it an attractive option for undergraduate teaching labs or even high school science and technology courses.

DESIGN

The freeLoader is a universal testing machine consisting of a four-beam load frame and two independent crossheads driven by geared servo motors attached to lead screws. An exploded assembly drawing of the design is shown in Fig. 3. The primary goals in designing this system were: minimizing cost and size, maximizing modularity and parallelizability, minimizing complexity and construction time, and ensuring usefulness. In particular, the trade off between ease of assembly and cost was key in driving the design. Parts were sourced from common online vendors in order to facilitate open sourcing, dissemination of the design, and modification by future users.

The freeLoader weighs 22 kg and has only a 31 x 31 cm footprint (height is 50 cm). The total cost of the machine is less than US$4,000 including all parts and shipping charges, and the required assembly time is less than two day's work. We designed each machine with two independent crossheads (Fig. 3h) so that a single machine can perform two simultaneous tests. Thus we estimate that for approximately one week's work and US$20,000, five freeLoaders could be constructed, capable of running a total of ten simultaneous tests – a tenfold increase in throughput for the same cost as one commercial machine. If cost is the major concern and high-throughput is not required (for example in a teaching lab environment), it is trivial to reduce the freeLoader design to a single crosshead, which reduces the cost of one machine to approximately US$2,500.

Each freeLoader has two crossheads that are independently driven by separate motors (Fig. 3d). The motors are Robotis Dynamixel geared servo motors rated for 64 kg-cm stall torque. We reduce the motors further with a 5:1 ratio from the motor to the lead screws using spur gears. The lead screws are 5/8-10 ACME threaded, thus we are able to estimate the maximum thrust force of the crosshead with the equation:

$$F = e\left(\frac{2\pi T}{L}\right) \tag{1}$$

where F is the thrust force, T is the torque applied to the lead screw, L is the lead of the screw, and e is the efficiency of the screw-nut assembly [11]. Assuming that the efficiency for a 5/8-10 ACME lead screw with a bronze nut is 30% [12], the efficiency for our spur gears is 97% [13], and measuring a 0.3 kg-cm loss in each of the four bearings, we can calculate the maximum thrust of the crosshead to be 22.5 kN.

The crosshead limits this maximum thrust however by its yield strength. We can calculate the maximum bending moment that the crosshead will support at yield with the following equation:

$$M_y = \frac{\sigma_y I}{K_t c} \quad (2)$$

where M_y is the bending moment at yield, σ_y is the yield strength of the material (6061 aluminum), I is the moment of inertia of the crosshead, K_t is the stress concentration factor of the crosshead geometry, and c is the distance from the crosshead's central axis to the edge [14]. Assuming that the force applied to the crosshead is a uniformly distributed load over the area of the contacting washer, and the yield strength of 6061 aluminum is 55 MPa, we find the resulting force at yield to be 7.1 kN. Thus, limiting the freeLoader to a 5 kN capacity provides a factor of safety of 1.4.

The load cell (Fig. 3m) is an S-beam style from Loadstar Sensors, Inc., rated for 8.9 kN with an accuracy of ±1.8 N and a safe overload up to 13.3 kN. This load cell can be configured for both tension and compression measurements. Suitable tensile test grips are hard to find for a machine this small, so we have instead employed clevis rod ends (Fig. 3n), which have proven to be sufficient, especially for test specimens that can be 3D printed to accommodate the gripping mechanism.

The maximum vertical testing space in the freeLoader is 27 cm. We have measured the maximum speed of the crosshead to be 30 mm/min; the minimum speed is 2 mm/min. Using the built-in motor encoder, crosshead travel can be measured with 0.0005 mm precision.

The accuracy of using the motor encoder to measure specimen elongation is somewhat suspect due to the possibility of unwanted deformation occurring in the crosshead, frame, load cell, and lead screws during testing (not to mention the deformation that occurs outside the narrow region of the specimen). For very accurate measurements of specimen elongation an external extensometer or strain gage should be used, as is commonly mandated by ASTM testing standards. However, as shown later in Fig. 4, results obtained on the freeLoader are comparable to those obtained on a commercial testing machine – indicating that encoder data from the freeLoader is likely as useful as the elongation data that commercial machines provide.

Table 1 shows a comparison of freeLoader specifications and seven commercial testing machines. Some of the specifications of the freeLoader have been optimized for tensile testing of 3D printed plastics, but relatively small modifications are necessary to adopt the design for other materials or for compression testing. For example, users may want to experiment with alternate gear ratios, load cells, or control strategies to better accommodate their testing needs. Replacing the clevis rod ends with compression platens or three point bending fixtures would also be required before performing such tests.

CONSTRUCTION

All of the parts required to build a freeLoader are available from online vendors. The complete parts list is included in Appendix A. As of May 5, 2011, the total price to order all of the necessary components was $3,687.46 plus shipping.

The vast majority of parts require no modification. Those that do require modification, mostly need only to be cut to length or have a few holes drilled. The minimum required tools for making part modifications are: a saw, a drill, a few drill bits, a #3-48 tap, and a 1/4-20 tap. Additional recommended tools include: a band saw, a lathe, a milling machine, a drill press, an 82° countersink drill, and especially a laser cutter.

The only two components that require significant modification are the crossheads (Fig. 3h) and motor attachment plates (Fig. 3b). To manufacture the crossheads, a stock aluminum plate must be cut to length and eleven holes must be located and drilled (eight of those holes must be tapped). We found that the time required to manufacture one crosshead was approximately two hours using a milling machine. The motor attachment plates can either be laser cut out of acrylic, or must be machined from a suitable replacement material. Laser cutting is preferable as it provides a tremendous time savings. Technical drawings of the crossheads and motor attachment plates are provided in Appendix B.

Several other parts require small modifications: the lead screws must be cut to length, the holes in the large gears must be enlarged, four holes need to be drilled in the small gear, four holes must be tapped in the motor servo horns, and four and six holes must be drilled in the top and bottom optical breadboard plates respectively. Once modifications are complete, the final assembly is straightforward. A specific set of assembly instructions, as well as a detailed description of each necessary part modification is included in the user manual on the freeLoader website. The only tools required for assembly are Allen keys, a crescent wrench, and a flathead screwdriver.

CONTROL

All communications with the freeLoader happen over USB connection. A console program was written in C++ using Microsoft Visual Studio, which enables the freeLoader to run tests and log data. The program was developed for the Microsoft Windows operating system, and has been on Windows XP and Windows 7 (it should also work with Windows Vista).

During a test, readings from the load cell and from the motor's encoder are logged to a text file with an accompanying time stamp; this occurs at a 5 Hz sampling frequency. At the beginning of a test, the user is able to set the speed and direction of crosshead motion. The user may also choose to have the test conclude on specimen failure or after a set time. During a test, the host computer's keyboard functions as the emergency stop, and the test will automatically conclude if the measured force

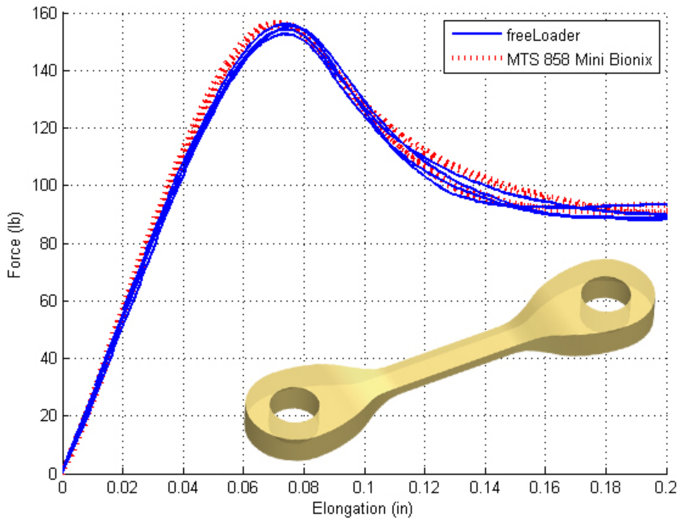

FIGURE 4. TENSILE TEST DATA FROM THE FREELOADER COMPARED WITH DATA FROM A COMMERCIAL TESTING MACHINE (MTS 858 MINI BIONIX). A CAD RENDERING OF THE 3D PRINTED TEST SPECIMEN IS SHOWN AT BOTTOM RIGHT. THESE RESULTS ILLUSTRATE THE REPEATABILITY OF THE FREELOADER MACHINE.

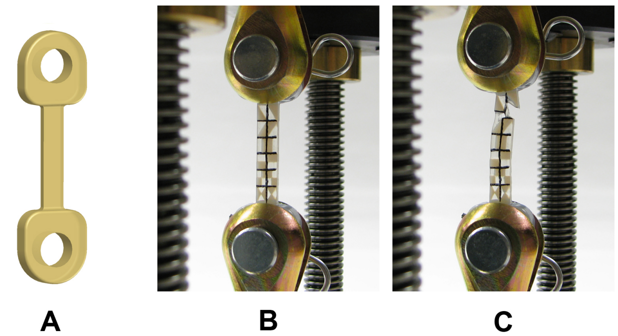

FIGURE 5. CAD RENDERING OF A CONCEPT TEST SPECIMEN SHOWING A PROPOSED NEW GEOMETRY THAT LIMITS STRESS CONCENTRATIONS AND CONFINES DEFORMATION TO THE NARROW REGION – ELIMINATING THE NEED FOR AN EXTERNAL EXTENSOMETER (A); A PHOTOGRAPH OF A SUBDIVIDED TEST SPECIMEN THAT WHEN COMBINED WITH DIGITAL IMAGE MEASUREMENTS MAY YIELD MULTIPLE DATA SETS FROM A SINGLE TEST (B), AND THE SAME SUBDIVIDED SPECIMEN SHOWN AFTER DEFORMATION ON THE FREELOADER (C).

reaches 5 kN.

In open loop, the crosshead speed is typically ± 2 mm/min with some constant offset from the set value. We have been able to reduce this error to ± 1 mm/min and no offset using a simple hand tuned proportional-integral (PI) control scheme. Future versions of the control software may achieve better results with a more complicated control scheme, but this has not been attempted yet.

VALIDATION

To confirm the accuracy of our freeLoader prototype, we performed identical tests with the freeLoader and with a commercial testing machine. The commercial machine was a MTS 858 Mini Bionix, which also has a 5 kN maximum capacity. Dog bone test specimens were 3D printed in the FullCure 720 photocurable polymer from Objet Geometries Ltd. The geometry of the specimen was based on the ASTM D638 testing standard [9], with modifications for added thickness at the ends to accommodate the freeLoader's clevis rod end grips. Five specimens were tested on each machine, as per the ASTM standard. The results from the comparison test are shown in Fig. 4 along with an image of the test specimen. It can be seen that the results obtained with the freeLoader show good repeatability and accuracy.

The traditional dog bone specimen specified by ASTM D638 is designed to minimize stress concentrations and permit specimens to be machined from plastic sheet stock. This design however results in significant deformation occurring outside the narrow region during testing. Thus to determine Young's modulus for the material, an external extensometer is required [9].

With 3D printed plastics, however, it is no more difficult or expensive to manufacture testing specimens with any particular geometry. Therefore we can begin to design new shapes that confine a much greater percentage of the deformation to the narrow region by thickening the specimen in other areas. Such a design is shown in Fig. 5A. A test specimen with a similar geometry to this might be able to adequately limit stress concentrations and also eliminate the need for an external extensometer – further accelerating the testing process.

Digital image correlation methods for measuring deformation [15], when combined with 3D printing, may also enable additional parallelization of the testing process. Figure 5B-C are photographs of a concept test specimen that has two different materials located throughout twelve subdivisions of its narrow region. By observing the deformation of these subdivisions with a camera during a test, it may be possible to glean multiple sets of data from a single tensile test.

OPEN SOURCING AND SAFETY

All designs, CAD files, documentation, software, and source code have been made freely available on our website (`http://creativemachines.cornell.edu/freeloader`) under the open source BSD license. We hope that doing so will make this technology available to as many potential users as possible, and will help accelerate the spread and development of high-throughput testing methods. These items are provided without warranty of any kind and in no event shall the authors or Cornell University be held responsible for any liability arising from dealings with this information or with freeLoader machines.

There are inherent risks associated with any machine that can exert 5 kN force on a specimen with the intent to tear it apart or crush it. Safety glasses are recommended during testing and special concern should be taken to ensure hands and clothes do not become crushed between, or entangled in, moving parts. During compression testing in particular, there is a risk that a specimen may shatter, ejecting shards at a high rate of speed. As an extra precaution against such an event, clear acrylic doors can easily be installed to cover the four sides of a freeLoader machine. These doors also serve to reduce the risk of injury by blocking access to the spinning gears. We have not shown the doors in Figs. 1, 2, or 3, but their cost is included in the parts list in Appendix A, and their installation is described in the user manual.

The freeLoader design should be able to withstand its maximum force without issue. Our calculations indicate that the limiting component in the design is most likely the crosshead, which can support 7.1 kN at yield. By limiting the maximum force to 5 kN in the control software the factor of safety for the freeLoader should be 1.4, although we have not yet tested the machine to failure. Tests up to about 2 kN have been safely conducted without issue.

CONCLUSION

In this paper we present the freeLoader – a low cost, desktop size, open source, universal testing machine that represents an order of magnitude reduction in cost compared to commercial systems. The design, construction, and control of a freeLoader prototype were discussed, and test results were presented that validated its performance. All designs, CAD files, software, source code, and documentation (including a user manual) have been made freely available on our website under the open source BSD license.

The freeLoader is well suited for use in research settings, undergraduate teaching labs, and possibly high school technology courses. A freeLoader can be built in less than two days for under US$4,000, and its design should be easily modifiable by users wanting to customize it to suit their needs. We believe that freeLoader machines will help to expand the use of data-driven experimentation, especially in the area of multi-material 3D printing, by making inexpensive high-throughput material testing methods more readily available. Future work will center on further accelerating testing methods through the use of new test specimen geometries and digital image correlation methods. Additional efforts will be made to decrease the minimum test speed, source alternative gripping fixtures, improve the control software, continue cost reduction, and develop a community of users.

ACKNOWLEDGMENT

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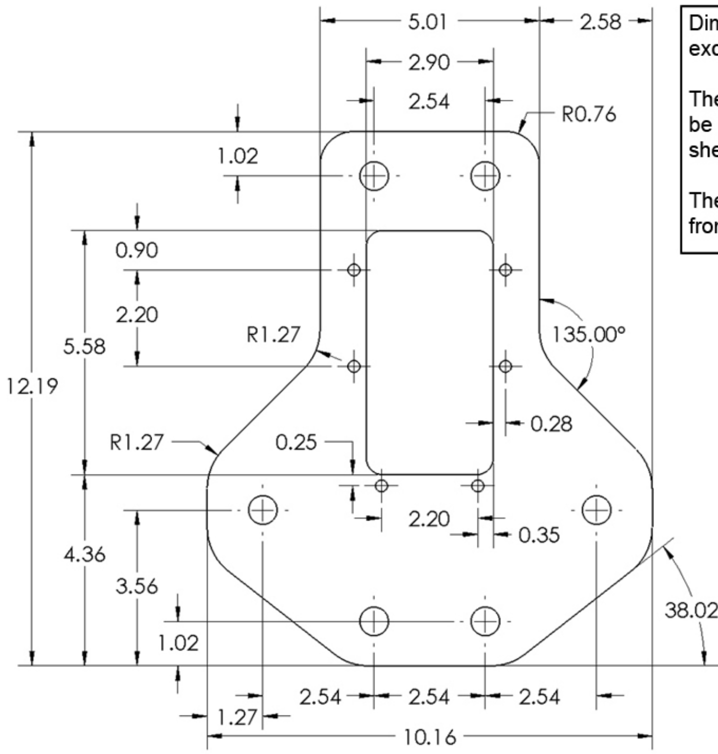
Appendix A: Parts List

Vendor	Component	Part #	Qty.	Unit Price
Mcmaster-Carr (www.mcmaster.com)				
	5/8-10 x 36 in precision steel ACME threaded rod	99030A328	2	$30.54
	5/8-10 precision bronze ACME nut	95072A149	4	$39.54
	precision ACME nut mounting flange	95082A642	4	$44.78
	5/8 in ID flange mounted ball bearing	5967K81	8	$32.85
	5/8 in ID Quick-Grip screw clamp bushing	5926K18	4	$43.71
	5/8 in OD thrust bearing	7809K33	8	$26.74
	1/2-20 x 2 1/2 in male clevis rod end	4749T151	4	$7.94
	3/8 x 1 in clevis pins (pack of 5)	97245A676	1	$3.49
	1/2-20 hex nuts (pack of 10)	96460A380	1	$5.63
	1/2 in ID flat washers (pack of 10)	95229A960	1	$8.29
	1/2-20 hex cap screw (pack of 10)	92620A745	1	$6.33
	1/4-20 x 1/2 in flange button cap screw(pack of 25)	91355A081	1	$7.51
	1/4-20 x 1 in flange button cap screw (pack of 25)	91355A083	2	$9.20
	1/4-20 x 3/8 in flange button cap screw (pack of 25)	91355A080	2	$7.28
	5/8 in OD male spherical washer	91131A031	16	$0.89
	#3-48 x 3/8 in socket cap screws (pack of 50)	92196A101	1	$2.77
	#3-48 x 1/2 in flat head screws (pack of 100)	90275A096	1	$3.99
	#3-48 hex nuts (pack of 100)	90480A004	1	$0.82
	12 x 12 x 3/16 in cast acrylic	8536K141	1	$18.85
	1 in x .031 in double sided foam tape	7598A963	1	$8.07
	12 x 24 in x .177 in clear cast acrylic	8560K219	4	$16.18
	1 ft surface mount piano hinge	1581A152	2	$6.70
Thorlabs (www.thorlabs.com)				
	12 x 12 in optical bread board	MB12	2	$161.10
	18 in optical construction rails	XE25L18	4	$15.70
	rubber dampening feet (set of 4)	RDF1	1	$5.10
	low profile t-nuts (pack of 10)	XE25T3	5	$8.70
Stock Drive Products (www.sdp-si.com)				
	5 in diameter spur gear, 120 teeth, 24 pitch	A 1C 2-N24120	4	$45.66
	1 in diameter hubless spur gear, 24 teeth, 24 pitch	A 1C 1-N24024	2	$8.99
Trossen Robotics (www.trossenrobotics.com)				
	Rx-64 Dynamixel servo motor	M-200-RS-RX-64	2	$279.90
	USB2Dynamixel adapter	FRS-B-USB2D	1	$47.41
	thrust bearing servo horn set	M-300-HN05-T101	2	$14.10
LoadStar (www.loadstarsensors.com)				
	s-beam load cell (2000 lb, .02% accuracy)	RAS1-02KS-S	2	$299.00
	USB converter	DI-100	2	$199.00
Newegg (www.newegg.com)				
	USB extension cable (6 ft)	N82E16812270105	1	$3.49
	AC Power Adapter (18.5V, 65 W)	N82E16834991082	1	$24.99
80/20 Inc. eBay store				
	80/20 T Slot Corner Bracket	25-4250	16	$4.50
MetalsDepot (www.metalsdepot.com)				
	aluminum flat (1 x 3 x 12 in)	F413	2	$24.30
			TOTAL:	**$3,687.46**

Appendix B: Technical Drawings

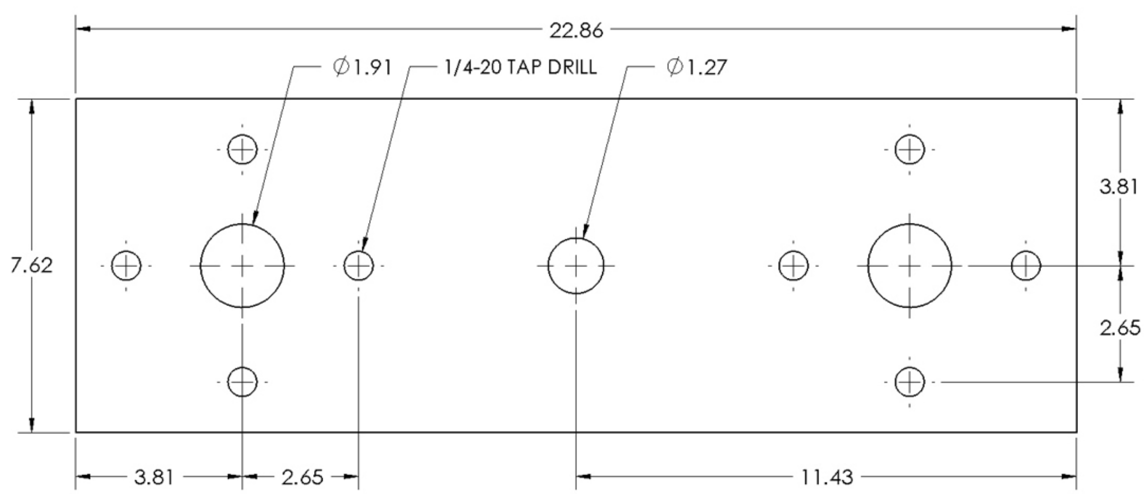


Dimensions are in centemeters except for the 1/4-20 in tap drill.

The motor attachment plate should be laser cut from 3/16 in acrylic sheet.

The crosshead should be machined from 1 in aluminum plate.

Motor Attachment Plate



Crosshead