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LOW COST TENSILE TESTING MACHINE FOR FDM PARTS MECHANICAL BEHAVIOR

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Abstract. This paper describes the project, construction and tests of a low cost Tensile Testing Machine in order to characterizing mechanical behavior of plastic specimens produced by FDM 3D printers, under uniaxial tensile loads.

Keywords: **Test Machine, Tensile Test, Polymer Testing.**

1. INTRODUCTION

A research following three stages strategy is being conducted in order to provide further knowledge about anisotropic mechanical properties of Fused Deposition Modelling process (FDM) manufactured parts. The research is specifically addressing to parts made of Polyatic Acid – PLA, a popular plastic used in desktop 3D printers particularly for its bio degradable characteristics. At this very first stage we look for mechanical behavior characterization under uniaxial tensile loads of samples produced by this addictive manufacturing process, related to parameters like thickness of deposited layer, number of contours, density and infill orientation, as well as others characteristics of FDM 3D printing technologies.

The research involves the tensile test of specimens printed on 3D FDM printers, with different parameters, especially those related to the anisotropy of deposition of layers characteristic of 3D printing.

Due to the unavailability of a universal test machine - UTM, the high cost of this type of equipment and the low budget of the research in progress, we opted by the construction of an apparatus (hardware and software) able to execute tensile tests. A key element in the research being conducted is the immediate disposition of a test machine in the laboratory without going through the bureaucratic and waiting time involved in testing by other departments or external laboratories.

2. THE DESIGN OF THE TEST MACHINE

The design of the tensile testing machine was carried out with the premise of complying with some specifications of the current research but, above all, complying with the plastics stress testing standards by the ASTM - American Society for Testing and Materials.
- Research specifications:
    o To perform load test up to 5 kN. This value was chosen because it represents a safety margin of twice the load values for the load test on specimens of the same type as the one used in the research, according to other authors. Still, this figure is higher than the ones expected for specimens of other plastics like acrylic, pvc and even other commonly used 3D printing plastics types, that was used during the project for comparison and calibration of the machine.
    o Electric actuator, controlled by a microcontroller capable of controlling the speed of application of the load and reading the values of the applied load, encoder, strain gauge and sensors of humidity and temperature.
    o Control software to control machine start-up, test run, monitoring of information generated during test, calculations, generation of graphs, reports as well as sample management and general test information.
    o Low manufacturing cost, using materials easily found on the market with a minimum of machined parts.
    o Interchangeable grips for testing specimen of different types of geometries such as dogbone and cylindrical samples.
    o Robustness.
    o Repeatability.
- ASTM standards – Considering the scope of the current research, the testing machine was designed in compliance with the main recommendations contained in ASTM 638 - Standard Test Method for Tensile Properties of Plastics, ASTM E4 - Standard Practices for Force Verification of Testing Machines and ASTM E83 - Standard Practice for Verification and Classification of Extensometer Systems:
    o A load cell with capacity of indicating the load with an accuracy of 1%. The ASTM E4 standard establishes procedures for calibrating the load measurement device.
    o Traction mechanism with speed control and constant variation of load application.
    o Self-aligning grips capable of moving freely once a force is exerted so that the major axis of the specimen coincides with the direction of the applied force.
    o Grips with serrated jaws to prevent slippage of the test specimen.
    o A method to measure the crosshead extension.
    o Extensometer to measure the extent of the gauge zone of the specimen.
    o Time recording of the load test.
    o Temperature and humidity measurement.

3. THE TEST MACHINE

Although most of the tensile testing machines available in the market use a system based on two columns of action to generate traction, we chose in our project to construct a force actuator of only one axis.

The machine described here is composed of a frame made from two 34 mm diameter steel tubes 0.74 m long joined at the top by a steel plate welded longitudinally to the tubes. Two stainless steel threaded bars 16 mm in diameter (M16) and 1 m in length each, cross the tubes longitudinally and fasten through the nuts another steel plate at the base of the tubes, thus closing the frame structure. This closed frame structure allows all forces applied by the traction system to remain internal to the frame. The thread bars are used to secure the frame to the base of the machine, made of extruded aluminum profiles, keeping the frame high, with enough room below it, for the installation of the actuator assembly. The actuator shaft passes through a hole in the center of the base plate of the frame. In this space are still accommodated the power supply and all the electronics of the machine. This whole system below the frame is enclosed by a box made of PVC boards, giving the machine a professional appearance as we can see in Fig. 1.

The actuator mechanism was built to generate a traction higher than the maximum 500 kgf supported by the load cell used in our machine so as to ensure a comfortable working range within the tractions expected in the tests and providing the required accuracy. The actuator uses a shaft made of a16 mm threaded rod (M16) that draws a steel tube internally threaded at the ends. The upper end of the tube is connected to the lower grip by a rotation ball joint rod end.

The actuator shaft is aligned with a set of two two-bolt flange-mounted ball bearings separated by a nylon block and connected to a gear 120 mm in diameter and 120 teeth. This gear is driven by another 20-teeth gear attached to the drive shaft of a DC motor of 1200 rpm coupled to a 125: 1 reduction box. This whole assembly causes the actuator shaft to produce a vertical movement of up to 2.8 mm per minute. A software controlled PWM circuit allows the actuator speed to be reduced to the 2 mm per minute or less as recommend by ASTM for the type of test being performed. An

encoder is coupled to the lower end of the actuator shaft to provide a comparative measure of the rotational speed of the actuator. The use of this encoder is, however, optional.

The entire actuator assembly (Fig. 2) - shaft, mounted bearings, thrust bearing, gears and motor - is supported by an aluminum plate of 180 mm X 70 mm with 10 mm thickness which in turn is attached to the lower steel plate of the frame by four 8 mm long screws (M8).

On the front of the machine a two-way mini toggle switch allows the actuator force direction to change up or down manually to facilitate adjustment of the distance between the specimen loading grips. On the back of the machine are the power cable connector and the USB port for connection of the microcontroller to the control and acquisition computer.
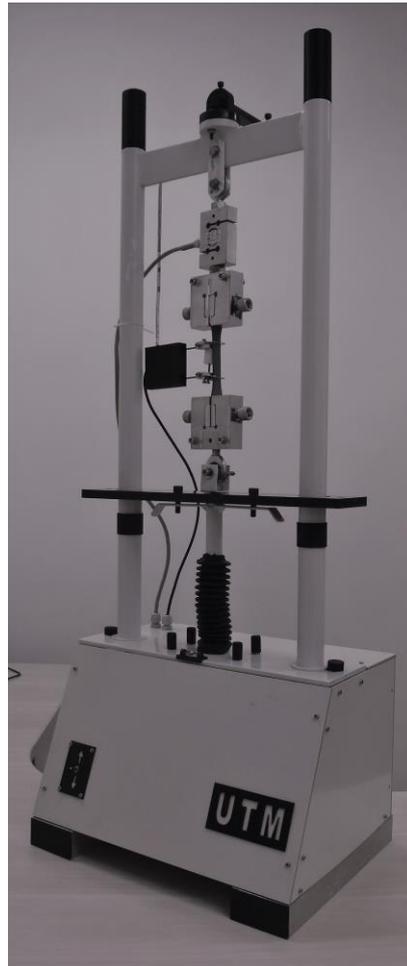

Figure 1. The test machine ready for a test, with the sample and the extensometer installed.
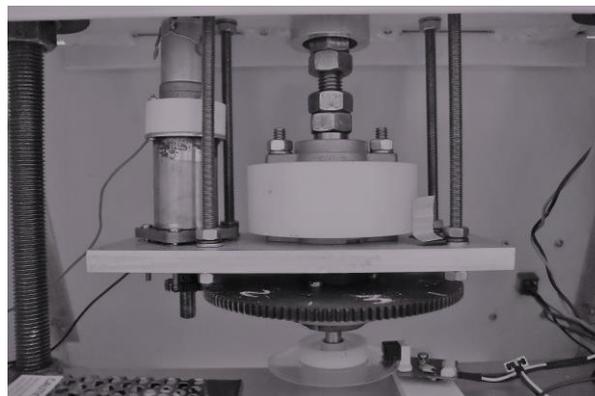

Figure 2. The actuator assembly.

3.1 Grips

The grips are a very important part of a test machine. They are the ones that will hold and transmit the traction exerted by the actuator to the test specimen. According to ASTM-D638 the grips must be as rigid as possible so as not to undergo measurable deformations within the forces ranges applied during the tests. In addition to stiffness, two other important conditions must be observed: The grips connections with both the fixed part of the machine and the actuator, must be made in a way to allow self-alignment of the grips/specimen so that as soon as the traction is started, the direction of the applied force coincides with the longitudinal axis of the specimen being tested. The other condition refers to avoiding, as much as possible, the slippage of the specimen related to the grip using jaws with serrated contact surfaces.

Two sets of grips were manufactured for our machine, both CNC machined from 6351 aluminum blocks (Brinell hardness 95). A set of grips with wedge jaws as seen in Fig. 3a and a set of grips with parallel vise-type jaws as seen in Fig. 3b. The two sets were sized for the use of dumbbell flatbed specimen (ASTM-D638 Type II), with lateral projections on the jaws to assist the operator to accommodate the specimens as aligned as possible to the grip axes. A sandpaper bonded to the jaws was used instead of the serrated surfaces and in both sets of grips, this technique proved adequate to avoid slippage of the sample.

The grips with wedge-shaped jaws has the valuable characteristic of increasing the lateral grip on the sample as the traction is applied longitudinally, preventing slippage of the sample. However, because the material (plastics) used in our specimen undergoes a relatively large thickness change when subjected to traction, this variation is translated by an appreciable displacement between the jaws and the grip itself, which compromises the extension measures, both the measure by the extensometer in the gauge zone of the sample (extension) and the measure to determining the extension between the grips (crosshead extension). This type of grip applies very well to samples with little or no variation in thickness under tension.

The parallel jaws grip acts as a vise where the pressure on the sample is exerted by the tightening of two 12 mm side screws (M12). It was milled as a 70 mm x 70 mm square with a 25 mm thickness. The grip design avoids sliding of the jaws and acts as a spring to compensate for sample thickness variations when subjected to traction. At the top of the grip, a threaded bore allows connection to the load cell using a 12 mm screw (M12). Two 2 mm acrylic plates accompanying the shape of the grip finish the assembly and guarantee the easy alignment of the jaws inside the grip.

The use of ball joint rod ends to connect the load cell to the upper fixed part of the frame and to connect the lower grip to the tractor system give the assembly the necessary degrees of freedom at each end ensuring that the interaction of the forces in the uniaxial test are confined to a single linear dimension.

Grips of different sizes should be used according to the dimensions and geometries of the samples being tested. With the demands of the research in progress, it will be necessary to accommodate specimens of different geometries - such as cylindrical specimens - and then build a third set of grips or adapt the existing ones.
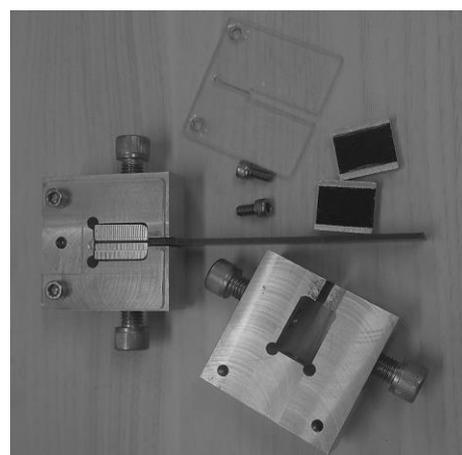
(a)   (b)

Figure 3. (a) Grips with wedge jaws. (b) Grips with parallel vise-type jaws.

3.2 The Eletronics

The electronics of the test machine was keep simple to reduce cost. A power supply, one microcontroller board, two relays, one drive power transistor, one encoder (optional), one humidity sensor, one temperature sensor and two HX711 weighing sensor board that allows easily read load cells to measure weight, one used to read the force applied to the load cell and the other to read the data from the extensometer. Indeed, we could use just one of these boards (the HX711 IC has a dual channel sensor) for both load cell and extensometer but we decide to put the extensometer strain gage and the sensor board in a single individual assembly. A diagram of the connections over all these parts is shown in Fig 4.

The power source is a regular 12 Volts DC 3 Amps power supply, enough to drive the motor and the relays. A voltage regulator LM7805 is used to get the 5 Volts necessary to drive the others circuits and sensors. The two relays are used to invert the direction of motor movement and are commanded by the microcontroller. Also, they are connected to a mini toggle switch in front of the machine panel to permit the operator move the actuator up and down manually.

A small driver board with a power transistor is used to control the current that goes to the motor in order to control the actuator speed. The base of the transistor is connected to a PWM output pin of the microcontroller board. Different preset speeds (predefined values of duty cycle for the PWM in the microcontroller firmware) are selected by a command of the control software in the PC. Default actuator speed value is set up to 2 mm per minute.

The microcontroller board is connected to the PC via a USB cable. The firmware running in the microcontroller read continuously the serial port and executes commands received from the PC control software. Those commands can change the motor speed, start and stop the motor, change direction of actuator movement, read temperature and humidity, read the force applied to the load cell, read the extensometer displacement, time of essay etc. The data values are sent back to the control program in a stream of plain alphanumeric characters. The default sample rate is 2 Hz but can be set up to 5 Hz in the control software before the start of the test. The accuracy for both the measures of load and extensometer is 0.2%.
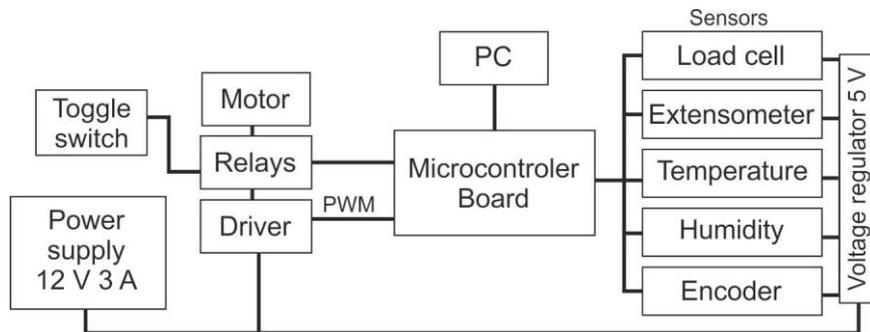

Figure 4. Electronic diagram for the test machine.

3.3 The Control and Data Accquisition Software

A computer running custom software written in C# .NET is used to controls the apparatus and collect the Test Machine raw data (Fig. 5). The software does all conversions and analysis necessaries to determine maximum sample breaking force and other parameters related to tensile test like stiffness (ex: Young's Modulus). The software also plots the stress-strain graphs (Fig. 6), shows data tables, prints test reports and exports graphs and data as plain text or in table format to MSExcel. Graphs and reports can be printed for a single specimen test or for the collection of specimen of a sample. The raw data are saved in XML format files for further analysis.

Following an object-oriented approach, three main class are defined in the software: amostra, especime and ensaio. The "amostra" (sample) class define the collection of specimen to be tested, with same geometrical and physical characteristics. The "especime" (specimen) class represents the physical object to be tested. They are identified by a sequential ID automatically generated by the program. The "ensaio" (test) class has one instance for each specimen and holds all the raw data from the test as well as some calculated values. Stress and strain values are always calculated during graph or table exhibition. Stress is expressed in MPa units considering the transversal area of the gauge region of the specimen measured using a caliper or micrometer. Strain (ε) is calculated in percentage of mm/mm using Eq. 1, where Δl is the extensometer value and lo is the gauge length between extensometer blades (Davis J. R., 2004).

$$\varepsilon = \frac{\Delta l}{lo} \times 100\%$$

(1)

The software interface shows the necessary buttons to control the machine and exhibit in real time the values of load, extensometer displacement and time of test. It also shows temperature, humidity and offsets values at the start of the test. It also exhibits in real time a tab panel with load X crosshead displacement graph, load X extensometer displacement graph and extensometer displacement X time graph. Any of these graphs can be selected during the test without disturbing it. After the test, annotations and measurements can be made in the graphs using an integrated cross hair cursor. A table of sampled data may optionally be displayed in real time on screen during the test.
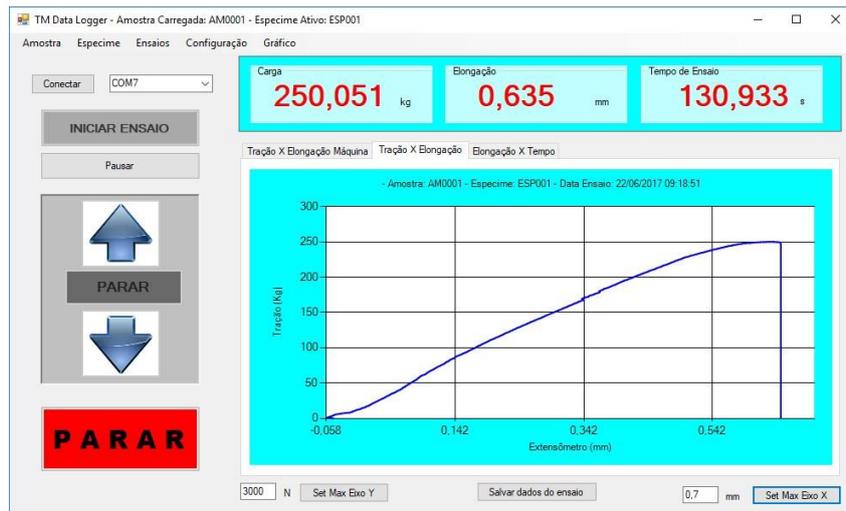

Figure 5. The main display of the Control and Data Acquisition software.

Figure 6. A display of the Stress-Strain graph for two Type I acrylic laser cut specimen.

3.4 The extensometer

In order to have the precision on generating the stress-strain curves as required by the ASTM standards it is absolutely necessary to use an instrument to measure the stretching of the gauge length of the test specimen as it is submitted to load. That instrument is called an extensometer and the proper use of it results in more accurate, reliable and reproducible measurements than the obtained using values of crosshead extension. We considered in our project different types of extensometer devices like LVDT, electronic calipers and others. However, the cheapest and easiest to

implement was a Type 1 (ASTM E83 standard) constructed using a strain gage sensor hacked from a small scale (Brow, R., 2002). The load cell was assembled in a case in order to accommodate the HX711 conditioning board. A couple of aluminum blocks with attached blades are connected to the load cell by steel wires as can be seen in Fig. 7. The blades are clipped-on in the gauge part of the specimen and tightened by rubber bands. As the specimen are submitted to load and the gauge portion stretches, a value is measured in the extensometer strain gage and translated in displacement. The work curve of the extensometer was obtained using a calibration device constructed using a micrometer screw (Fig. 8). The length of the steel wires was chosen to get a 10 mm maximum deflection. If case of test of samples with larger expected extension values, these wires can be extended to accommodate the new situation. The calibration of the extensometer curve was approximated by a straight line in this interval according to the equation 2,

$$e = 0.0125 \times m \tag{2}$$

where the m is the value in grams read in the signal conditioning board HX711 connected to the extensometer load cell and e is the converted extension in millimeter. The slope parameter in Eq. 2 is saved in the program configuration file and can be edited every time the extensometer is calibrated.
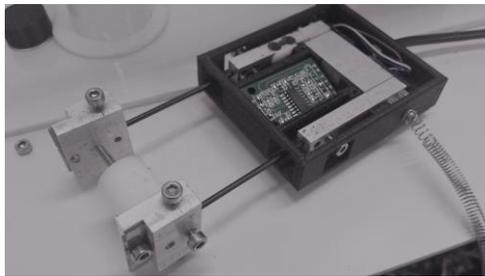

Figure 7. Extensometer with a strain gage and knife-edge contacts.

Figure 8. Extensometer calibration device.

3.5 Validation

In order to validate the accuracy and repeatability of our machine we execute identical tests with our machine and with a commercial one. We tested a set of 3D printed PLA specimen printed with 100% cross 45° infill. The commercial test machine used was a INSTRON/EMIC DL2000 of the Departamento de Construções e Estruturas da Escola Politécnica da Universidade Federal da Bahia.

It is impractical to compare directly measured data of load and deformation once those values don't take account of geometrics properties of the specimen (Alvin, J., Flint, Jr., 1998). This problem can be solved by converting the values of load and deformation to values of stress and strain respectively. The tests in the DL2000 were performed without an extensometer and for comparison effect we have to convert the load values to strain using an estimated crosshead distance. The Fig. 9 shows a stress x strain graph with four tested specimens and the Tab. 1 shows a summary of important values from the tests.

Although the "toe" compensation had not been applied to the data, what can change slightly the curves, we may observe that the results for each machine has as excellent repeatability and between the test machines the values recorded are very similar, with differences of no more than 1%. The small variation between the tests in the commercial test machine is attributed to the estimated crosshead value used to calculate the strain from the supplied test data.

The very good repeatability can be seen in the before shown stress-strain graph (Fig. 6) for two Type I acrylic laser cut specimens tested in our machine.
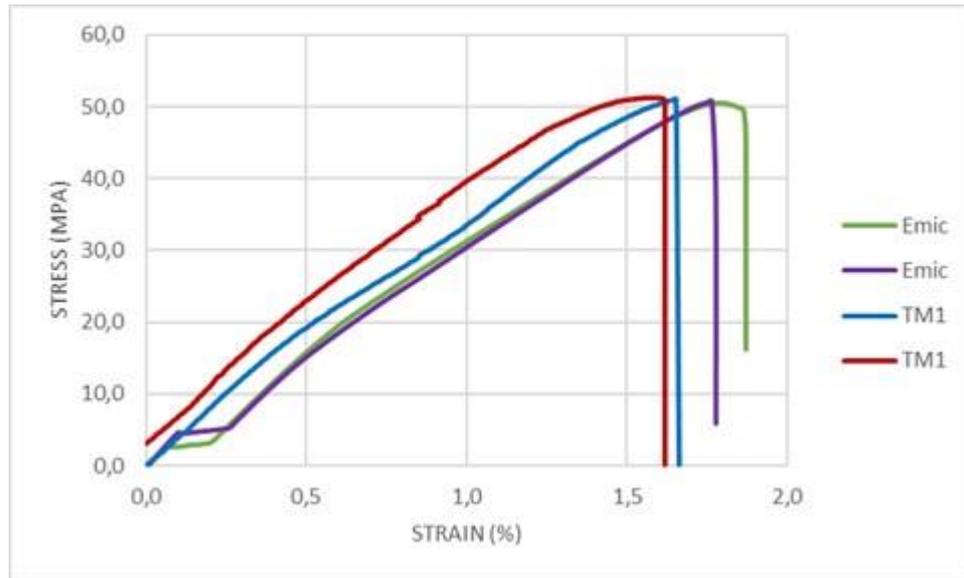
Figure 9. Stress-strain comparing identical tests in two machines

Table 1. Breaking values for the four tested specimens.

	Load at Break. (kN)	Stress at Break (MPa)	Strain at Break (%)
TM1 Specimen 1	2,47	50,6	1,61
TM1 Specimen 2	2,48	51,0	1,66
Emic Specimen 1	2,46	50,5	1,79
Emic Specimen 2	2,47	50,8	1,76

4. COSTS

As said, our aim is to maintain costs as low as reasonable possible. Estimated material costs and labor costs are summarized in Table 2.

Table 2. Estimated material and labor costs.

Part	Item	Cost
Frame	34mm steel tube	$20.00
	75mmX 40mm Al. tube	$15.00
	Steel plates	$10.00
	PVC white plates	$15.00
	5/8" threaded bar, washers and nuts	$12.00
	Stainless screws	$5.00
	Paint	$20.00
	Labor and weld	$30.00
	Subtotal	$127.00
Actuator	Al. plate	$15.00
	6mm threaded bar and stainless screws	$8.00
	Steel gears	$15.00
	12V motor and reduction box	$20.00
	M16 threaded bar and nuts	$5.00
	Threaded steel tube	$10.00
	Flange-mounted ball bearings	$20.00
	Trust bearing	$5.00
	Nylon spacer	$5.00
	Quick adjustment steel arm	$5.00
	Encoder wheel and sensor	$10.00
	Black plexiglass plate	$5.00
	Labor 5h ($15.00/h)	$75.00
	Subtotal	$198.00

Grips	Al. bar	$15.00
	Stainless screws and nuts	$5.00
	Transparent plexiglass plate	$2.00
	CNC labor 16h ($10.00/h)	$160.00
	Subtotal	$182.00
Load Cell	500kgf Load Cell	$150.00
Attachment	Rotation ball joint rod end	$12.00
	Al. plate	$2.00
	Stainless screws and nuts	$4.00
	Subtotal	$18.00
Electronics	Microcontroller board	$10.00
	Relay interface and motor driver	$10.00
	Power supply	$8.00
	Sensors	$5.00
	Cables, connectors and switch	$6.00
	Subtotal	$39.00
Extensometer	Scale load cell	$13.00
	Blade attachment	$6.00
	Plastic case	$2.00
	Suspension Spring	$1.00
	Subtotal	$22.00
	Total cost	$586.00

5. DRAWINGS

Simplified drawings with dimensions and an exploded view of the actuator are shown in Fig. 10. Detailed drawings of the test machine, as the control software and electronics schematics can be obtained from the authors.
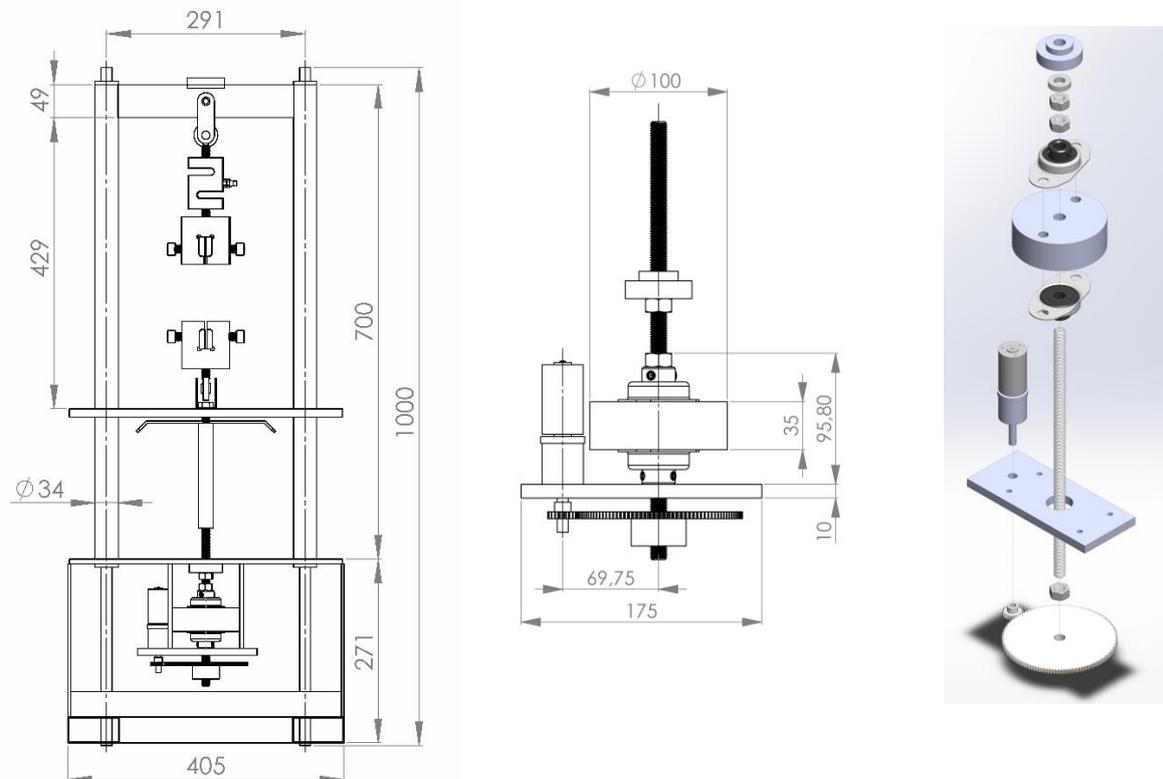

Figure 10. Simplified drawings with dimensions and a exploded view of actuator.

6. CONCLUSIONS

A low cost Tensile Testing Machine capable to characterizing plastic sample mechanical behavior was projected, constructed and tested as part of a three stages research to enlarge knowledge about anisotropic mechanical properties of 3D Fused Deposition Modelling manufactured parts.

The developed testing machine was submitted to a set of load tests, so far has perform as expected, providing compatible results with the ones of identical specimens tested in a commercial test machine.

As planned, the total cost for the construction of the test machine, included hardware and labor, was very low, being around US600.00 that is far low compared with commercial systems.

7. REFERENCES

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