Custom Automated Tensile Tester

Development of Carbon Fiber 3D printed High Performance Custom Footwear

Science Research Program
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Abstract

Continuous Carbon Fiber (CCF) is a recent method of 3D printing with carbon fiber composites. Its introduction to the personalized footwear industry yields a wide spectrum of benefits: enhanced flexibility, high elastic deformation and heat resistance, lightweight, faster shape recovery, corrosion resistance, and increased compressive and tensile strength. However, given the extensive resources and funds required for using CCF, one of the major challenges is finding a balance between the number of passes of laid carbon fiber and shoe integrity. The custom-built Tensile Tester this paper explores poses a reliable solution to standardizing the integrity of custom 3D printed footwear exoskeleton. An onboard raspberry pi, 100kg load cell, and 1320lb linear actuator function as one system to standardize the required passes of laid carbon fiber for a specific compressive strength, ensuring a balance between footwear integrity, and manageable manufacturing costs.

Introduction

Sixty percent of people at any given time are walking around in the wrong size shoe. Half a million people complain about purchasing the wrong shoe size per year– just in North America (Marchese, 2019). Over the past decade, the personalized footwear industry has welcomed a future where digital technologies transformed the customer journey (How 3D Printed, 2020). Recent advancements in smartphone compute power and enhanced depth-sensing capabilities mean that personalized footwear is now accessible from the comfort of your own home. With a sub-minute conversion from smartphone scans to 3D models, users receive a spectrum of custom-fit modeling benefits. The complete tailoring of shoes presents further opportunities and enhancements that have just become commercially possible via 3D printing: biomechanical efficiency, eco-friendly shoe production, and most relevant to this study, the experimentation of printed composite materials (Farhan et al., 2021).

For decades, manufacturers tried to use continuous carbon fiber (CCF) to achieve enhanced flexibility, high elastic deformation, faster shape recovery, and low recovery temperature (Shen et al., 2019). Carbon fiber's compressive and tensile strength are rooted in the intricate weaving of the fibers within the composite. However, the traditional forming processes of continuous carbon fiber (CCF) reinforced composites are very complex, and have long production cycles and high cost. Thus, manufacturers had to splice the carbon fiber segments in order to integrate them into footwear personalization. The utilization of an efficient 3D printed manufacturing process known as Fused Deposition Modeling (FDM) is one proven solution (Shen et al., 2019). FDM is a technology nearly identical to 3D printing where thermoplastics are melted and deposited according to a specific pattern (Varotsis, n.d.). Unfortunately, experimentation of 3D printing with advanced composites in custom footwear is still in primary stages of development.

Companies such as 3D Shoes, Wiivv, Feetz, Dodge Ski Boots (Krassenstein, 2015) are making strides in the employment of laid carbon fiber reinforcements. Among these pioneering companies is Orbital

Composites, the first to create a fully personalized carbon fiber 3D printed bike shoe. However, given the extensive resources and funds required for using CCF, one of the major challenges is finding a balance between the number of passes of laid carbon fiber and shoe integrity. The custom built Tensile Tester explored here poses a reliable solution to measuring and standardizing the integrity of custom 3D printed footwear exoskeleton. There exist various other tensile testers within the field of engineering. Ultimately, what sets this one apart is the spectrum of functionalities that the tensile tester can run thanks to the on-board microprocessor raspberry pi. Using a raspberry pi to intake analog readings from a load cell to automate the extension and retraction of a linear actuator, the custom-built machine brings further promise to improve and accelerate the high performance personalized footwear industry.

Methods

Hardware Setup

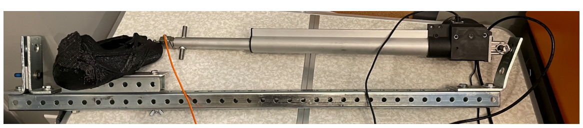


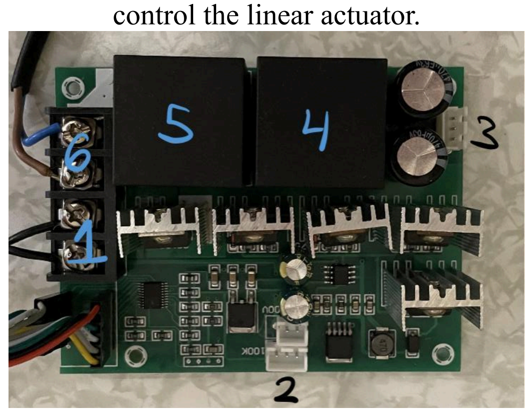
Figure 1: Image of the linear actuator, tensile tester frame, and load cell

Figure 1 isolates the hardware features of the tensile tester ("Tensile Tester" refers to the motor that can apply compressive force to an object, or test its tensile strength). As visualized, a rectangular shaft was used as the base of the tensile tester. Connected to the base shaft is a mounting platform for the tested object; a 3D printed carbon fiber shoe. On this platform, the 3D printed shoe is screwed in for minimal movement during testing. On the right end of the base shaft sits an "L" shaped metal piece to attach the linear actuator (Oukai Motor DC 12V, 1320LB/6000, 200mm extension). Screwed between the "L" shaped piece and the linear actuator is a swivel joint that provides free movement to the linear actuator. This is fundamental for adjusting the angle of pressure applied to the shoe. Lastly, the tip of the linear actuator shaft houses the load cell (DYLY-106 100 KG Micro Compression and Tension Pull Force Cell). This load cell sends a reading of the applied force on the 3D printed shoe to the raspberry pi.

Electrical Control and Configuration

The electrical construction of the custom tensile tester began with connecting a GPIO Raspberry Pi BreadBoard to a Raspberry Pi 4 8 GB Ram, an essential step for connecting mechanisms to the Raspberry Pi (FreeNove, n.d.). Next, connections were established between the GPIO breadboard and the "main module" to control the tensile tester.

Figure 2: The "main module" is a large circuit, provided by Orbital Composites, used to control the linear actuator.



Numbers 1 through 6 on Figure 2 are used to illustrate the path of current throughout the module in order. First, power was connected via an outlet into the port on the far left (number 1). Port 2 is used to control the speed of the linear actuator. This was completed with the use of a relay (SunFounder Relay Module 5V DC Trigger by HIGHLO). The relay connected port 2 to the raspberry pi in order to control the current, ultimately turning on and off the linear actuator (FreeNove, n.d.). Similar to the manipulation of port 2, a “SunFounder” relay was used for port three to control the direction of the linear actuator. The two black boxes numbered 4 and 5 are in-house relays used to transmit the current from the circuit to port 6. This current was then used to power the linear actuator and send signals of which direction to move.

The final electrical component of the tensile tester is the load cell, referenced to in the “Hardware Setup” Section. The load cell mounted on the tip of the linear actuator shaft was connected to an amplifier in order to magnify small voltage values from the load cell. These amplified values were then sent to an ADC, a device used to interpret voltage values to analog inputs read by the raspberry pi.

Software

A raspberry pi 4 8 GB Ram functioned as the brain for the automated tensile tester. Python was the primary programming language; VS Code was the platform used. The general purpose of the code was to extend the linear actuator and begin deforming the mounted shoe until a certain magnitude of force was reached. Before use, the load had to be calibrated. This was completed by reading voltages of known masses and changing the analog input value for the raspberry pi accordingly. These values were then confirmed using a third party datasheet for the specific load cell. After reading in the desired force from the load cell, the tensile tester held it’s x-position momentarily, then retracted until no more pressure was applied to the 3D printed shoe. The code contained four main functions: “on”, “off”, “extend”, “retract” (FreeNove, n.d.). These methods are called in the program when certain force parameters are met. For instance, if the user wants to apply 10 N of force to the 3D printed shoe, the program would continue to extend the linear actuator until the load cell reads 10 N.

Overview

To summarize, the tensile tester contains three engineering components that work in unison to communicate and share information. The linear actuator and related hardware features are essentially the exoskeleton for the tensile tester. The raspberry pi and “main module” bridge the software and hardware components; the pi is the brain for the system, it intakes voltage from the load cell and instructs the linear actuator to extend, retract, or stop. The python program brings the tensile tester to life. It represents instructions for the raspberry pi that interprets intake voltages and tells the pi what appropriate methods should be run to activate the linear actuator.

Results & Discussion

The autonomous tensile tester was ultimately successful in measuring the compressive force applied to the shoe and responding accordingly. Its purpose of standardizing force applied to an object in order to reliably measure the deformation of the object was upheld. The python program requires the assignment of a input force to reach, and the linear actuator would extend until the assigned force was met and momentarily rest in place. It is during this time that any deformation in the tested object becomes apparent. A method for quantifying the deformation is currently absent from this tensile tester. Future modifications to the system will enable more effective measurements of the deformation during this period of rest.

Future Enhancements

Three future areas of development for the tensile tester remain: an enclosure, rewiring of the main circuitry, and a depth sensing camera to accurately measure deformation without human assistance.

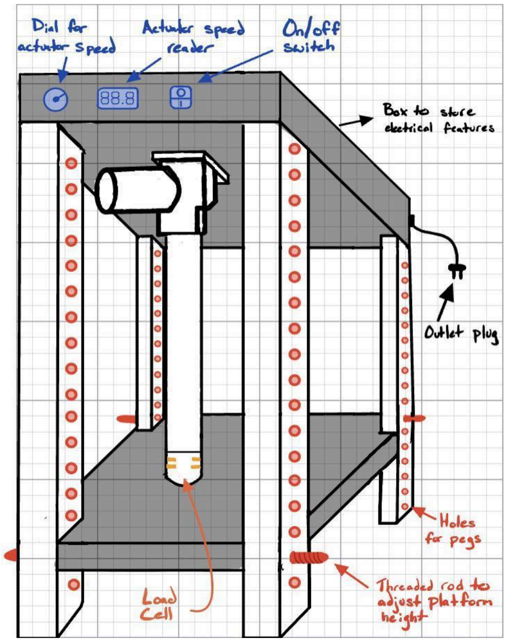


Figure 3: Enclosure sketch; construction set to be completed by end of April 2022. All features are labeled in the image

An enclosure for the tensile tester is aimed to increase user safety during testing trials as well as reduce variation in testing (*NOTE: the construction of the enclosure was completed by April 2022*). The enclosure, which is currently in construction, will consist of four UNISTRUT columns, two quarter-inch steel plates (10"x10"), two high-strength steel threaded rods, and a box on the top to hold electrical components. The shoe will be screwed into four pre-threaded platform holes and can be mounted at any angle, paramount to studying the compressive strength of the entirety of the shoe, not just one side. The linear actuator will apply a downward force onto the mounted shoe. Ultimately, the elimination for variance provided by the enclosure is fundamental to the project's ultimate goal of standardizing applied force to the tested object.

The connection cables from the GPIO breadboard to the main module require rewiring. In engineering, this final step in the construction of a product is known as wire management. There are hundreds of wires connecting the systems of the tensile tester. It is very easy for a single cable to be partially removed or fully unplugged from it's socket. Soldering the wires to the GPIO board would ensure that the socket connections are secure. However, it is still possible for wires to wear. The solution is housing the entire electronic system in a metallic box that would sit at the top of the enclosure. This accessible box would enable the user to efficiently access the main circuitry of the tensile tester. In addition, the existing wires must be color coordinated and taped together to indicate their electrical purpose.

The implementation of a camera aimed at the tested object will assist in quantifying the amount of deformation to the shoe. Standardization is the overarching purpose of the tensile tester. This high resolution camera (specifications still to come) can be programmed using pre-existing libraries that count the change in pixels and return a percentage of deformation. This change in pixels correlates to the steady change in structure of an object (its compression). Ultimately, visualizations can be generated that display the deformation of an object as a function of the applied compressive force. According to current design concepts. The camera will be housed roughly forty-five degrees above the horizontal, and will be fastened onto one of the enclosure columns. This angle permits the camera to focus on the entire shoe without any visual obstacles.

Design Considerations

The main roadblock during the development of the tensile tester was reading the input from the load cell. When the ADC first tried to directly read the voltages from the load cell without an amplifier, the voltmeter was unable to pick up a voltage (it read 0.00). Through research, it was concluded that a device between the load cell and the ADC was necessary; a "load cell amplifier" was the solution. With the implementation of the amplifier as a median between the load cell and the analog input on the ADC, the ADC could now pick up substantial voltage alterations. This granted the raspberry pi the ability to know exactly how much force is being applied to the load cell at all times. Again, this parameter is crucial to the program as the linear actuator is only instructed to apply force within a specific threshold.

Conclusion

Footwear personalization, enhanced performance, accessibility, and integration of composites all begin with a powerful 3D scanning device already sitting in your pocket. Shattering a prior tradeoff between precision and accessibility, high computing smartphones have demonstrated the ability to enable widespread footwear personalization (Farhan et al., 2021). Every step in the customer footwear process, mobile scan to 3D models, and 3D models to 3D printed custom shoes, introduce radical improvements to footwear fitting customization that, a decade ago, were merely a dream. However, the impact of the three-step process brings a degree of uncertainty and areas for improvement, especially as manufacturers begin experimentation with advanced composites. Companies printing with CCF must strike a balance between passes of laid carbon fiber and cumulative expenses in order to continue pushing the boundless potential of high performance custom carbon fiber footwear (Shen et al., 2019).

The tensile tester, if implemented on a significantly greater scale, contributes to one effort for the future of dimensional customization, and, with further research and democratization, enhanced performance footwear for all. The final product will enable users to quantify the compressive strength of any carbon fiber 3D printed shoe. This numerical scaling will enable users to standardize the required passes of laid carbon fiber for a specific compressive strength, ensuring a balance between footwear integrity, and manageable manufacturing costs. With the common goal to further research in custom 3D printed footwear, the tensile tester will yield further confidence in the complex printing of carbon fiber 3D printed custom footwear.

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