Sprayable Piezoresistive Strain Gauges

ENMA490 Capstone Design Final Report

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The smart textile industry is a rapidly evolving field with great potential for applications in physical therapy and sports rehabilitation. Our group set out to design a new type of wearable electronic based on our previous research experience. Dr. Elisabeth Smela, of the University of Maryland Mechanical Engineering Department, has been conducting research focused on developing miniature air vehicles (MAVs) and has developed a composite electrical device that can be sprayed onto an MAV wing to read the instantaneous strain on the surface during operation. We were able to build off of the strain gauge that Dr. Smela has developed and successfully redesign the strain gauge for a variety of smart textile applications.

Our group decided to design a sprayable, piezoresistive strain gauge for the application of a basketball shooting sleeve. We selected this specific application because the elbow has such a large range of motion and the concept could easily be generalized to other wearable electronic applications. The initial design was heavily dependent on previous knowledge, literature review and ANSYS modelling. A literature review revealed that Young's modulus and electrical conductivity were key properties of the elastic host material and the conductive filler particle matrix. By varying the weight percentages of our conductive filler, we were then able to determine which volume percent would yield a composite with optimal Young's modulus and electrical conductivity. This method involved many unknown values, which forced us to select many design parameters based on what was done in previous literature. With our developing design, we moved on to an initial prototype. This strain gauge that was sprayed onto a basketball shooting sleeve consisted of latex as the host material and exfoliated graphite as the conductive particles. The testing of the device confirmed that we successfully fabricated a functional piezoresistive device that cohered to our polyester textile.

We came to the realization that our project required much more focus on the design elements rather than our prototype. We began to focus on justifying our design parameters and undergoing a quantifiable material selection process. Low Young's modulus and a high gauge factor were key parameters to take into account to optimize the functionality of the strain gauge. Using the Mori-Tanaka model [3], we were able to predict the Young's modulus of our particle-reinforced composite. After applying these design constraints to our list of possible materials, we refined our search and determined that latex and PDMS are the ideal host and conductive filler components respectively.

Table of Contents

Materials Science & Engineering Aspects

The most important MSE element of our design is the piezoresistive nature of our device. In piezoresistive materials, a change in electrical resistivity is observed upon the application of mechanical strain. This mechanical strain will affect the material's band structure by making it easier for electrons to be excited into the conduction band [1]. In turn, the density of the current carriers changes which affects the resistance of the material. In our case, the mechanical strain is going to be provided by the motion (bending) of an arm shooting a basketball. Based on the change in resistance, we can measure the angle made between the forearm and bicep to measure the optimal angle for shooting a basketball. The current design aims to represent a simplified model that eventually could be realized in sports therapy.

Our device is a composite material where exfoliated graphite particles with a diameter on the order of 10 microns are dispersed in latex. From a MSE perspective this means that we are dealing with a large-particle reinforced composite. In other words, particle-matrix interactions cannot be treated on the atomic or molecular level. The graphite particles will somewhat restrain the movement of the latex especially at the vicinity of each particle. This will increase the Young's modulus of the composite to some extent, however, at the 15 wt% filler material (graphite) we use, the composite will remain ductile. Once graphite is added to the latex the material changes from an insulator to a semiconductor as the number of defects in the composite decreases. To achieve effective reinforcement and proper electrical conductivity of the composite, it is imperative to have an even distribution of particles throughout the matrix, which is one of the reasons why we selected graphite particles. Smaller particles such as carbon nanotubes tend to agglomerate due to the strong interaction forces (binding energy) between the particles, which will lead to poor dispersion if careful mixing processes are not utilized.

The relationships between processing, structure and properties were entered into the design in a way that would optimize the performance of our device. For our host material we chose latex which is an elastomer and a thermoplastic that may be converted into a thermoset through vulcanization. In the relaxed state latex is made up of a disorganized cluster of chains. Upon stretching, the chains become almost linear. The high elasticity of the latex host proved to be essential in order to use our device on surfaces such as a bending arm. However, the final

properties of the latex will change after adding the exfoliated graphite. This processing step will be done through sonication of the solution containing the latex and exfoliated graphite. The final properties that we desire to have in the final composite include: ductility to withstand a strain of 320%, electrical conductivity and sprayability.

Previous Work

There has been a great deal of work done in the field of piezoresistive strain gauges. Here, we will describe four different works to give a broad overview of the field. In one work, strain gauges were successfully fabricated by blending an insulating polydimethylsiloxane (PDMS) elastomer with a conductive exfoliated graphite filler material as described in Kujawski et al.[5]. The exfoliated graphite filler in this research was produced by microwave irradiation. It was found that more than 3 wt% of exfoliated graphite in the mixture made the samples conductive. Furthermore, the samples remained elastomeric upon 25 wt% of exfoliated graphite loading [5]. Scanning electron microscopy revealed that the samples contained voids, as opposed to no voids in pure PDMS, which explains the relatively low modulus of the samples. Overall, the performance of the strain gauges fabricated in this research was comparable to other designs where PDMS was loaded with carbon black, however significant cost reduction was achieved.

In another work by Pang et. al., authors reported using two interlocked layers of PDMS with Pt-coated nanofibers [11]. This double layer architecture allowed for highly reproducible results and strain cycling measurements showed that the sensor was accurate for up to 10,000 cycles. Moreover, what is fascinating about this work is that the sensor was accurate in measuring strains ranging from a human heartbeat to the falling of a drop of water and strains such as tension and torsion can be measured with this sensor. Strain was measured based on the change in resistance that the sensor experienced [11].

Work by Bae et. al., transparent strain sensors based were etched on CVD-grown graphene [12]. The overall purpose of this work was to detect human movements, and the authors demonstrated it by patterning the strain sensor onto a glove and measuring the movements of fingers. Their piezoresistive properties were investigated under a tensile strain up to 7.1%, and showed moderate success up to this level [12]. Traditional strain gauges only

measure strain in one direction, but the authors used a rosette (multi-axial) strain gauge in order to measure the magnitude and direction of strain for various applications [12].

Lastly, in a work by Behrens et. al., a sensor was fabricated using solution blow spinning and subsequent nanoparticle nucleation [13]. A unique aspect of this paper was that the device could be patterned onto any non-uniform substrate and the metallic nanoparticles could be patterned in any manner. The solution that was blow spun was a 20% SIS in THF solution, then the optimal nanoparticle loading percentage was found to consist of a 25% STFA in ethanol solution [13]. After nucleation, the electrical and mechanical properties were measured and it was found that there was low strain loss and high conductivity measured up to 400 strain cycles [13]. Moreover, the device was patterned on a glove and various movements could be detected based on a change in resistance [13].

While there has been moderate success, there are several challenges presented when fabricating piezoresistive strain gauges. To begin with, selecting the filler material and matrix is the most important aspect of the design because it dictates the mechanical and electrical properties. There is a tradeoff between conductivity and flexibility, that being the more conductive a material is, the less flexible it is and vice versa. Moreover, many strain sensors in the field experience hysteresis and lose conductivity after a certain number of strain cycles or uses, so being able to understand how that works is key.

Design Aspects

The goal of our design is to realize a sprayable piezoresistive strain gauge that gives a proportional response based on the strain experienced by the device. We want our device to be sprayable, so it can easily be applied to different surfaces. We want piezoresistivity, so based on the change in resistance, we can measure the angle made between the forearm and bicep to measure the optimal angle for shooting a basketball. For the purpose of this project, we chose to implement our strain gauge on the surface of an elbow, because an elbow goes through a relatively long range of motion as it bends to throw a basketball. Thus it is an appropriate surface to start modeling. Upon successful realization of this preliminary design, our ultimate goal is to

use the device in sports therapy to measure the range of motion of the injured body part versus a healthy body part. Although similar devices have been fabricated before, most of these devices aim to detect deformation on machines with the exception of the work done by Bae et.al., where movements of human fingers were analysed to improve similar movements in robots. Our design is unique in the sense that we aim to use our device for physical therapy. This means that our device needs to withstand higher strains than the ones demonstrated in previous works. The materials we used and the fabrication processes reflect this criteria.

Technical Approach

In order to best decide on what host and conductive filler material to use, we developed a table comparing relevant properties of candidate materials (shown later in this section). The materials we considered for the host were natural rubber and PDMS, and the materials we considered for the conductive filler were exfoliated graphite flakes, and single-walled carbon nanotubes. The main issue with the loading of conductive fillers is that the material remains insulating if the loading is too low and dramatically increases in stiffness if the loading is too high. In other words, a low percentage of filler is needed to minimize stiffness but at the same time it is necessary to identify the percolation threshold: the loading at which the material becomes conductive.

In Kujawski's publication in the journal *Carbon* [5], exfoliated graphite was chosen as the conductive filler material as opposed to others such as carbon nanotubes. To Kujawski's research group, exfoliated graphite was deemed best because it can be used to produce low modulus composites having good conductivities at low loadings.

The next approach after we selected our conductive material was in identifying the weight percentage (wt. %) we wanted to load our conductive material into our host material. In order to do this, we found some relevant articles pertaining to conductive material loading in order to identify what percentage would be best for our design. In Wissman's publication in *Smart Materials and Structures* [4], strain gauges consisting of latex mixed with exfoliated graphite were prepared with higher and lower loadings to ascertain the optimal level. Figure 1

below from Wissman's publication shows unstrained, baseline resistance R0 vs. loading: which decreased exponentially between 8 and 17 wt%.

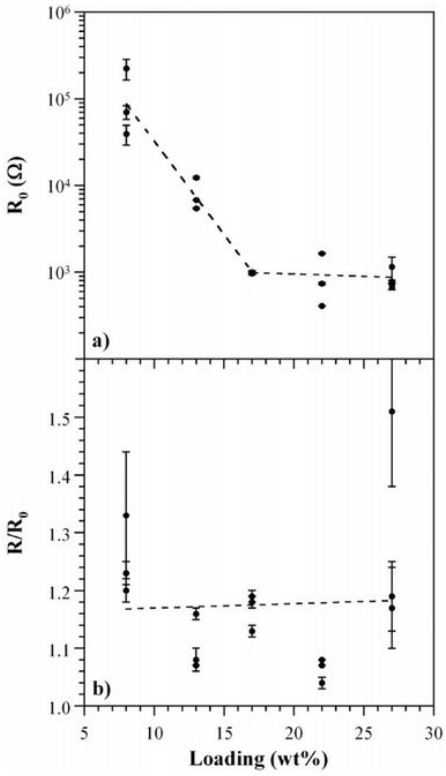

Figure 1: a) Initial resistance versus loading percentage of EG in latex. b) Relative change in resistance upon a load of 50 grams versus loading percentage of EG in latex [4].

Therefore, the percolation range extended to approximately 17 wt%. This behavior is similar to the behavior of carbon black in latex, where resistivity decreased and flattened with carbon black content up to 20 wt.% [6]. This information gave us a great background in choosing the best wt.% of our conductive material in our design.

Furthermore, more information was found on electrical properties: specifically, the electrical resistivities of the exfoliated graphite filled polymers vs. the graphite filler concentration for three different graphite size filled polymers: small, medium, and large graphite additives [9]. The graphite flakes used in this study had an average diameter of 500 um, and were separated by using mesh gratings stacked on top of one another. The graphite flakes were separated using 50 (297 um), 100 (149 um), and 150 (~100 um) size mesh sieves and correspond

to large, medium, and small flakes respectively. This method of sorting does not determine a specific particle size, rather it determines a range of particle sizes. If a particle is smaller than the grating size it will pass through, but will get stopped when the grating becomes more fine than the particle itself. Figure 4 shows that the electrical resistivity of the exfoliated graphite filled polymers decreases with increasing exfoliated graphite concentration. This ties into how we stated earlier how nanoparticle loading changes sensitivity. For all three sizes at 8 wt.% of exfoliated graphite, the resistivity became nearly four orders of magnitudes lower than the baseline polymer (epon resin 862). At 20 wt.% of exfoliated graphite, the resistivities reached levels up to eight orders of magnitude lower than the baseline for all three sizes. The trend showed that the large graphite flake filled polymers showed the lowest resistivities at each graphite concentration: followed by medium and then small. Overall, the electrical resistivity decreased along with increasing the particle size.

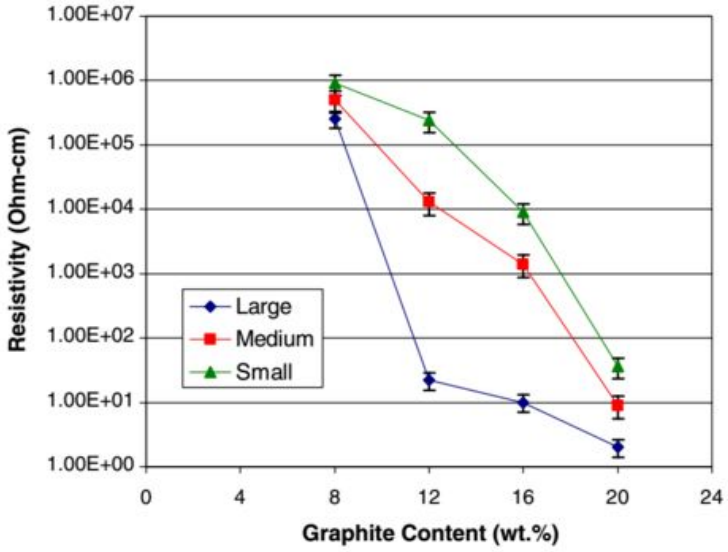

Figure 2: Electrical resistivities of exfoliated graphite filled polymers vs. the graphite filler concentration for three different size filled polymers: small, medium, and large graphite additives

With these advantageous properties and coupled with the fact that exfoliated graphite was easily obtainable in Dr. Smela's lab, we decided to choose exfoliated graphite as our conductive material. Moreover, since no optimum weight percentage has been identified as of yet, especially specific to exfoliated graphite as the conductive filler and latex as the host material, we took

these findings on the loading and resistivity to choose 15 wt.% for our design due to the conductivity, sensitivity to strain, and mechanical viability.

We tabulated the properties of the candidate materials as shown below. This was done so that we could create graphs of dependence of mechanical properties to loading percentage using the set of equations (equations 2 to 9) that are described. The table was also used to conduct all our calculations.

	Young's Modulus, E (MPa)	Bulk Modulus, K (MPa)	Shear Modulus, G (MPa)	Poisson's ratio	Yield Strength, σ_m (MPa)
Natural rubber (latex)	1 - 2	8.3 - 16.6	0.34 - 0.68	0.48	25
PDMS	0.36 - 0.87	6 - 14.5	0.12 - 0.29	0.49	2.24
Graphite flakes	795 - 1153	581.1 - 842.8	312.5 - 453.2	0.272	N/A
Carbon nanotubes (single-walled)	1000	666	400	0.25	N/A

For compliant strain gauge applications, the two most important properties to consider are gauge factor and Young's modulus. Gauge factor is the measure of a strain gauge's sensitivity to applied strain. It is described as the relative change in resistance to applied strain, or in mathematical terms:

$$GF = \frac{\Delta R/R}{\varepsilon} \quad (1)$$

We naturally want the highest possible gauge factor so that the strain gauge can pick up even a slight deformation. However, we found no proposed method or equation to predict the gauge factor of a composite as it is a property determined through a test. Thus, to acquire the best gauge factor possible, we will look into the literature and determine which combination of materials yield the highest gauge factor.

The effective Young's modulus of a composite is highly dependent the on the loading percentage of the filler. We will use Voigt's, Reuss', and Mori-Tanaka's empirical models to produce graphs showing the dependence of Young's modulus to the loading percentage. Voigt's model, the upper bound, is expressed as:

$$E_c = E_f V_f + E_m(1 - V_f) \tag{2}$$

Where E_c, E_m, and E_f are the Young's moduli for the composite, matrix, and the fibers, respectively. V_f is the volume fraction of the fibers. Reuss' model, the lower bound, is expressed as:

$$E_c = \frac{E_f E_m}{E_f(1-V_f)+E_m V_f} \tag{3}$$

Mori-Tanaka's method, which assumes particle-reinforced composite, is expressed as [3]:

$$E_c = \frac{9K_c G_c}{3K_c+G_c} \tag{4}$$

$$K_c = K_m + \frac{V_p K_m(K_p-K_m)}{K_m+B_2(1-V_p)(K_p-K_m)} \tag{5}$$

$$G_c = G_m + \frac{V_p G_m(G_p-G_m)}{G_m+B_1(1-V_p)(G_p-G_m)} \tag{6}$$

Where K and G are bulk modulus and shear modulus, respectively. Constant B_1 and B_2 are expressed as:

$$B_1 = \frac{2(4-5U_m)}{15(1-U_m)} \tag{7}$$

$$B_2 = 3 - 5B_1 \tag{8}$$

Here, U_m refers to the Poisson's ratio of the matrix. We will also use equations that have been proposed in the past to predict the strength of the composite. Assuming that the load experienced by the composite cannot be transferred to the filler particles (the particles take up space but do not carry load), the following expression can be appropriate to predict the strength of the composite [3]:

$$\sigma_c = \sigma_m(1 - 1.21V_p^{\frac{2}{3}}) \tag{9}$$

This equation, proposed by Nicolais and Nicodemo, predicts the lower bound strength of the composite [3]. The upper bound strength of the composite assumes perfect adhesion between the particles and matrix and thus the strength of the composite is simply the strength of the matrix [3]. However, there are no universally accepted models or theories to predict the strength of a composite due to the complexity of its load-bearing capacity [3]. Thus, we will use the lower

bound to account for the worst case scenario. We will use the graphs produced by the previously mentioned equations to determine the range of loading percentages that gives the mechanical properties that are suitable for our application. The expected maximum strain for our application is determined by measuring the deformation at the apex of elbow.

Prototype

We were able to prototype our design in Laboratory of Microtechnology, managed by Dr. Smela. It has all the tools necessary to fabricate and test the basic function of the strain gauge. The lab has Textronix DMM 4050 6-½ Digit Precision Multimeter that we can use to measure the resistance of the strain gauge, along with other equipment such as a high precision scale, mixer and sonicator. Ansys and Creo Parametric were used for simulation and modeling, however, we were unsuccessful in re-creating an accurate model in the time frame. Both are readily available in UMD virtual lab. Moreover, we used CES EduPack to search for ideal materials for our purpose based on certain material constraints. To read the resistance change in the strain gauge as the person wearing it does a shooting motion, we used an Arduino. We also were very thankful for the guidance of Dr. Smela as well as Dr. Ankem.

The first step in making a successful prototype is making the latex-exfoliated graphite solution. In order to obtain exfoliated graphite, the exfoliation methods employing microwave irradiation presented by Kujawski et al. [5] was used. This method required us to start with acid-washed graphite flakes. The microwave oven used had a power of 1100 W and operating frequency of 2.45 GHz. It is important that the graphite flakes are in close proximity of each other in order for successful exfoliation to occur. Once placed in the microwave, exfoliation was complete after a few seconds.

Our strain gauge solution was prepared by mixing 1 g of the exfoliated graphite to 100 ml of deionized water. In addition to the DI water, 0.75 g of Triton X-100, a nonionic surfactant, and 4-5 drops of SE-15, an antifoaming agent, were added. The solution was stirred until the the exfoliated graphite mixed in. The container was cooled in an ice bath before performing horn sonication for about 19 minutes at 100% amplitude. We added 10 g of the aqueous EG solution

to approximately 1.1 g of mask-making latex. The solution was vortex mixed at 3000 rpm for 60 seconds until there was no visible latex lumps. Now our solution was ready to be sprayed on.

Once the solution was prepared, we used the fume hood located in Dr. Smela's laboratory that has a spray apparatus that is ideal for spraying on our solution. Before spraying on the strain gauge, we needed to measure and determine the rough measurements of the rectangular shape we would be spraying onto the sleeve. We did this by having one of our members wear the sleeve and marking the sleeve at important points, such as where the ball of the elbow is when the sleeve is completely stretched out and where the ball of the elbow is after the shooting sleeve has been bent by the user. We did this to make sure that the strain gauge would be long enough and wide enough to cover and measure the area of interest to us as the elbow is bending. It is important to note that there is no ideal measurement for the strain gauge as it depends on the particular use.

Spraying on the strain gauge is a long and tedious process. The strain gauge cannot be applied in one spray, but actually requires multiple layers of spraying. Once one layer has been applied, we had to wait around 15 minutes to apply the next layer. We had to repeat this step about 10 times. The dimensions of our sprayed on area were 8 cm by 1.5 cm. After the sleeve had been sprayed on, we let it sit under the hood overnight to let it dry. Once dried, we applied glue on the ends of the strain gauge, placed carbon fiber wires, and poured 5 drops of the 15wt% EG solution on top of the strain gauge. Once the 5 drops of the solution dried, the wires were fixed in place.

Ethics and Environmental Impact

For a device such as ours, trade offs between societal needs and environmental impact will exist. For example, structural health monitoring (SHM) is a technology used for the safety assurance of mechanical, aerospace, building structure and human life: with the most commonly used strain sensor being a piezoresistive thin-film strain gauge. Unusual structural behavior and hidden structural issues can be detected early with SMH, which enables for better use of materials/components and decreased risk. Despite the fact that we will be using a piezoresistive strain gauge for the application of a basketball shooting sleeve, there is amazing potential for the

device to be used for a myriad of applications if engineered correctly. Nevertheless, key issues exist with SMH and include a variety of factors. The factors include measurement of chemicals (pH, oxidation, corrosion, etc.), mechanical issues (strain, deformation, stress, etc.), and physical complications (temperature, humidity, etc.). Therefore, the challenge exists in developing reliable and sensitive techniques, and in developing robust algorithms to detect and prevent specific parameters. Moreover, in terms of future development, commercial implementation could be difficult as piezoresistive strain sensors are incredibly sensitive to temperature changes.

The environmental impact of developing plastic-based wearable electronics is another important factor for the wearables industry. The use on non-renewable resources for the development and manufacturing of modern technology can have a vast influence on our environment: especially considering how many components are made from petroleum-based plastics. Nevertheless, research and development in finding new and more sustainable plastics, and in finding energy efficient devices has been exponentially growing. Breakthroughs in these technological developments could make huge impacts for the wearable/flexible electronics industry and for the future environment.

Intellectual Merit

By carrying out this project, we hope to gain a better understanding of piezoresistive strain gauges. Specifically, we hope to quantify and best understand what combination of materials produces the most effective strain gauge through extensive design, model development, and prototyping. Moreover, we hope to be able to gain insight on how to best apply the film so that it fits our application and it remains durable. Intellectually, this project will be especially beneficial when considering the interfaces between the conductive material, adhesive material, and the surface on which the strain gauge solution will be sprayed. With our project, we deemed exfoliated graphite to be the best conductive filler material, and latex to be the best host material for our basketball shooting sleeve application. Going through the materials selection design process with the team showed us that considerable research and design will also be necessary before using a sprayable strain gauge for other applications before prototyping.

It is also of interest to consider a reinforcing layer for other projects and how that will affect the sensitivity of the overall device. The reinforcing layer could be necessary to stabilize the device and might also need to be adhesively bonded to the surface of interest. If the reinforcing layer is very strong, it may make the device less sensitive to smaller strains, and vice versa. Currently, in the field of measuring strain, most devices are rigid, and thus exploring the possibility of a flexible, robust device would be unique and novel in this field.

We also want to emphasize how sprayable strain gauges could be greatly beneficial in the field of physical therapy and sports if used as wearable electronics. To illustrate, neurorehabilitation researchers from Italy were able to develop a low cost, wearable system consisting of strain sensors made of conductive elastomers printed onto fabric [10]. Conductive elastomers are polymers with piezoresistive properties, and are non-toxic and waterproof. They can be smeared on fabrics by means of a cheap industrial printing, and this process can be done without considerable modifications in the mechanical properties of the underlying substrate. The wearable system was used to collect a comprehensive set of over 600 different movements at varying speeds and repetitions. In all cases, the sensor was able to accurately measure movement. A device such as this will allow remote monitoring of physical therapy exercises at home, fix posture, and help with flexibility during normal everyday tasks. Therefore, wearable technology can be used for sports and and also to monitor movements and aid rehabilitation.

Broader Impact

Physical therapy and the ability to efficiently rehabilitate and accurately measure movement have been growing exponentially. Being able to precisely and effectively monitor movements could be strongly beneficial for rehabilitation patients and sports athletes: allowing for enhanced recovery, fewer patient visits, and accuracy in a multitude of sports. To illustrate, smart textiles, or wearable electronics, have been emerging as a unique approach to monitor body movements and receive information from other stimuli. Our strain gauge is sprayable, and is able to be applied to any uniform or nonuniform substrate and we have been able to show this with our project by using the strain gauge on a basketball shooting sleeve to obtain the ideal

angle of a shot. While our goal was to show the versatility of the strain gauge for physical therapy applications, it is most definitely not limited to just these applications.

Another potential use for our strain gauge, which was an idea we initially considered for our project was its use for vehicles and structures, or more specifically, unmanned aerial vehicles and drones. Drones and aerial vehicles experiences many different forces when flying either due to turbulence, environmental factors or unforeseen objects. With many of these vehicles, a major concern is weight. While for some of the larger vehicles it may not be a primary concern, for many of the UAV's and drones it is. That is where our strain gauge comes into play. It can be sprayed onto almost any surface and in any shape, but most importantly, the strain gauge weighs almost nothing, making it ideal for use in drones.

Results and discussion

Shown below are graphs of the effective Young's modulus and effective strength as a function of volume fraction of filler of the composite.

PDMS Host

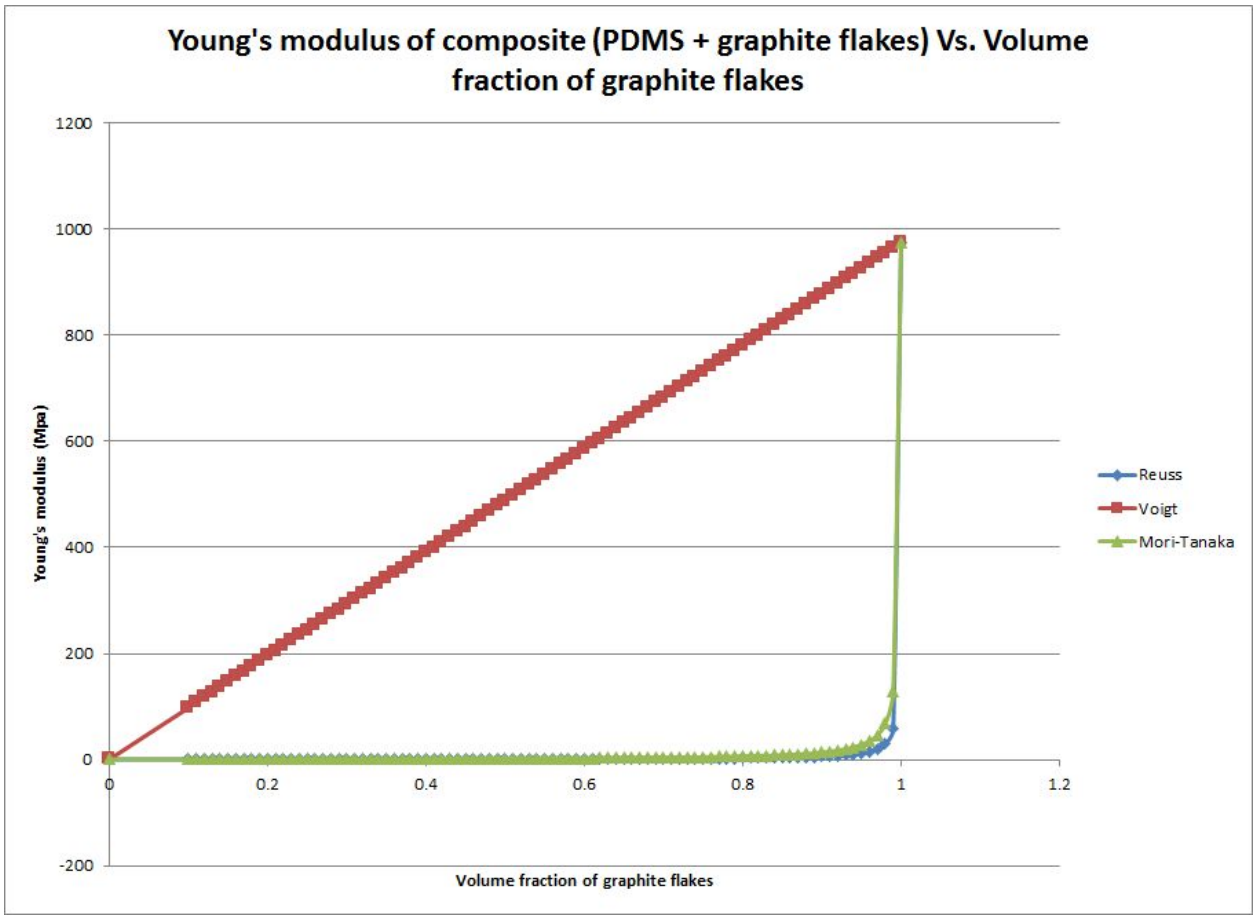

Figure 3: Effective Young's modulus of PDMS and graphite flakes composite in MPa versus volume fraction of graphite flakes using Voigt's (red), Reuss' (blue), and Mori-Tanaka's models.

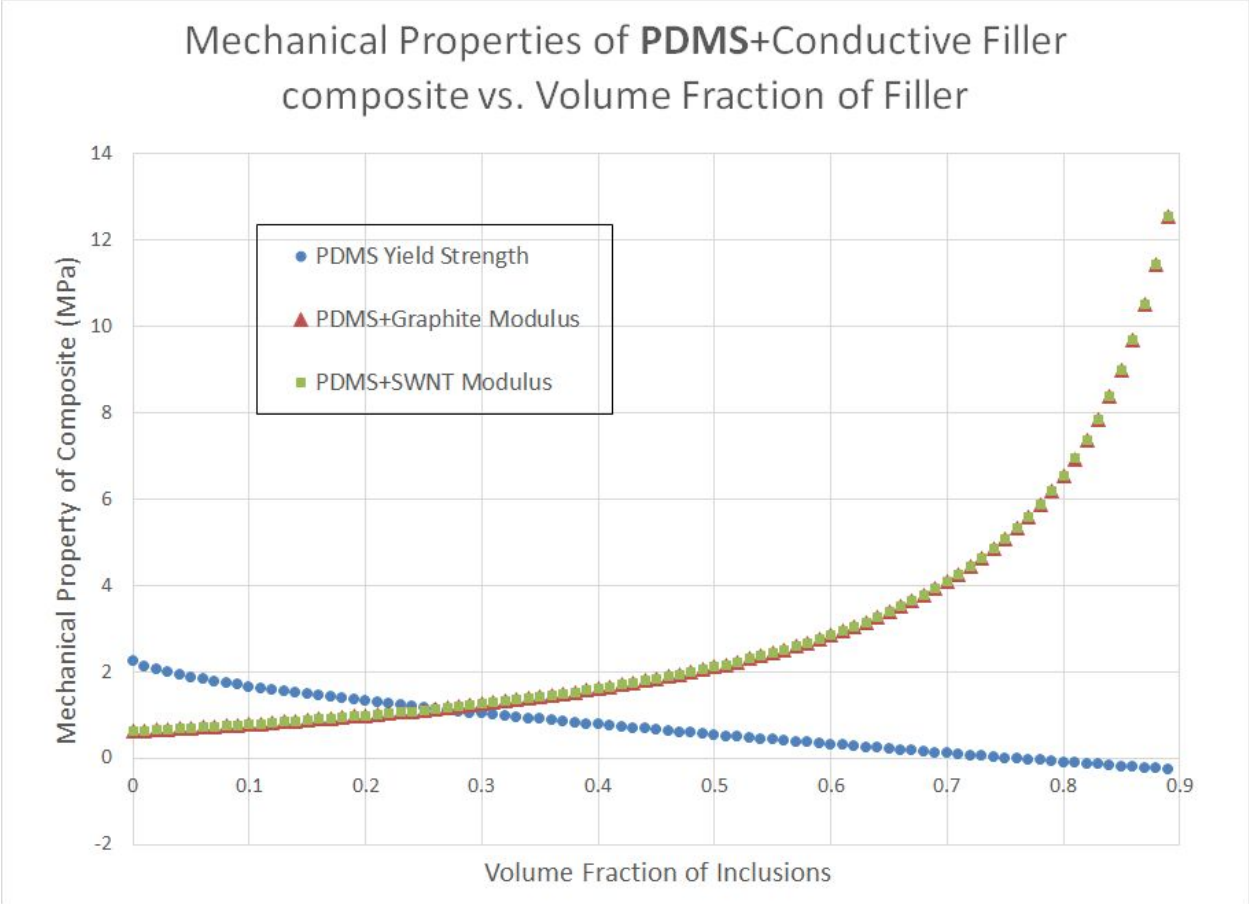

Figure 4: Mechanical properties of PDMS and conductive filler versus volume fraction of the conductive filler

From Figure 3, Mori-Tanaka's model does indeed lie in between the Voigt's and Reuss' models. Mori-Tanaka's model is the best suited for our application as it assumes particle-reinforced composite. For the graphs of mechanical properties of composite versus volume fraction, we used Mori-Tanaka's model to predict the composite's modulus. It is observed that above 85% loading, the effective Young's modulus of the composite increased dramatically. At higher loading, the strength of the composite gets below zero, which is reasonable because equation 9 predicts that the strength of the composite should decrease with increasing loading. This leads us to assume that equation 9 is more accurate for lower loadings. Therefore, for now, we will look to the lower loading percentage for our application. It is important to note that equation 9 does not depend on the filler materials.

Natural Rubber (Latex) Host

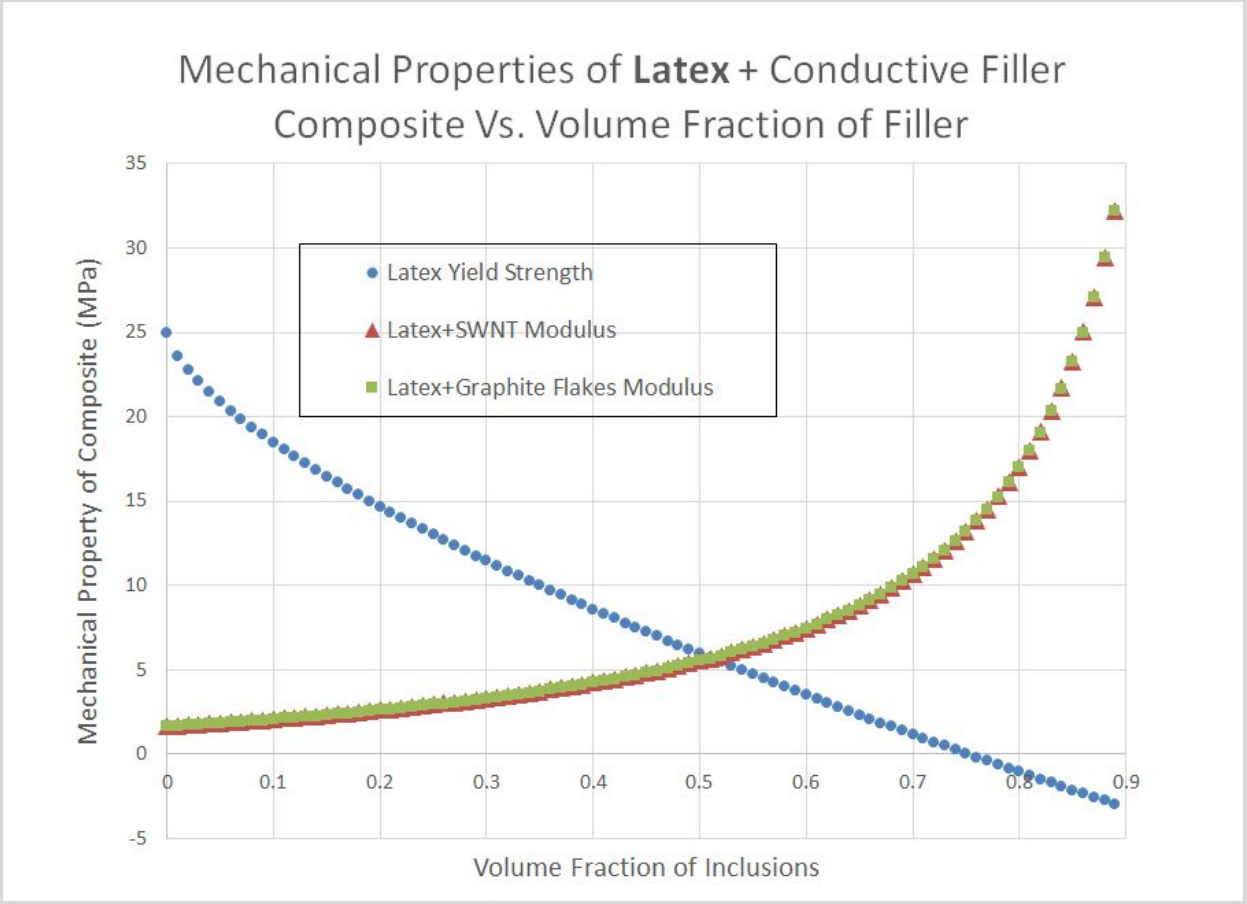

Figure 5: Mechanical properties of PDMS and conductive filler versus volume fraction of the conductive filler

As shown on figures 4 and 5, single-walled carbon nanotubes and graphite flakes alter the modulus of the composite very similarly, due to their minute difference in Young's modulus. Young's modulus is then an insufficient reason to choose one over the other. We will have to research about their influence to the gauge factor. If we can find data showing that one material gives a higher gauge factor than the other, then we can safely say that material is better than the other for our application.

It is also observed that PDMS composites have slightly lower moduli (a few MPa lower on lower loading), but they have significantly lower strength. After we calculate the expected load on the strain gauge, we will be able to see that if the superior strength of latex is needed for our application.

After determining the conductive filler material, we will still have to figure out the correct weight percents to use. However, the weight percents also depend on the host material that we decide to use. After looking through literature, we have narrowed our results down to two host materials: PDMS and latex as they are two of the most studied host materials for our purpose. Each host material has their own benefits and drawbacks and we need to compare and contrast the different host materials to determine which one works best.

It is important to note that there is no graph or equation that shows the optimal wt% of conductive material to use. However, Kujawski et. al were able to show that there are definitely bounds for the optimal wt%. For example, too low of a wt% results in the piezoresistive material to be too insulating and too high of a wt% results in it being too stiff and thus compromising the flexibility of the strain gauge. We will consider the optimal loading percentage to be the one which will give the highest gauge factor while still satisfying our mechanical requirement. We will find the gauge factor data through literature research. As mentioned before we are interested in a spray on strain gauge and need to make sure that whichever material we pick can be sprayed on. We know that the PDMS can be sprayed on and has been shown [6].

While PDMS does seem like a great fit for our need, we are more interested in using the water-soluble latex as our host material for a couple of reasons. Unlike PDMS, the latex does not require any curing. Another key advantage of the latex is that it can be applied onto a wide range of surfaces as a thin and flexible coating. The same holds true for the wt% of exfoliated graphite to be used in the latex matrix; too low and it would be too insulating and too high would make it too stiff.

As mentioned previously, we want to have a combination of materials that give highest gauge factor while still being mechanically compliant. Latex and EG was reported to have gauge factor of 28 [4]. Carbon nanotubes have also been used to create strain gauges by dispersing them in PMMA and PVDF, yielding gauge factor of 1 to 15 and 6.2, respectively [4]. However, we cannot conclude for sure that EG is the better conductive filler than CNT for strain gauge application because so far we have not found data on EG and CNT in the same host material. Using the method described in the technical approach, we measured the expected maximum strain to be 320%. We multiply the effective young's modulus of the composite by 3.2 (the strain

value) to obtain the expected maximum stress and compare it to the effective yield strength of the composite. Our results are shown in figure 6 and 7 below. We found that PDMS only give a small range of viable volume fraction of conductive filler in order to satisfy the mechanical requirement of our properties. Using PDMS gives very little margin of mechanical safety and it is possible that even at the maximum viable volume fraction (~ 0.04), the percolation threshold isn't reached. This proves that latex/natural rubber is the better host material for our application. With a latex host, loading up to ~ 0.35 volume fraction is still mechanically viable. Ideally we would like to keep the loading low to ensure the composite is still flexible. Upon literature review, we decided to use exfoliated graphite because it is the particle that reportedly yields the biggest gauge factor (28) when dispersed in latex [4]. We use 15wt% of EG in latex because it gives conductivity and sensitivity while still being mechanically compliant. This corresponds to 0.07 volume fraction. Thus our composite strain gauge is expected to have modulus of 5.7 MPa (Mori-Tanaka) and strength of 19.9 MPa (Nicolai-Nicodemo). Using our measured strain of 320% multiplied by the calculated modulus of 5.7MPa, we obtain a loaded stress of 18.24 MPa in the film. A loaded stress of 18.24 MPa is less than the composites yield strength of 19.9 MPa and therefore satisfies our mechanical requirement that the device must not plastically deform.

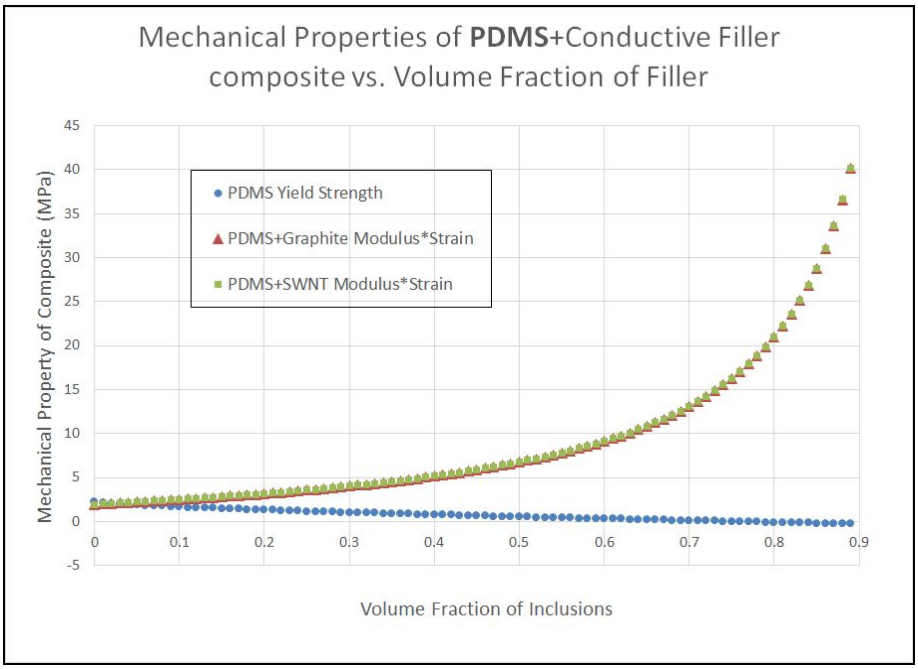

Figure 6: Plot of expected stress and strength of PDMS-host composite versus the volume fraction of conductive fillers.

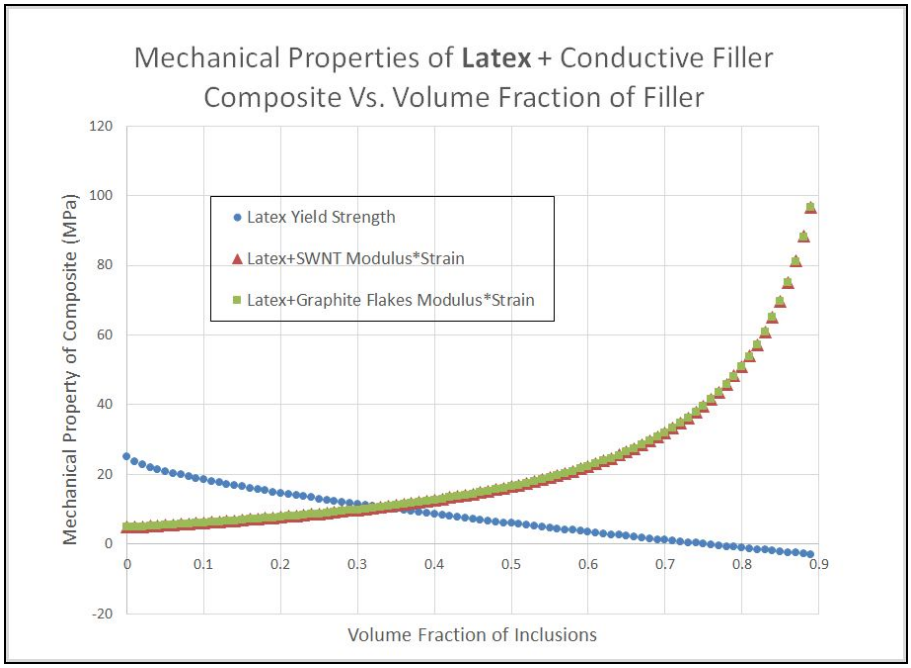

Figure 7: Plot of expected stress and strength of PDMS-host composite versus the volume fraction of conductive fillers.

Conclusions

In conclusion, our group was able to successfully design a sprayable, piezoresistive strain gauge for the application of a basketball shooting sleeve. In order to pick the host material and conductive materials, we had to consider many different material characteristics such as conductivity, low Young's modulus, high gauge factor etc. One of the methods that was key to helping us determine the necessary Young's modulus was the Mori-Tanaka model. It helped determine the dependence of the Young's modulus on the loading percentage. After much literature review and mathematical modeling, we were able to refine our search and determine latex to be a better candidate than PDMS because it is mechanical more viable over a broader range of volume fraction than PDMS. After determining the host material, we determined the best filler material would be exfoliated graphite as it yields the highest gauge factor when paired with latex. By finding the right host material and conductive filler, we were able to design and prototype a sprayable piezoresistive strain gauge for the application of a basketball sleeve.

Future Work

If more time was available, we would have taken into consideration the findings that percolation thresholds in polymers containing disc-shaped nanoparticle fillers (such as exfoliated graphite) have been shown to depend on the thickness and diameter of the discs [8]. This also implies that the uniformity of the dispersion can play a role. Figures 8 and 9 below show the effects of thickness and diameter of graphite nanoplatelets (GNP) on percolation threshold.

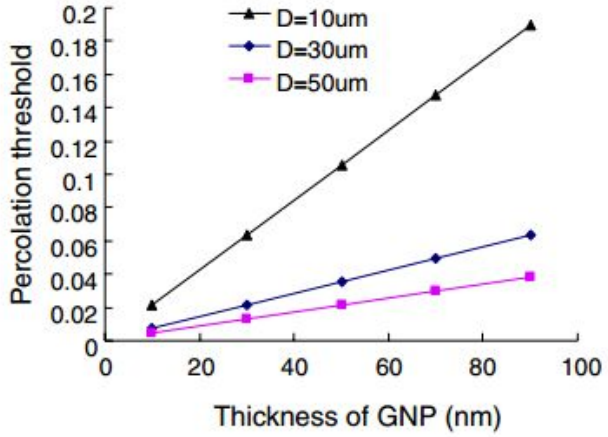

Figure 8: Effect of thickness (t) of platelet on percolation threshold

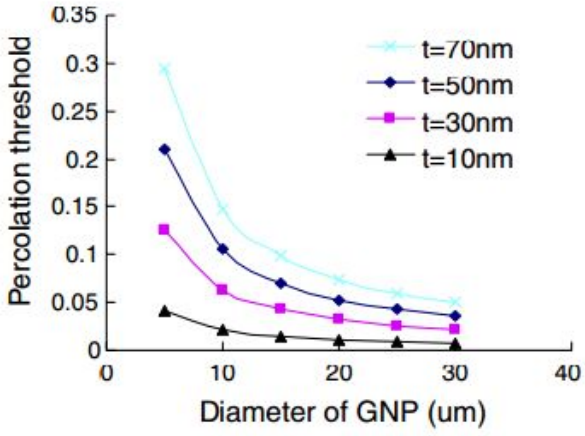

Figure 9: Effect of diameter (D) on platelets on percolation threshold

Figure 8 shows how the percolation threshold increases linearly with increasing platelet thickness: with the rate of increase being higher for fillers with a smaller diameter (D = 10 um). Figure 9 shows the opposite trend, with the dependence of percolation threshold on filler

diameter being nonlinear. It was shown that the percolation threshold decayed exponentially as the filler diameter increased for a given filler thickness. These results showed that there is a larger variation in percolation threshold with a larger filler thickness. Overall, the observations made with the percolation threshold of graphite nanoplatelets would have further helped our group in designing and tailoring the shape and geometry of conducting fillers in order to best maximize the properties of our conducting filler, and also in determining the percolation threshold.

We may be able to predict the hysteresis of the strain gauge using the gauge factor equation (eqn 1). Rewriting equation 1, taking into account the fact that the strain gauge composite is viscoelastic in nature, we have:

$$\varepsilon(t) = \frac{\Delta R/R}{GF} \tag{10}$$

This equation does not predict a linear response to applied strain, as the strain gauge response will be time- dependent. While there are proposed general solutions to viscoelastic stress-strain, we do not yet find studies that address the hysteresis nature of viscoelastic strain gauge. It may be worth looking into the hysteresis for future works.

We created a voltage divider circuit and Arduino code to look at the response of the strain gauge to shooting motion. We used a resistor which has a value close to the strain gauge initial resistance. This was done so that when the strain gauge is unstrained, the voltage drops across the resistor and the strain gauge are the same. We were only able to read the voltage drop through the strain gauge, not the resistance change of the strain gauge itself. Our result is shown in figure 10 below. While this is still a good measure to observe the trend of strain gauge response, it is not an accurate representation of the response to a shooting motion as Arduino voltage input is capped at 5V. The peaks in the plot correspond to when the arm is fully bent, and the voltage drop sharply decreases as the arm goes back to straight position. The voltage drop does not go back immediately to initial value after each shooting motion possibly because of the hysteresis nature of viscoelastic material. It could also because the four shooting motions done were not exactly the same. For future work, a better circuitry and code will be needed to read the resistance change of the strain gauge, instead of the voltage drop. This will be needed to obtain meaningful data that represent the motion that we would like to track.

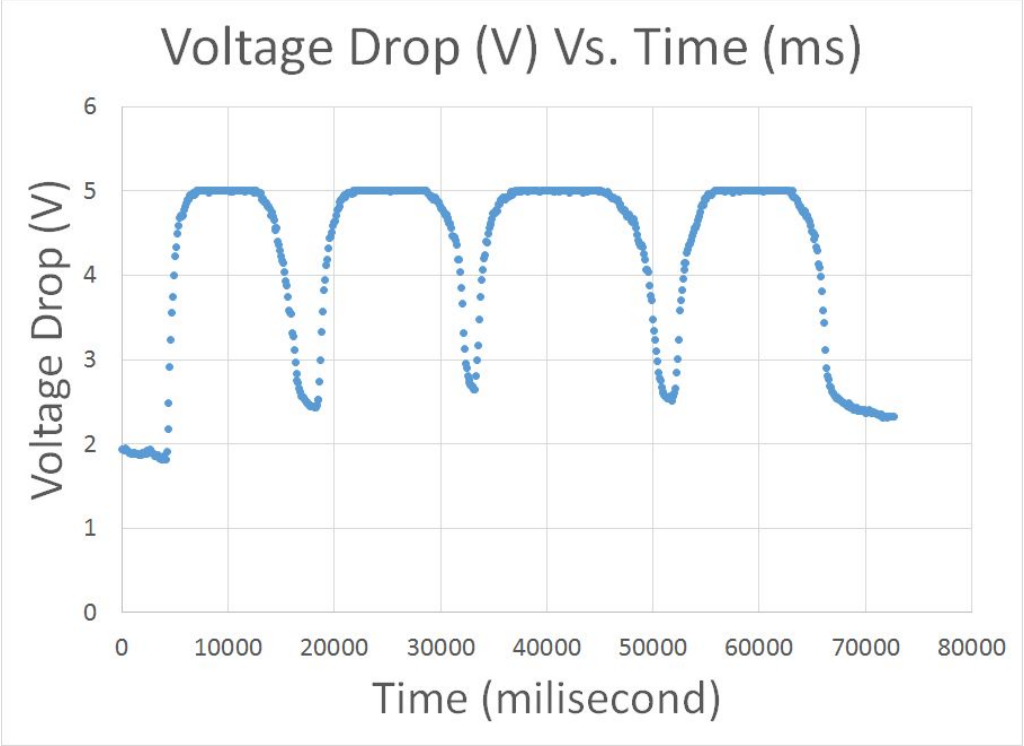

Figure 10: Voltage drop across strain gauge (V) vs. time (ms).

Acknowledgements

We would like to express our gratitude to Dr. Elisabeth Smela, whose insight and guidance were crucial to the success of this project. We also deeply appreciate the assistance from her group's members, Ephraim Zegeye and Nehemiah Emaikwu. In addition, we would like to thank Dr. Sreeramamurthy Ankem and his student, Samuel Schwarm, for their aid in a part of this project. Last, we sincerely thank Dr. Ray Phaneuf, without whom this project would not be possible to complete in the given time.

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