Twisted and Coiled Polymer Actuators

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Abstract

Twisted and coiled polymer actuators are a form of soft actuator that are composed of nylon sewing thread or fishing line and use joule heating to contract or expand in length. The strands of polymer are twisted under load to produce a spring-like structure. Joule heating is the process of converting electrical energy to thermal energy through power dissipation by a resistor. For TCP actuators, voltage is applied (approximately 10V) to the coils and the current drawn heats the structure. Nylon thread has a negative thermal expansion in the axial direction, which provides a way to have reversible contractions by heating. Upon heating, the coils untwist, producing a torque that contracts the length of the coils. The benefits of this variety of actuator are the inexpensive lightweight polymer fibers, high energy density, reversible contractions, self-sensing (by inductance), and negligible hysteresis compared to other soft actuators. This literature review focuses on the problem of heat dissipation as it relates to restricting actuation frequency, and the methods that may enhance heat transfer. In particular, the proposed research is focused on increasing convection and conduction coefficients by increasing fluid flow, altering fluid medium, and embedding conductive nano-particles in an elastomer substrate or depositing directly on the polymer coils. The expected outcomes of the research are to determine the validity of the various restoring methods and ultimately produce a more competitive TCP actuator in the soft robotics industry. The impact can be summarized as creating a viable solution for more applications requiring a low voltage, inexpensive, and self-sensing actuator for fine control under moderate stress. Examples of applications where this can be used are with extensor muscles in forearms and biomimetic applications requiring actuator performance approaching human capability.

Soft Actuator Background

Soft actuators are unlike classical methods of actuation in that they are flexible and composed of compliant materials that exhibit large strain [10]. In classical robotics, linear actuation is achieved numerous ways, but typically rely on rigid actuators. A standard linear actuator is composed of a DC motor that rotates a ball screw, converting rotational to linear movement. Other methods used to deform linearly include rack and pinion, pneumatics, or pistons. In these cases, to achieve linear motion a rotary source is required. Common DC motors rely on alternating electromagnetic fields in order to operate. For these motors the motion is time dependent because alternating fields drive rotation, this is not always the case with soft actuators. Rigid actuators are useful in many applications; however, there are areas where reduced weight, increased efficiency, increased flexibility, and simplicity are needed.

A common drive method for soft actuators is electricity, specifically electrostatic force. An example being a Dielectric-Elastomer-Actuator (DEA), where high voltage (kV) is applied to electrodes surrounding the elastomer. Due to the large voltage potential, the two electrodes are attracted and the substrate compresses. Although advantageous due to the low power consumption (limited current draw), there is difficulty in safely creating high voltage in a desired form-factor. There are compact power supplies available, but it is uncommon for the output to be greater than 6kV and the units are cost prohibitive [13]. A DEA is also difficult to implement in areas where soft actuators are used (bio-mimetic/bio-compatible).

Another widely used soft actuator are shape memory alloys and polymers (SMA, SMP). Both varieties of actuators are thermally operated using the substrate temperature to deform to and from a programmable shape. The material is useful for applications requiring slow actuation at low temperatures and can be created with alloys to increase the actuators strength. However, due to the non-linear deformation, the actuator does suit control systems, and the low transformation temperature limits the overall benefits [14].

Introduction to Twisted and Coiled Polymer Actuators

An alternative method for inexpensive, repeatable, linear actuation are twisted and coiled polymer actuators (TCP/TCPA). In principle, the actuators look similar to skeletal muscle with fibers twisted and coiled together to make a cohesive structure. Commonly composed of nylon, TCPs are essentially created out of coiled fishing line operating on the principle of negative thermal expansion through joule heating. In contrast to current rigid motors, the only necessary items to create a linear actuator is the twisted nylon thread, an electrically and thermally conductive material to provide heat to the material, and an external load. Upon heating, the coils untwist providing a torque that results in the linear contraction of the overall structure. The benefits associated with this variety of soft actuator are the low cost, low voltage actuation (~10V), repeatable actuation (minimal hysteresis) with self sensing. The design and construction of TCPs have desirable characteristics and are an attractive solution for low frequency actuation. In addition to the simple design, the performance is comparable to other soft actuators driven thermally. TCPs can achieve strain above 49% depending on coil geometry. The performance is linear, which is beneficial for controllability, and the average mechanical output power is high (27.1 kW/kg). Although conversion efficiency from input power to mechanical power is (~1-2%), this metric is comparable to SMA/SMP [3]. Additionally, the actuator can operate in environmental conditions that normally would be detrimental to common rigid actuators, such as magnetic fields or submerged under water. Two of the major hindrances of TCPs are with poor actuation frequency, and power consumption under continuous loading. Unlike a DEA or other electro-static actuators, TCPs require a constant temperature to remain in a given deformation. To achieve this, current has to be continuously supplied to heat the resistive material in order to compensate for cooling by the environment. In general, the overwhelming benefits over competing soft actuators is the inexpensive construction, simple design, and controllability.

How They Work

Although similar in appearance to muscle fibers, TCP actuators operate on different principles of actuation. In the case of TCPs, the contraction and expansion of the actuator is dependent on material properties, manufacturing methods, and temperature. At the most simple element, the synthetic polymer fibers (polyethylene, nylon, spandex) have a negative coefficient of thermal expansion in the axial direction that induce significant deformation when heat is applied. The amount of strain increases with temperature by reducing the conformational entropy of the polymer. The temperature of the material is raised by resistive (joule) heating caused by power dissipation through the resistance of a conducting material. A common method used to pass current through the material is to deposit a conductive film on the surface of the threads, typically silver using electroless plating [2]. Other methods used are carbon nano-tube (CNT) sheets and copper wiring [4]. For a given TCP, the temperature of the material must be raised to approximately 240 C to observe the maximum contraction. Polyethylene has a lower melting temperature and only has a 0.3% nominal strain, but is useful in applications where the actuator is coiled and requires larger loading. In the most commonly used material Nylon 6,6, strain is observed to be approximately 4% nominally and is used more often due to its ability to reach appreciable temperatures and subsequently strain [3].

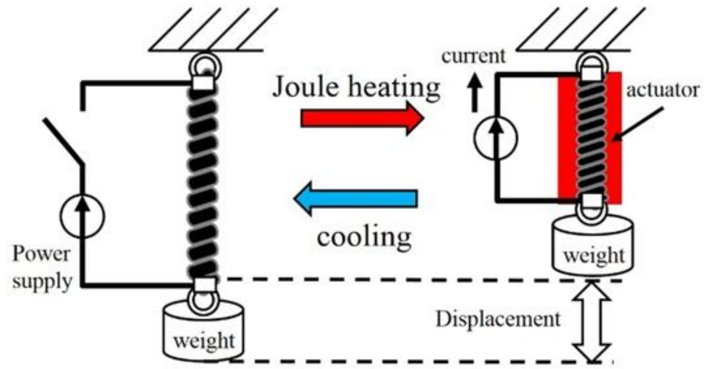

Figure 1**:** Joule Heating overview in TCP actuators where current heats up the material [7]

TCPs further compound the effect of thermal contraction by introducing twist into the fibers. Adding twist into the actuator effectively allows them to act as torsional muscles that can exert torque in the rotational direction while they contract in length [3]. Although the tensile strength of the actuator increases, the strain decreases compared to the initial fiber. If the fibers become maximally twisted under the initial loading (pre-load), the twist will compound and begin coiling into a spring like structure. The addition of these coils significantly increase the properties of TCPs, specifically delivering strain upwards of 49% [3]. During the coiling process, a useful metric that contributes to the performance of the TCP is the spring-coil index. The index compares the diameter of the coil to the diameter of the fiber, as a measure of how tightly coiled the structure is. The two parameters can be adjusted to create an actuator with customized properties. Larger diameter coils result in larger strain with reduced load capacity, while the converse is true for small diameter coils [3]. The Manufacturing process is simple and allows for easy replication of TCPs. Nylon fiber is strung from a motor with a pre-load weight. The weight serves to hold the actuator while the motor introduces twist, it is chosen to keep the fiber from snarling (approximately 500-1300g) [5].

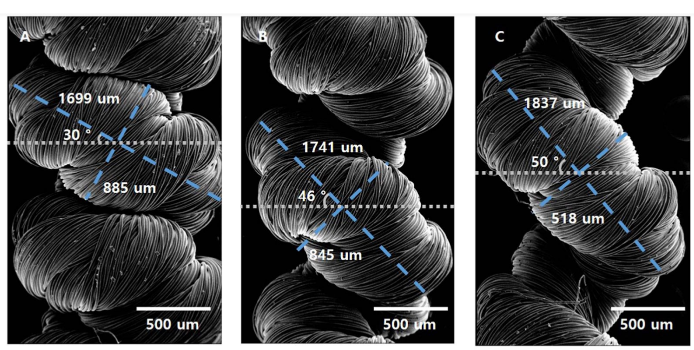

Figure 4. SEM images of after training process under different F_{tr} 500 g (A), 900 g (B), and 1300 g (C).

Figure 2**:** The coil bias angle after the training process for different coiling pressures 500g(A), 900g(B), 1300g(C)) [5]

In addition, the pre-load weight determines the number of coils able to be added to the fiber and thereby the tensile properties. The variable geometry of the actuator can be changed by the use of a mandrel during coiling to change the coil diameter. Once the TCP has been completely coiled, adjacent fiber coils will be in contact. It is important to either increase the weight at this point or decrease the number of coils to allow for proper actuation. Without separating contacting coils there is no room to contract. Once the structure is set it can be coupled with an additional coiled fiber to torque balance the actuator. Making a multi-ply fiber increases the overall tensile strength of the actuator. It is common to anneal the resulting structure to remove residual internal stresses and keep the actuator from unwinding. A training load is used to refine the performance of an actuator until contraction is highly repeatable. As seen in figure 2, the weight affects the coil bias angle, twisted diameter, and coil diameter. In general, the heavier the training load, the smaller coil diameter and greater maximum tensile actuation [5].

An important concept to introduce is chirality, or how the geometry and structure of the twisted fiber relates to the coiled structure as a whole. If the two are in alignment, (homochiral) the actuator will contract when heated. If they are opposing twists (heterochiral) the actuator will extend when heated. Due to how the coils untwist during heating, it is more efficient and more common to have homochiral TCPs. The untwist and length contraction are in the same direction resulting in larger observed strains. For the converse, the two forces are opposing. This is visualized in Figure 3 [3], where 'D' represents heterochiral, and 'E' represents homochiral.

Applications

Many of the benefits of TCP actuators lend themselves to applications with lightweight, inexpensive and relatively slow actuation. The field of TCPs can be divided by variations of the actuator, including super coiled polymer actuators (SCP), surface modified, embedded, and varied material.

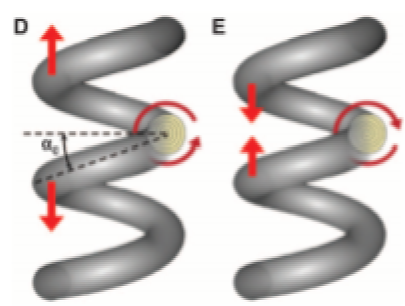

Figure 3. Chirality of twisted and coiled polymer [3]

SCP actuators are a subset of TCPs where the fiber is twisted significantly to induce the additional coiling as seen in Figure 2. There has been research into polymer fiber heat delivery regarding the material used as the resistive heater. Two of the areas include copper wound SCPs and surface modified TCPs. Surface modification entails coating/depositing a thin film of silver directly onto the fiber. Polyethylene terephthalate (PET) in particular was the fiber used in the research. The benefits of using electroless silver plating with PET were the increased actuation performance and thermal response [5]. Additionally, conductive plating is a convenient method to heat the actuators due to both the resistive heater and polymer contained within a single strand. The research on copper wound SCP was focused on determining the effect of fiber-copper diameter ratio, copper winding pitch, coiling pressure (pre-load) on performance (spring-coil index, thermal dynamics, specific work) [4].

The more novel areas of research are with material variation focused on specific applications. For instance, spandex TCPs have better strain characteristics than nylon 6,6. A spandex actuator can deform the same amount as nylon using a shorter actuator [12]. Spandex and nylon both lend themselves to existing processes in the textile industry for applications as smart fabrics. Weaving the material together provides greater tensile force, and can be used to construct geometries obtainable by fabric (cylindrical and planar). Spandex actuates at a lower temperature range during actuation, making the material an area to be researched further as the standard TCP. Currently the lifetime of nylon 6,6 has been studied in greater depth than spandex, which has only been observed up to 200 cycles [2]. Of the areas studied, the research group created fabric that was composed of spandex TCPs woven together to create a constricting material under heat as seen in figure 4. This has applications in the aerospace industry with g-suits to constrict blood flow during high-g maneuvers, or in assistive clothing that could aid in physical rehabilitation [12]. Unfortunately, the temperature needed to obtain significant actuation requires an insulative barrier for skin contact.

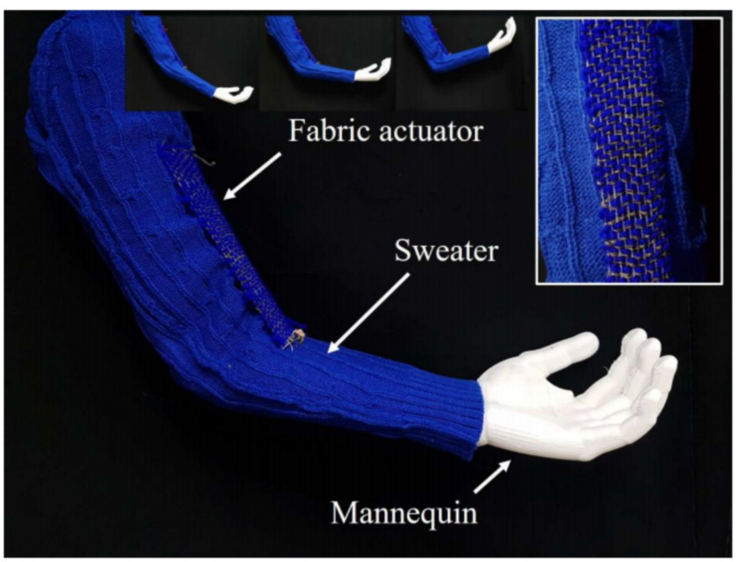

Figure 4: Spandex TCP woven into a fabric to actuate a mannequin arm thermally [12]

Another burgeoning area are TCP actuators embedded in an elastomer substrate. This variation uses normal TCP actuators with a conductive coating to provide length contraction, but due to being surrounded by a flexible substrate, the actuator achieves motion in multiple modes. This design thereby allows the actuator to deform in multiple dimensions rather than only axial deformation.

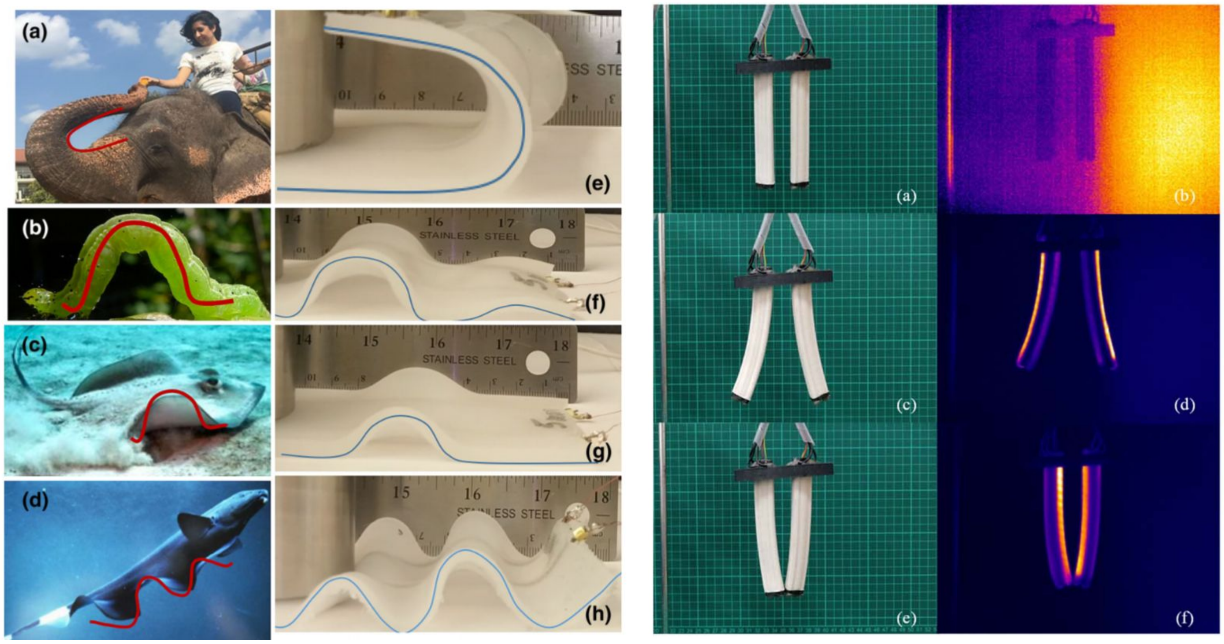

Figure 5: TCP actuators embedded in an elastomer substrate in a planar fashion(left)[1] and in a radial orientation (right) [8]

General applications of these actuators are biomimetic to replicate organic motions found in nature. Observed in the research, ripples caused by length contraction of the actuator could be used to create an undulating motion similar to caterpillars and eels. By using embedded TCPs in marine application, the surrounding water can act as a heatsink and aid in heat dissipation and the frequency of actuation. Deformation of the embedded TCPs allows the actuator to conform to non-uniform objects, which could enable the actuators as grippers as seen in Figure 5. Another benefit of using silicone is in bio-compatible applications, due to silicone having approval for medical implants.

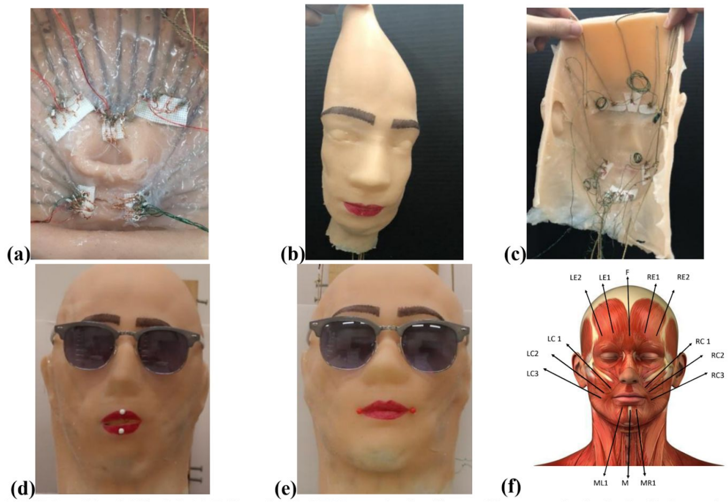

Figure 6: TCP actuators embedded in a humanoid silicone face to replicate facial muscles [2]

Biomimicry in the form of human expression was also researched with TCPs to replicate facial expressions as an alternative to the pneumatic and bulky actuators currently used. In particular, human jaw muscles and facial muscles were replicated. The facial muscles were embedded in a thinned silicone solution. Although less efficient than traditional methods, the space required for the actuators is significantly reduced [2].

Due to these actuators being implemented in controlled applications, an important feature of TCPs is their self-sensing ability. A self-sensing actuator is capable of determining outputs based solely on the intrinsic properties of the material. Twisted and coiled polymer actuators are also highly linear which makes them easily controllable, unlike shape memory alloys. There has been several research groups focused on the controlling actuation and modeling the system dynamics. An example being an anti-windup compensator that was designed and implemented on TCPs to aid in the use of an integrator during saturation. The modeling component of TCPs is focused on determining how deflection, force, and temperature are related to electrical impedance. Through measuring the resistance and inductance of the coils, accuracy of the estimations are averaged to be 0.8%, 7.6%, and 0.5% for estimating respectively deflection, force and temperature [11].

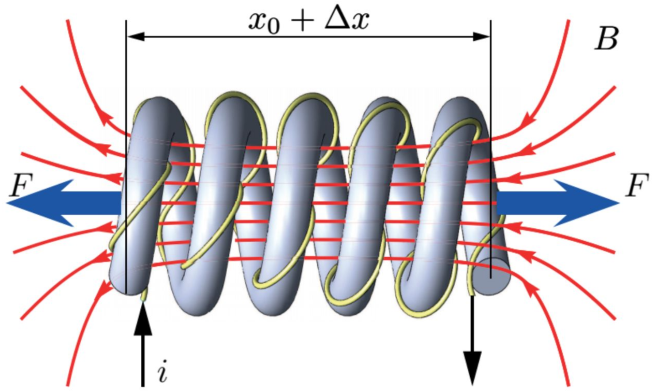

Figure 7: Electrothermal model of TCP actuators, producing force F upon heating [11]

Unsolved Problems

Twisted and coiled polymer actuators have many benefits associated with their fabrication, intrinsic properties, and functionality, as compared to similarly applied technologies, like shape memory alloys/polymers. Unfortunately, there are also several disadvantages that must be discussed to develop a wholesome understanding of this rising technology. First and likely most significant, heat dissipation is a major problem that has somewhat of a trickle-down effect, impacting a variety of different parameters relevant to the optimal functionality of these actuators.

First, as mentioned previously, joule heating is the primary actuation method for TCPAs. This heating process is relatively slow in causing actuation, especially compared to the pneumatic and hydraulic methods that other soft actuators feature. The slow cooling is due to the fact that the primary heat transfer mode for standard TCP actuators is convection in air. As can be seen in Figure 8, the actuator reaches the desired actuation temperature after approximately 140 seconds and takes another 160 seconds to cool to within ten degrees of the original temperature. This time-intensive process leads to unfavorable results, like low actuation frequencies. Although increasing the temperature within the TCPAs can be time-intensive, decreasing the temperature is really where the main issue is focused. Due to the nature of the twisted part of these actuators, effective heat transfer can be limited. For example, in the instance of woven TCPAs, heat transfer at the center fiber can be seriously limited. Since there are other surrounding fibers that are also very hot, dissipating the heat (radially) can yield long cooling times, again decreasing the frequency with which these actuators can be operated.

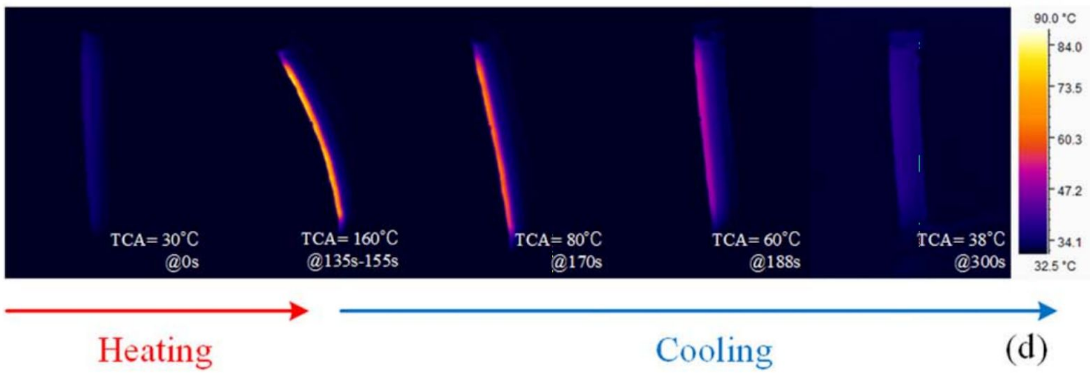

Figure 8: Thermal representation of an embedded TCP actuator [8]

Another issue that TCPAs face is low efficiency. Nylon fibers have been operated experimentally at efficiencies up to 1.08% and polyethylene fibers up to 1.32% [3]. This is comparable to shape memory polymers, but is still significantly lower than even human muscle, which is in the 20% realm. While TCPAs do have features that may offset this downside, it is still an important consideration that needs to be understood, especially when there is a desire to use these in applied scenarios. Next, TCPAs also suffer from a variation of hysteresis. Under normal operating conditions, this is of relatively low concern because TCPAs have lower hysteresis than many comparable actuators (in the range of less than 1.2 degrees Celsius [3]). Despite this, there has been some interesting research conducted on a relatively new phenomenon. When the load weight and applied temperature are changed, hysteresis is suddenly a major problem and can severely affect the typically robust controls for these actuators. To be more specific, the research group that is investigating this phenomenon describes it below:

"If a TCPF [TCP fiber] is operated in a state of a constant load, the equilibrium position does not change before and after heating. However, after the load weight is changed, the equilibrium position changes just after heating, compared with before heating. The temperature-dependent hysteresis has also been observed at temperatures below the glass transition temperature" [9]

This is of concern and still needs to be addressed because changes to two parameters, even within the allowable temperature operating limits, can cause changes that will negatively impact the reliability of control systems that are established.

Finally, high temperatures are required to output the desired strains for these TCP actuators. This compounds the problem of heat dissipation, but can have other implications as well. There is a lot of promise for the implementation of these actuators within wearable technologies. Unfortunately, when the fibers reach 160 degrees Celsius, for example, this cannot be in contact or even very near to human skin. This leads back into what is a major problem for these actuators - they operate at high temperatures and are difficult to cool down. There have been efforts made to improve heat dissipation through enhanced modes like forced convection and finned surfaces to improve conduction. Figure 9 shows an encapsulated TCP actuator that uses forced liquid convective cooling to improving dissipation, but still faces various challenges.

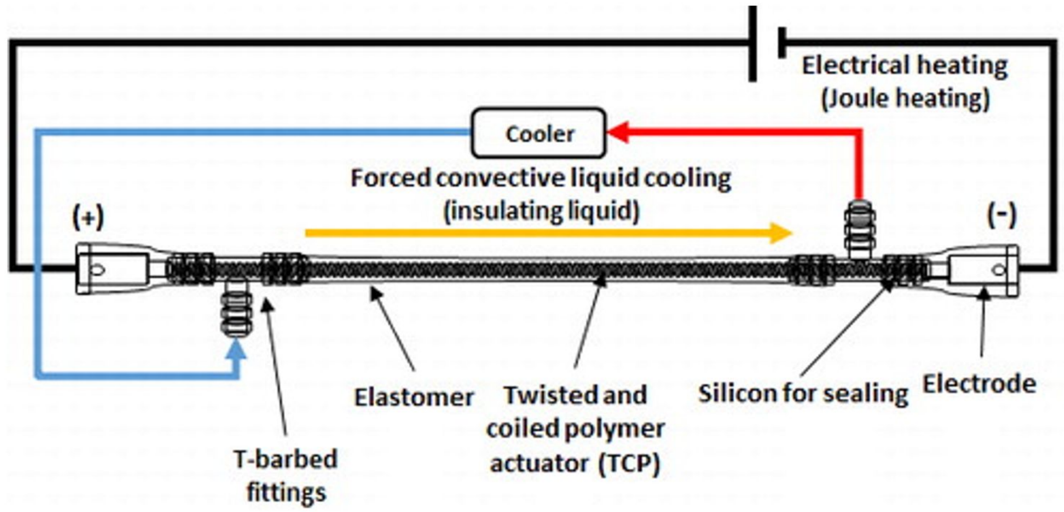

Figure 9: Forced convective cooling of an embedded TCP actuator [6]

With that said, the main problems associated with TCP actuators are derived from the rate at which heat dissipation can be achieved. This is a problem, but with further research and development into improved heat transfer methods and mechanisms, this problem can be solved, or at least mitigated. Once this is done, TCPAs will be near the forefront of actuator technology and will have far reaching benefits to a variety of different systems, both research and industry related.

Proposed Research

Twisted and coiled polymer actuators have many advantages, including low cost and high force characteristics. Their main problem is their low efficiency and frequency of activation. These both stem largely from an inability to effectively and efficiently cool these polymer actuators. This problem is exacerbated in embedded TCPs. This is due to the fact that the elastomers that these actuators are commonly embedded in form an insulating layer between the actuator and the cooler environment (air) which is typically utilized for cooling. Embedded TCPs have high potential, and finding a solution to cooling them will help advance the field and allow other research groups to focus their efforts on applications.

Our research will consist of fabricating embedded actuators, implementing various cooling schemes with them, and measuring their performance. The cooling methods to be tested include:

1. Increasing surface area for convection
    a. Fin structures (on elastomer or in contact with TCP)

    b. Perforating elastomer (allowing air to contact TCP)
2. Liquid cooling
    a. Liquids flowing across TCP within elastomer (forced convection)
    b. Liquids only contacting elastomer (submerged)
3. Electrical cooling (Peltier, Seebeck)
    a. Main components on surface of elastomer with fins reaching TCP
4. Increasing the heat dissipation of the TCP into the elastomer
    a. Modifying surface of TCP
    b. Using thermally conductive materials between TCP and elastomer
5. Other methods found in Phase 1 research

The research project will consist of 4 phases. These are summarized in Figure 10. Phase 1 will consist of research and setup of manufacturing process/test apparatus. All the TCPs that will be used will be manufactured by us. We will be creating TCPs out of nylon fishing line. We will be utilizing a motor for twisting and coiling the nylon, as well as an oven for annealing. After the actuator is annealed it will be coated in a very thin layer of silver. These actuators will be cycled until their un-actuated length remains constant between tests (~20 actuations). The actuators are now ready to be embedded. This process will consist of placing the TCPs into molds, and silicone will be cast around them. These molds will be 3D printed to achieve complex geometries (internal cavities, fins, perforations, etc.). This is the basic manufacturing process that will be utilized for nearly all techniques. Some alterations may be made to this manufacturing process to benefit the cooling characteristics of specific methods, such as thicker or thinner silver coatings and tubes for water/air flow. While the manufacturing techniques are being prototyped, research will be conducted into other techniques/methods of heat dissipation. These results will be added to the list of cooling methods to be tested. Leading researchers will also be contacted to obtain input on cooling methods that may be tested and what additional data may be pertinent. An initial test platform will also be developed. This will consist of a stand, power sources, and weights. The embedded TCPs will be hung vertically with various masses hung from the ends.

Actuator testing will begin in phase 2. The second phase will largely utilize only the manufacturing techniques described above, with few improvements made to increase cooling. The general testing will be as follows.

1. Hang (fully cooled) embedded TCP from stand
2. Add specific weight to TCP according to desired performance
3. Heat TCP to 170C, recording power required
4. Maintain TCP at 170C for specific duration
5. Activate cooling mechanism

6. Record length, power draw and temperature required to cool actuator to 99% initial length
7. Repeat test for various weights hung from TCPs, time maintaining hot temperatures, and repeated cycles.

As mentioned in part 5 above, this testing procedure will be repeated for various weights, wait times, and cycles. The values of these 3 parameters will be changed as follows.

Weights (lbs)	Time maintained at 170C (seconds)	Cycles
0	0	1
10	60	10

All of these parameters will be varied independently, resulting in 8 tests for each cooling method. This means that every combination of the 3 variables, each with 2 values, will be tested. 0 weight, 0 time, 1 cycle will be tested, then will be 0 weight, 0 time, and 10 cycles, and so on until all 8 permutations are covered. This may seem excessive, but any correlations between variables will be found through this testing. This data will be very useful when determining the best cooling method for a specific application, as force and frequency of actuation vary greatly for different applications. The testing will be automated to increase the ease of testing and increase the accuracy and consistency of results. The tests will be automated using a position sensor, thermal camera and power consumption measurement tools. The thermal camera will be used to evaluate average temperature of actuator as well as to find temperature deviations for optimization purposes. The data recorded from these tests will include:

- Weight added
- Cycle number
- Initial position
- Power required to heat TCP
- Time maintained at max temperature
- The following variables will be recorded continuously during cooling
    - Length
    - Temperature
    - Net power required

All of this data will be utilized in later phases to compare cooling methods and search for potential optimizations of the TCPs. These datasets are only preliminary, and may be changed from feedback acquired in phase 1.

Phase 3 will be an extension of phase 2. In this phase, the preliminary data already captured will be analyzed to search for potential optimizations. Small changes in the shape of the elastomer substrate can drastically change the performance of the actuator [1]. These optimizations will largely be in the manufacturing processes. These optimizations will be made iteratively, with rounds of testing to justify changes. At the conclusion of phase 3, all of the cooling methods will have extensive amounts of data for various forces and duty cycles.

Phase 4 will consist of compiling the results of all testing, analyzing the data, and creating documentation. We expect to find one cooling method that outperforms the others in efficiency, but loses in speed. We also expect to find that our updates to the manufacturing processes can increase speed and efficiency by over 10%. This is because small changes to a system can have huge changes in heat transfer rates and efficiencies. We also expect to find that specific cooling methods outperform others in other areas, including cooling under increased force, cooling from longer actuation periods, and cooling for repeated actuations. Out research findings will include a cost-benefit analysis for each of the cooling methods that will be tested.

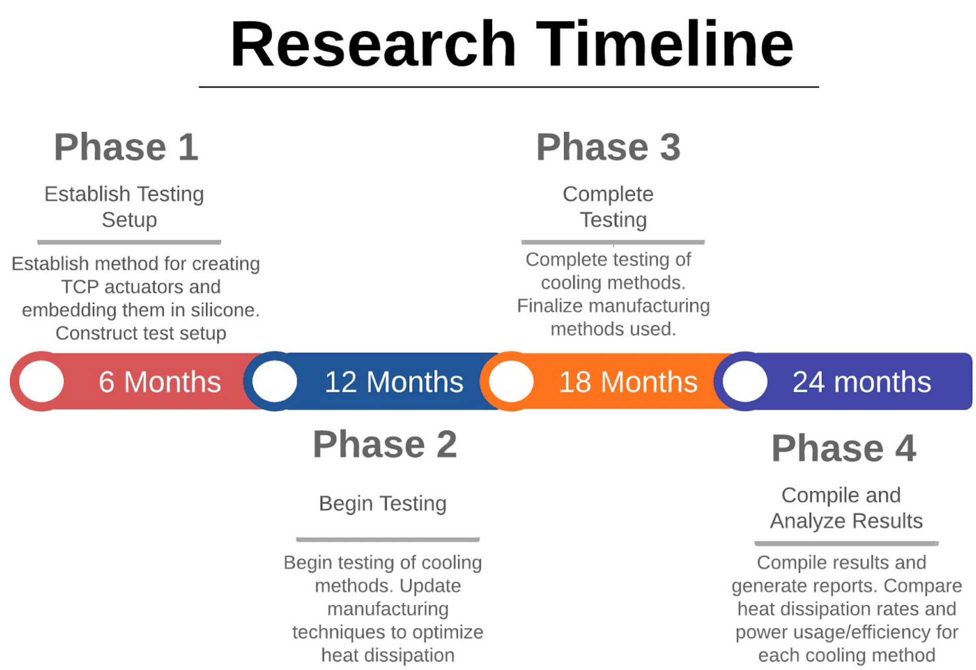

Figure 10: Research timeline, detailing the major goals of each phase of the project.

Another major advantage of the research we are proposing is that it could discover subtle optimizations that could be applied to all TCPs, even non-embedded actuators. For instance, our research might find that TCPs are most efficient in the middle of their actuation range. This would be easily discovered in testing, as power draw is recorded constantly during the cooling procedure. This could lead actuators to be used mainly in this mid-range, potentially increasing efficiencies by 20% while decreasing net strain by 20% as well. Another example is that some cooling methods could cause repeated heating or actuation to require more power, such as liquid cooling. This example may be obvious, but many similar examples likely exist and have yet to be discovered. These kinds of results can only be discovered with testing like we have suggested above.

Cooling of embedded TCP actuators is a subject that has almost no published research behind it. Our group hopes to produce a document that will be used by future research groups so that they do not have to do their own research into cooling. They will be able to look at our results and choose the appropriate cooling method and associated manufacturing process for their application. This will hopefully increase the number of groups working in this field by decreasing barriers to entry, and increase the progress that all groups can make. We will provide a strong starting point that future groups can jump off from, hopefully accelerating the field.

Soft actuators have a huge amount of promise. TCPs are an incredibly cheap and high powered actuator, and when embedded in elastomers the list of potential applications skyrockets. The main problem facing TCPs is in cooling. This influences their efficiencies and achievable frequencies of actuation. With major improvements in cooling and greater knowledge in the field about the benefits of various cooling methods, TCPs could become quite a competitive actuator, specifically in applications such as electronic skin and cheap robotic hands. We hope that our research can help to accelerate the field of soft actuators. This will benefit society in countless ways, including cheaper, easier to control prosthetics, passive blinds, the list goes on. TCP actuators, including embedded TCPs, have numerous applications, many of which will positively benefit society.

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