A compliant gripper with integrated twisted-coiled polymer muscles

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**A COMPLIANT GRIPPER WITH INTEGRATED
TWISTED-COILED POLYMER MUSCLES**

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**SCHOOL OF MECHANICAL AND AEROSPACE
ENGINEERING**

2019

A COMPLIANT GRIPPER WITH INTEGRATED TWISTED-COILED POLYMER MUSCLES

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A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirement for the degree of
Master of Engineering

2019

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ABSTRACT

The field of soft robotics has emerged as a viable complement to conventional industrial robotics. Soft robotics does not displace industrial robots from their traditional roles, but extends the benefits of robotic technology into fields where traditional robots have proven inadequate. The foundation of a robot's 'softness' is derived from its structure and actuation mechanism(s). The twisted coiled polymer (TCP) artificial muscle, discovered in recent years by Haines, has shown promise as a potential solution to the actuation needs of such soft robots.

This study aims to characterise the properties and behaviour of TCP actuators, and the precursor fibres used to make them. To that end, a twist insertion rig and a heating element winding device were built to fabricate Joule heated TCP actuators while a tensile actuator test rig was constructed for the characterisation work. An optimal heating element insertion method was identified through testing; the TCPs thus produced are capable of maximal strokes of 27%, matching the best performance of even TCPs without inserted heating elements. In a first such study, the effect of fibre draw ratio on TCP performance was investigated and the results presented.

Based on the foundation work conducted, the specifications for a demonstrator which highlights the unique strengths of TCP artificial muscle were laid down. An intrinsically powered compliant gripper design capable of multiple degrees of freedom motions was chosen to demonstrate the close integration of a network of lightweight artificial muscle with an adaptive structure. A breakdown of the design thought process, as well as the analytical basis for the design features which serve as the building blocks for the compliant gripper, is detailed in this report.

The compliant gripper was 3D printed in PETG and successfully assembled with the TCP muscles. The gripper comprises a parallel opening/closing jaw and a rotating jaw. The gripper is submitted to gripping tests and the results are presented.

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Chapter 1 INTRODUCTION

1.1 Background

The contemporary image of the modern working Robot is one of industrial complexes filled with rows of Robotic arms working tirelessly on assembly lines. Driven by electrical motors that are highly geared, modern industrial robots are heavy, bulky and stiff machines that possess the potential to inflict significant harm on human workers and their surroundings in the event of accidental contact.

In contrast, the emerging field of soft robotics has evolved as an offshoot from traditional Robotics. ‘Soft’ implies a softness or pliability that is inherent in the machine’s structure and actuators. Table 1.1 summarizes the key differences between hard, stiff robots and softer compliant machines, from an applications standpoint.

Table 1.1 Differences between stiff and soft robots, from an application standpoint

Problems associated with hard stiff robots	Potential solution offered by soft robots
Dangerous to human workers. Must operate within demarcated zones. Can damage itself or environment in event of collision.	A soft robot with pliable structure, joints and actuations will not injure a human in the event of inadvertent impact. Soft robots will be lightweight, further mitigating risk of injury.
Unable to operate in unstructured environments where obstructions in workspace are not prescribed or may vary dynamically with time in a random manner.	A soft robot can take advantage of its flexible deformable structure to adapt to variable conditions and continue to function, within reasonable limits
Unable to match compliance to work. For example, manipulate soft structure items like fragile objects, food and perishables etc	Soft robots can utilise its lower actuator/body stiffness to match the compliance of the workpiece.
Lacks sufficient dexterity to perform in or access highly constrained or geometrically challenging spaces.	Flexible snake-like, trunk-like and tentacle-like robots can be designed to reach deep within an accident zone or parts of the human body.
Typically heavy and bulky.	Soft robots are comparatively lighter in weight.
Energy wasted on deceleration, as noise and heat.	Energy generated in deformation of elastic structures or actuators can be partially recovered.

1.2 Soft Actuators as Artificial Muscles

In tandem with the growth of soft robotics, there has been an increasing focus on the development of soft actuation mechanisms. It is no coincidence that researchers' attention has been drawn to animal muscle, as nature has turned out numerous designs that exemplify the very qualities so desired in soft robots.

Beyond merely providing an actuation force/torque, animal muscles are inherently soft, can act as a store of recoverable elastic energy, vary its stiffness or even double as sensing devices. Increasingly, the term 'artificial muscle' is being used as a generic label for new classes of devices that mimic the behaviour, size and form factor of musculotendon muscle fibre. Madden et al. [1] provides an excellent overview of such artificial muscles. Huber et al. [2] proposes a methodology based on performance indices for selecting actuators that best fit the required application.

Three of the more successful and researched devices, to which the term 'artificial muscle' has been associated with, are the McKibben Pneumatic device, Dielectric Elastomers and Shape Memory Alloy (SMA) devices. Key performance characteristics of these artificial muscles are benchmarked against mammalian muscle, in Table 1.2.

Table 1.2 Key performance parameters of major muscle types. [1]

	Mammalian Muscle	Dielectric Elastomer	SMA	Pneumatic [3]	Twisted Coil [4]
Strain %	20-40	20-100 (typical)	5 (typical)	50	10 – 25
Stress (MPa)	0.1(sustained)- 0.35	0.3 (typical) - 3.2	200 (max)	0.7	20 – 50
Work Density (kJ/m ³)	8 - 40	10 (typical)	1K (typ.) - 10k	175	2800
Specific Power (W/kg)	50 - 284	500 (cont) – 5k	1000 (typ.) - 50k	400 – 5k	12,000
Efficiency %	up to 40	25 (typical) - 80	< 5%	90	1.0 - 1.5
Modulus (MPa)	10 - 60	0.1 - 1.0	20 - 83		
Actuation	Chemical	Voltage (>1kV)	Heat	200-500 kPa	Heat

In particular, polymeric artificial muscles (reviewed by Mirfakhrai et al. [5]) capable of generating reversible large strains with useable stress from molecular level transformations hold the greatest promise for future soft robotic applications.

In 2014, Haines et al. [4] revealed the development of a new type of linear artificial muscle fabricated using twisted and coiled precursor polymeric (TCP) fibres from commercial fishing lines and sewing threads. The TCP is capable of a relatively long stroke, good actuation stress, scaling and miniaturization flexibility, as well as a muscle fibre like form factor.

1.3 Motivation

This research is motivated by the desire to advance the understanding and development of artificial muscles that meet the actuation needs of soft robotic applications. Existing artificial muscles are hampered by difficulties that currently limit their application beyond research hallways.

Dielectric elastomers require high voltages (which precludes its adoption in devices that come in contact with people), possess a large footprint from its planar form and are difficult to fabricate. McKibben actuators require a heavy external compressed air source and suffer from nonlinearities in its behaviour. Shape Memory Alloys suffer from high material cost, large hysteretic behaviour, low strain and bandwidth limitations from cooling time when used as reversible actuators.

On the other hand, TCP actuators are fabricated from low cost lightweight precursors, and possess a form factor most similar to animal muscle fibres. It can be thermally actuated by forced convection (or conversely cooled) or via Joule heating from entwined heater wires.

At the same time, it experiences viscoelastic and creep behaviour like all polymeric muscles. Just like shape memory alloys, actuation bandwidth is constrained by the cooling time. These limitations must be minimised and mitigated in order to harness the full potential of this unique artificial muscle.

Since 2014, more than 50 research papers have been published on the TCP. However, research into this type of artificial muscle is still very much in its infancy and many gaps in the knowledge exist in modeling, control as well as effective thermal activation of the TCP.

Finally, existing research into artificial muscles has not adequately considered the application and proper integration of the muscle unit with its transmission mechanism. The proper design of such strain induced actuators should take into account its geometry, mechanical properties and primary operating mode (tensile, bending etc) in order that it may be seamlessly integrated with its host structure.

1.4 Objectives and Scope

The objectives of this research are to characterise the properties and performance of the TCP artificial muscle and its precursor filaments, and to use these muscles to actuate a compliant gripper as a demonstration of the TCP actuator's capabilities.

Experimentally characterise the mechanical properties of the precursor monofilaments used to fabricate the TCP actuators for testing. Design and construct suitable test rigs to determine the thermomechanical and thermoelectrical behaviour of the TCP. Establish the fabrication and processing parameters that optimise TCP performance.

Demonstrate the functional capabilities and versatility of the TCP by developing a multi-mode compliant gripper driven by integrated, intrinsic TCP muscles.

1.5 Organisation of the Report

The contents of this report are organized as follows -

Chapter 2 is a literature review on the fundamental properties of the precursor polymer filament, the fabrication and processing, as well as the operating principle of the TCP actuator.

Chapter 3 covers the theoretical models of twisted fibres and TCP actuators.

Chapter 4 describes the test equipment and the experimental setup used to characterise the TCP actuator.

Chapter 5 reports the results of isotonic, isometric and dynamic response tests for TCP actuators made from nylon 66 monofilaments of different draw ratios.

Chapter 6 provides the background to the application of linear artificial muscles and its integration with compliant structures. The design of the compliant gripper via the building block method is described next. Finally, the fabricated gripper is tested and the results are presented.

Chapter 2 LITERATURE REVIEW

Understanding and harnessing the full potential of the TCP is a truly multi-disciplinary endeavour. The unique morphology of drawn polymers, when combined with thermally activated entropic elasticity of the molecular tie chains results in anisotropic thermal expansion/contraction of polymer fibres. Twisting and coiling such fibres create a nested helical structure that can produce large linear contractile strokes with temperature increase.

The following sections are an overview of the literature survey spanning different fields of science and engineering that aids the understanding of the TCP artificial muscles.

2.1 Twisted Coiled Polymer (TCP) Actuators

The Twisted Coiled Polymer (TCP) actuator is a unique artificial muscle created through inserting extreme twist into commercially available, inexpensive polymer fibres like fishing line or sewing thread. This is the most recent development in the field of soft artificial muscles. The discovery of the unique properties of the TCP actuator was attributed to Haines et al. [4].

The basic polymer fibre from which the TCP actuator is constructed, is the starting point for understanding how this coiled muscle works. These precursor fibres are manufactured with specific molecular chain alignment profiles to improve tensile strength in the axial direction. An unintended effect of this processing is that the drawn filament can possess a highly orthotropic thermal expansion profile with widely varying and even opposite polarity thermal coefficients in the primary axial and radial directions.

By twisting these drawn fibres, the constituent polymer chains are forced into a helical orientation within the still straight fibre. To visualise this configuration, Haines described a simple exercise in

which a single untwisted nylon monofilament is marked with a red line along its length. This line establishes the original direction of the cold strained polymer chains.

Twisting the nylon displaces this line into a helical surface pattern as shown in Fig. 2.1. Polymer chains within the fibre are similarly twisted from their original linear arrangement into helically oriented chains. The parameter α_f indicates the bias angle, or degree of shift in the polymer chains. This angle varies from zero at the centre of the fibre to its maximum value at the fibre surface.

Figure 2.1 Twisting of polymer precursor fibre. [4]

Oriented polymer chains are known to exhibit negative thermal expansion in their drawn direction. Haines has shown a simple nylon fishing line can contract up to 5% when heated. When such a fishing line is twisted, it now displays a new phenomenon - a reversible temperature linked untwist.

In a twisted filament, untwist occurs when (a) the filament contracts in length with its diameter constant, (b) the filament diameter expands while the length is constant. In other words, untwist is possible in any material with sufficient thermal anisotropy. In the case of nylon, thermally induced radial expansion is accompanied by simultaneous axial contraction, thereby magnifying the untwist and actuation stroke.

Continued twisting of the nylon filament eventually results in coiling and formation of a helical polymer spring. This coiling enables the thermally activated fibre untwist to be converted into the tensile stroke of the TCP. Fig. 2.2 depicts how such a twisted coil can be used to generate large linear contractions.

Figure 2.2 Working principle of the TCP Muscle

Haines et al. [4] tested a variety of polymer filaments for suitability as use for TCP muscles. Fig. 2.3 shows the tensile strokes obtained for different polymeric fibres over the range of working temperatures.

Figure 2.3 Comparison of the negative thermal expansion of braided polyethylene, nylon 6 monofilament, nylon 6,6 monofilament, and silver-coated nylon 6,6 multifilament fibres before twisting (inset) and after coiling by twist insertion. [4]

2.2 Oriented Polymer Fibre Morphology

In order to understand the basis for the negative expansion coefficient of oriented polymeric fibres, a basic appreciation of the morphology and structure of drawn semi-crystalline fibres must first be attained.

At present, there is still no all-encompassing model of the oriented semi crystalline polymer morphology that predicts all behaviours of oriented fibres completely. The first model was based on a fringed micelle theory attributed to Lindenmeyer [6], but it was soon deemed inadequate when polymeric chains were observed to form folded lamella like structures. Melt crystallized polymers showed such lamella structures growing outward in a spherulitic fashion.

Hearle [7] proposed an improved fringed fibril morphology, shown in Fig. 2.4(B), where fibrils are assumed to be long, imperfect, possibly branched crystals made up of comparatively short segments of the long-chain molecules packed together. Any one long-chain molecule will pass alternately through a number of crystalline fibrils and through the non-crystalline regions between them.

Figure 2.4 (A) Fringed micelle structure. (B) Fringed fibril structure in oriented polymer [7]

When subjected to unidirectional drawing and necking, the lamella structures are pulled out of the crystalline zones and aligned in a shish kebab structure. Peterlin [8] described a 2 phase microfibrillar model of transformation of lamellar structures into microfibrils during the drawing process, as illustrated in Fig. 2.5. Prevorsek et al. [9] proposed a Swiss cheese model shown in Fig. 2.6 for nylon 6, which differs from the microfibrillar model in the location of the origins of the interfibrillar tie

molecules and their volume fraction change during drawing. Prevorsek also assessed differently the role played by the structure of the microfibrils and the matrix in determining the fibre properties.

Figure 2.5 Transformation of lamellar in the microfibrillar structure by fracturing the initial lamellae in blocks which are incorporated in microfibrils. [8]

Figure 2.6 Three phase Swiss cheese model [10]

Bukošek and Prevorsek [10] compared the applicability of Peterlin's 2 phase and Prevorsek's 3 phase model for nylon 6. A more contemporary treatment by Breese and Beaucage [11] reviews the different modeling approaches for semi-crystalline polymers. Ward and Sweeney [12] provides a broad treatment of polymer morphology and their associated mechanical properties.

Figure 2.7 Structure of a highly oriented semi-crystalline polymer. (C) Chain-folded crystal blocks; (B) crystalline bridges; (A) amorphous region; (TM) tie-molecules [13]

As shown in Fig. 2.7, crystalline zones alternate with amorphous regions in the drawn direction. Crystalline bridges may span the crystalline zones, thus forming a combined crystalline shorter-range structure. As the polymer chains are typically much longer than the lamella dimensions, a single molecular chain can traverse through more than one crystalline and amorphous region.

The sections of chains that connect 2 crystalline zones are named tie molecules. These sections play a critical role in determining the structural strength and elastic behaviour of the drawn polymer. They are also responsible for the unique anisotropic lengthwise contraction of semi-crystalline polymer filaments.

Predating the discovery of the TCP by Haines by decades, the negative thermal expansion of polymer fibres is a well-known phenomenon that has been observed and studied by various researchers. Most of the research have described the negative thermal expansion of the polymer crystal lattice but it is the behaviour of the molecular tie chains spanning the crystalline blocks that provides the large contractions driving the TCP. The seminal paper by Choy et al. [13] offered the clearest yet explanation of this phenomenon. Referring again to Fig. 2.7, the interaction between crystalline bridges and tie molecules play a key role in this thermal behaviour.

Below the glass/rubber transition temperature of a polymer, both crystalline bridges and tie molecules cooperate in restraining the deformation and expansion of the amorphous regions. This leads to the high tensile modulus in the draw direction, typical of oriented polymer fibres. However, above the transition temperature, a significant divergence in properties of both regions begin to emerge. Tie molecules acquire sufficient thermal energy to attain more probabilistically likely chain conformations, but are restrained by the crystalline bridges which maintain its high moduli until close to the melting temperature of the polymer.

The elasticity of elastomers and polymers is made up of an energetic and entropic component as described by Mark et al. [14]. Stress induced deformation of the strong covalent bonds in the polymer backbone increases the internal energy of the polymer network. Upon release of the external stressor, strain recovery of the polymer is considered energetic elasticity.

Entropic elasticity works on the basis of the proclivity of freely jointed polymers chains to assume a statistically more probable conformation. To illustrate this conceptually, a straight or extended chain has statistically one possible conformation whereas a curved chain has more conformations and the wrinkled and crumpled chain has the most (see Fig. 2.8). A polymer chain is therefore more likely to assume a wrinkled contractive state (higher entropy) than a straight chain (lowest entropy).

Figure 2.8 Simple line model of polymer molecular chains. From left to right - lowest molecular conformations to highest.

With the addition of sufficient thermal energy to the polymer, the tendency of the tie molecules to contract begin to overcome the restraining crystalline bridges, which are then energetically deformed. On lowering of the temperature, the crystalline bridges begin to recover their original form and in the process, stretch the tie molecules again. This is the basis for the reversible thermal contraction of the polymer fibre. The contraction of various fibres from the Haines et al. [4] study is shown in Fig. 2.9.

Figure 2.9 Negative thermal expansion measured by TMA [4]

In this work, TCP will be made from nylon 6 and (mainly) nylon 6,6 monofilaments. The work of Hadley et al. [15], Leung et al. [16] and Demsar et al. [17] established elastic moduli of oriented nylon 6,6 with respect to draw ratio and moisture content. This data serves as a starting point and reference for characterisation of the nylon precursors, as well as for modeling and predicting TCP behaviour.

2.3 TCP Research

Subsequent to the publication of Haines et al. [4], other researchers have added to the literature with more than 50 papers on the TCP muscles published. This section reviews the work started by Haines and built upon by others.

The starting point of Haines' kinematic description of the TCP is the elastic theory of the helical spring by Love [18], where $\Delta\phi$ is the change in twist, D is the coil dia. and α_c is the coil bias angle between fibre and the coil cross section. Primed variables are the final values.

$$\Delta\phi = \frac{\sin(\alpha'_c) \cos(\alpha'_c)}{\pi D'} - \frac{\sin(\alpha_c) \cos(\alpha_c)}{\pi D} \quad (1)$$

For a coil of N turns and length L made from a fibre of length l (assumed constant), Haines predicts the change in coil length L from change in fibre twist via

$$\Delta\phi = \frac{N \Delta L}{l^2} \quad (2)$$

As N remains constant in a tethered coil, the change in twist is linearly related to change in coil length L . A more general equation (Haines et al. [4] supp. Material page 6) showing the relationship between twisted fibre length l , diameter d , length of twisted molecular chains λ , bias angle α_f (relative to fibre axis) and fibre twist ϕ is

$$\frac{\Delta\phi}{\phi} = \frac{\Delta\lambda}{\lambda} \frac{1}{\cos^2\alpha_f} - \frac{\Delta d}{d} - \frac{\Delta l}{l} \tan^2\alpha_f \quad (3)$$

Early TCP researchers focused on the phenomenological and experimental aspects of the TCP. Cherubini et al. [19] performed an isothermal and isometric characterization of the TCP. Kianzad et al. [20] modeled the TCP on the basis of its modulus and measured the change of elastic modulus with

temperature/frequency, as well as the effect of load on stroke (see Fig. 2.10). Murin et al. [21] performed an experimental and numerical analysis of the TCP.

Figure 2.10 A) Variation of elastic modulus with temperature, B) with frequency [20]

Other researchers focused on the thermal generation of twist and torque from the twisted fibre itself. Aziz et al. [22] modeled the torsional actuation of a twisted (but not coiled) muscle using a single helix approximation of the twisted molecular chain on the outer surface of the fibre, as shown in Fig. 2.11. Their model assumed fibre and molecular chain lengths remained unchanged while radial expansion is taken to the sole cause of the TCP contraction.

Shafer et al. [23] adopted a different approach; their model accounting for the axial contraction and radial expansion of the fibre. Unlike Aziz, the Shafer model allowed for differing molecular chain bias angles which vary with the fibre radius as illustrated in Fig. 2.11(C).

Swartz et al. [24] compared both the Aziz and Shafer Models and offered a modification to the Shafer model by averaging the radial variation.

Figure 2.11 Single helix chain geometry, (A) before actuation, and (B) after actuation. L = fibre length, l_s = length of wrapped string, d = fibre dia., and n = amount of twist, α_f =helix bias angle. Zero subscripts represent the initial state [22]. (C) Variable helix chain bias angle with radial distance from axis.

While useful, kinematic models do not provide a physical explanation for the driving force behind the contractile behaviour of the TCP. A mathematical model for the relationship between the coupled tensile force and twisting moment driving the deflection of the TCP coil is needed.

To this end, Yang and Li [25] carried out a multi-scale modeling of the actuation response of the TCP. Their macro scale model establishes the deflection of the TCP in terms of the recovered torque M_{rec} and modulus of the coil, while at the meso scale, they derived a thermomechanical relationship between the temperature increase and recovered torque M_{rec} . This is achieved by considering the twisted fibre itself (not the coil) to be a concentric helically anisotropic laminate and performing a composite laminate analysis to derive the elastic coefficients.

Tang et al. [26] performed a finite element analysis of the TCP and compared the results to the macro and meso scale analytical models developed by Yang and Li, with good agreement found between the analytical and numerical data, as shown in Fig. 2.12.

Figure 2.12 Comparison between FEA and analytical model [26]

The multiscale models, while comprehensive, are unwieldy and difficult to compute. Abbas and Zhao [27] proposed instead a macro scale physics-based model that captures the relationship between temperature, force and displacement of the TCP.

Other researchers, with an eye towards developing control schemes for the TCP, focused on the thermo-mechanical and thermo-electrical models whose parameters are obtained through system identification methods, Arakawa et al. [28] used a black box approach to model a first order system while Oiwa et al. [29] developed a grey box model of the TCP. Yip and Niemeyer [30] proposed a linear 2nd order spring, mass, damper system. Finally, Mendes and Nunes [31] adopted a novel experimental investigation of the thermomechanical behaviour of the TCP by the digital image correlation method (DIC) to extract full-field displacements from images of the coiled fibre. This is shown in Fig. 2.13.

Figure 2.13 Actual displacement of fibre during thermal actuation [31]

2.4 Demonstration of TCP capabilities

Researchers have been looking at the application of the TCP in various robotic devices. Wu et al. [32] modeled the kinematics of the human hand and utilised the TCP on a robotic hand, shown in Fig. 2.14. Yip and Niemeyer [30] developed a 3D printed robotic hand (see Fig. 2.15). Sutton et al. [33] designed an wrist orthosis powered by TCP and Bahrami and Dumond [34] built a spastic hand exoskeleton.

Saharan and Tadesse [35] developed a robotic hand with locking mechanism, while Cho et al. [36] worked on yet another a robotic finger. It is clear the favourable form factor of the TCP has inspired many researchers to incorporate them into robotic arms/hands/fingers. However, the use of the TCP to drive mechanisms akin to discrete joint cable driven systems merely employs them in traditional robotics and does not harness the full potential of the TCP.

Figure 2.14 Compact humanoid hand powered by nylon artificial muscles [32]

Figure 2.15 Robotic hand using TCP as the actuation mechanism, with integrated fans [30]

Pawlowski et al. [37] recognised this shortcoming in the current research. By embedding the TCP within a soft substrate body to generate distributed actuation, they created a gripper which skillfully integrates the TCP with a soft robotic mechanism, as shown in Fig. 2.16.

Figure 2.16 Fully embedded TCP actuator in soft gripper [37]

In a similar vein, Li et al. [38] conceptualised a trailing edge mechanism driven by TCP. Similar with TCP embedded within soft matter, the TCP behaviour is coupled with the compliance of a flexible base spine and skin.

The last 2 examples are better platforms for representing the potential of the TCP. On this note, the next section reviews prior work in using thin aspect ratio actuators similar to TCP, for use with driving soft or flexible structures.

2.5 Shape Morphing and Beam Shaping

SMA wires have a form factor similar to TCP and have decades of accumulated research in its use as actuators. Much of the proof of concept models are again traditional discrete joint robotic designs. A much smaller fraction of these designs are coupled soft mechanisms, which can be further grouped into three categories.

- 1) Embedded within and bonded to structure.
- 2) Free running within sleeve bonded to surface or encased in structure.
- 3) Externally connected to discrete points on structure.

Rodrigue et al. [39] developed a (category 1) SMA based soft composite structure that is capable of multiple modes of operation, as shown in Fig. 2.17.

Figure 2.17 Embedded SMA actuators, Rodrigue et al. [39]

Kim et al. [40] proposed a (category 2) soft morphing hand driven by SMA wires inserted in sleeves bonded to the surface (see Fig. 2.18). This allows the actuator to deform independently from the structure and the force is primarily directed through the actuator mount points, rather than distributed all along its length.

Figure 2.18 Surface bonded actuators, [40]

Category 3 applications are most common and employs external mounted muscles to bend the beam structure by means of the tilting of forces. This is called the tilt buckling configuration described by Simitses and Hodges [41]. Examples of such applications are shown in Fig. 2.19.

Figure 2.19 Beam bending and shaping with external actuators, (A) [42] , (B) [43]

Chaudry and Rogers [44], [45], [46] performed extensive theoretical work on the bending and shape control of beams using various strain induced actuators like SMA wire. The driving principle behind these controllable beams is the tilt buckling motion. While buckling is highly undesirable in structural load bearing members, they can be useful in generating large motions in compliant structures.

The above categories of artificial muscle and structural integration serve as building blocks for adaptive structures. In the words of Wada et al. [47] these are structures with integrated actuators that enable the alteration of system states or characteristics in a controlled manner. Wada's classification framework for smart structures is shown Fig. 2.20.

Figure 2.20 A=integrated actuators, B=integrated sensors, C=integrated actuators+sensors, D=integrated control, E=integrated electronics [47]

TCP possess the qualities useful for not only adaptive structures but also possibly controlled structures. Weijde et al. [48] investigated self sensing TCP that can report deflection, force and temperature.

In adaptive structures, control of morphing sections offer a potential avenue for utilising TCP muscles. Forster and Livne [49] describes such a concurrent synthesis of host structure and strain actuated devices for aerospace structures, which are flexible and deform under variable flight loads.

Trease and Kota [50] suggested a framework for the concurrent design of compliant mechanisms with embedded actuators and sensors, as illustrated in Fig. 2.21. To better differentiate systems with actuators actually embedded and bonded within the structure (category 1), this work proposes use of the term ‘integrated’ instead. This includes actuator installations of all 3 categories, with the additional requirement that the actuators are intrinsic, or residing within the envelope or boundary of the system.

Figure 2.21 A compliant mechanism with embedded distributed actuation [50]

2.6 Remarks

In this section, the primary publications introducing the working principle of the TCP artificial muscle and its underlying oriented polymer fibre morphology are presented.

Next, further research performed by other researchers since the publication of Haines et al. [4], is reviewed. These researches mostly focus on physical understanding of the behaviour of TCPs, with the aim of expanding upon the limited kinematic model proposed by Haines et al. [4]. A number of physics based models and black box models have arisen from this research activity.

Additionally, early TCP researchers have constructed various robotic models to demonstrate the application of TCP muscles. As of late 2018, there have been 6 papers detailing robotic hands and fingers actuated by TCPs in antagonistic cable drive configurations. Pawlowski et al. [37] deviated from this trend by embedding the TCP within a soft substrate to create a soft TCP gripper. In a similar vein, Li et al. [38] employed the TCP to drive a flexible spine. Compared to the former, the latter two works are more representative of true soft robotic design principles.

A similar situation has developed with other soft artificial muscles, which are frequently deployed in cable driven systems with rigid links. To obtain a clearer view on possibilities of soft actuation of true compliant structures, the literature survey is expanded beyond the nascent field of soft robotics into the subjects of structural beam shaping and morphing structures.

From this literature review, 3 gaps in the research have been identified. First, the increasing number of TCP models needs to be reviewed, compared and classified. Chapter 3 of this report will provide an overview and classification of important TCP theoretical models.

Secondly, researchers have been using commercial off the shelf fishing lines for TCP research without regard to their different draw ratios of manufacture. This work includes a first such study on the correlation between draw ratio and TCP performance.

Lastly, the unique potential of the TCP to be scaled down in size and deployed in large numbers has not been adequately recognised by researchers thus far. To this end, a multi-mode compliant gripper powered by integrated TCP actuators, and capable of compounded multiple DOF motion will be designed and used to demonstrate the capabilities of these versatile artificial muscles.

Chapter 3 THEORY OF TWISTED COILED POLYMERS

There are 3 mathematical approaches to a concise description of TCP behaviour; (1) Kinematic models, (2) Static models and (3) Dynamic models. Kinematic models are useful for showing the geometrical parameters and relations of the twisted and helical coil; as well as predicting the displacements. The relevant equations have been briefly treated in the literature review.

Static models based on physical principles offer the most succinct elucidation of the fundamental behaviour of the TCP. The dynamic models are typically phenomenological models with parameters obtained through system identification and experiments.

Finally, no study of TCP actuators is complete without a basic understanding of polymer viscoelastic behaviour, with its time, temperature and rate dependent characteristics.

3.1 Static Models of TCP

TCP artificial muscles belong to a class of actuators called induced strain transducers, which include dielectric elastomer, shape memory and piezoelectric transducers. As explained in section 2.2, temperature change drives the anisotropic expansion of the polymer chains which have been twisted into helical arrangements within the fibre.

This strain in the helical structure generates stress, which can be computed via the constitutive relations and continuity/boundary conditions. This resultant stress in the TCP manifests itself as a recovered torque and can be used to determine the linear output stroke of the TCP coil. The different aspects of modeling TCP are graphically depicted in Fig. 3.1.

Figure 3.1 Mathematical modeling of TCP actuation

Once the temperature field is known, the relevant coefficients of thermal expansion (CTE) can be applied to the anisotropic twisted structure to determine the resulting strain. Different methodologies to modeling this anisotropic twisted structure have been adopted. Among the kinematic approaches, the simplest is the 1D single helix representation proposed by Aziz et al. [22]. This is based on the assumption that the twisted molecular chain (wrapped around the surface of the fibre) length remains constant while the radius of the fibre undergoes thermal expansion (see Fig. 2.11). This single helix is taken to represent the entire assembly of molecular chains in the fibre, whose twist Φ can be computed from the kinematic relations and simplified to

$$\frac{\phi}{\phi_0} \approx \sqrt{\frac{Vol_0}{Vol}} = \frac{d_0}{d} \quad (4)$$

$$\Delta\phi = \phi_0 - \phi = \phi_0 \left(1 - \frac{d_0}{d}\right) \quad (5)$$

where d is the diameter of the fibre, l is the molecular chain length and Vol is the cylinder volume. Aziz then derives the maximum torque (blocked) when the twisted fibre is constrained from rotating,

$$\tau_{blocked} = \Delta\phi \frac{\pi d^4 G}{32 l} = \frac{\pi d^4 G \phi_0}{32 l} \left(\frac{d_0}{d} - 1\right) \quad (6)$$

where G is the shear modulus. The single helix representation is a gross simplification as the molecular chains are twisted to different bias angles depending on their radial position. In contrast, Shafer et al.

[23] accounts for this helix angle variation in his model, as well as allowing for both axial and radial expansion of the fibre - see Fig. 3.2.

Figure 3.2 Geometry changes in twisted fibre before and after heating. The 2D element illustrates the shear, axial and tangential strains caused by temperature increase. Radial (r), tangential (θ), axial (z) and molecular chain coordinates (1 and 2 directions) are shown. [23]

In the virgin (untwisted) fibre axis, ϵ'_{11} is the strain in the axial direction and ϵ'_{22} is the tangential (or transverse) strain. Using coordinate transformation, the respective twisted fibre direction thermal strains can be found as follows –

$$\begin{Bmatrix} \epsilon^t_{\theta} \\ \epsilon^t_z \\ 0.5\gamma^t_{z\theta} \end{Bmatrix} = \begin{bmatrix} \cos^2\alpha & \sin^2\alpha & -2\cos\alpha\sin\alpha \\ \sin^2\alpha & \cos^2\alpha & 2\cos\alpha\sin\alpha \\ \cos\alpha\sin\alpha & -\cos\alpha\sin\alpha & \cos^2\alpha - \sin^2\alpha \end{bmatrix} \begin{Bmatrix} \epsilon^t_{11} \\ \epsilon^t_{22} \\ 0 \end{Bmatrix} \quad (7)$$

Simplifying, Shafer derives

$$\epsilon^t_{\theta} = \frac{\epsilon^t_{11} x^2 + \epsilon^t_{22}}{1 + x^2} \quad (8)$$

$$\epsilon^t_z = \frac{\epsilon^t_{22} x^2 + \epsilon^t_{11}}{1 + x^2} \quad (9)$$

$$\gamma^t_{z\theta} = 2(\epsilon^t_{11} - \epsilon^t_{22}) \frac{x}{1 + x^2} \quad (10)$$

where the non-dimensional initial twist $x = \frac{r\phi_0}{L}$

As shown in Fig. 3.2, untwist of fibres is related to $\gamma_{z\theta}^t$ via

$$\frac{\Delta\phi_r}{L} = \tan \gamma_{z\theta}^t \approx \gamma_{z\theta}^t \quad (11)$$

Therefore, untwist can be found,

$$\frac{\Delta\phi}{\phi_0} = \frac{(\varepsilon_{11}^t - \varepsilon_{22}^t)}{1 + x^2} \quad (12)$$

Swartz et al. [24] modifies the Shafer equations by performing an area weighted average over the fibre cross section

$$\overline{\Delta\phi} = \frac{\int_A \Delta\phi dA}{\int_A dA} = \frac{2\pi \int_0^{R_0} \Delta\phi r dr}{\pi R_0^2} \quad (13)$$

Substituting into

$$\overline{\Delta\phi} = 2(\varepsilon_{11}^t - \varepsilon_{22}^t) \frac{\ln(\phi_0^2 + 1)}{\phi_0} \quad (14)$$

The above are 3 derivations of fibre twist. The only unknowns are the untwisted fibre thermal strains ε'_{11} (axial) and ε'_{22} (transverse). Both values can be determined experimentally or from literature. External loads are not considered so these are essentially zero load predictions of twist versus temperature.

In order to predict the actual fibre torque, the constitutive matrix of the precursor fibre must be ascertained. Based on the work of Pipes and Hubert [51], Yang and Li [25] proposed a mesoscale model which divides the fibre into a series of concentric helically anisotropic laminae, as shown in Fig. 3.3.

For axisymmetric radial deformation, shearing twist, and uniform axial extension, displacements are functions of radial and axial coordinates only.

Figure 3.3 Concentric multi-layer analysis and nomenclature [25]

Thus,

$$u = u(r), \quad v = v_0 r z, \quad w = w_0 z \quad (15)$$

Mechanical Strains are

$$\epsilon^r = \frac{du}{dr}, \quad \epsilon_\theta = \frac{u}{r}, \quad \epsilon_z = w_0, \quad \epsilon_{z\theta} = v_0 r, \quad \epsilon_\theta = \epsilon_{rz} = 0 \quad (16)$$

Equilibrium equation to be satisfied,

$$\frac{d\sigma_r}{dr} + \left(\frac{\sigma_r - \sigma_\theta}{r} \right) = 0 \quad (17)$$

The familiar constitutive material compliance matrix from composite theory

$$\begin{Bmatrix} \sigma_z \\ \sigma_\theta \\ \sigma_r \\ \sigma_{z\theta} \end{Bmatrix} = \begin{bmatrix} \bar{C}_{11} & \bar{C}_{12} & \bar{C}_{13} & \bar{C}_{16} \\ \bar{C}_{12} & \bar{C}_{22} & \bar{C}_{23} & \bar{C}_{26} \\ \bar{C}_{13} & \bar{C}_{23} & \bar{C}_{33} & \bar{C}_{36} \\ \bar{C}_{16} & \bar{C}_{26} & \bar{C}_{36} & \bar{C}_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_z - \alpha_z \Delta T \\ \epsilon_\theta - \alpha_\theta \Delta T \\ \epsilon_r - \alpha_r \Delta T \\ \epsilon_{z\theta} - \alpha_{z\theta} \Delta T \end{Bmatrix} \quad (18)$$

where the effective (fibre direction) CTEs are transformed from the molecular chain CTEs by,

$$\begin{Bmatrix} \alpha_z \\ \alpha_\theta \\ \alpha_r \\ \alpha_{z\theta} \end{Bmatrix} = \begin{bmatrix} m^2 & n^2 & 0 & -mn \\ n^2 & m^2 & 0 & mn \\ 0 & 0 & 1 & 0 \\ 2mn & -2mn & 0 & m^2 - n^2 \end{bmatrix} \begin{Bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ 0 \end{Bmatrix} \quad (19)$$

Combining Eqns. 16 & 18, and substituting into Eqn. 17 yields a 2nd order ODE. Solving for displacement

$$u = C_1 r \sqrt{\frac{\bar{C}_{22}}{\bar{C}_{33}}} + C_2 r - \sqrt{\frac{\bar{C}_{22}}{\bar{C}_{33}}} + \frac{r(\bar{C}_{12} - \bar{C}_{13})}{(\bar{C}_{33} - \bar{C}_{22})} w_0 r + \frac{(\bar{C}_{26} - 2\bar{C}_{36})}{(4\bar{C}_{33} - \bar{C}_{22})} v_0 r^2 + \frac{(\bar{C}_{13} - \bar{C}_{12})}{(\bar{C}_{33} - \bar{C}_{22})} \alpha_z \Delta T r +$$

$$\frac{(\bar{C}_{23} - \bar{C}_{22})}{(\bar{C}_{33} - \bar{C}_{22})} \alpha_\theta \Delta T r + \frac{(\bar{C}_{33} - \bar{C}_{23})}{(\bar{C}_{33} - \bar{C}_{22})} \alpha_r \Delta T r + \frac{(\bar{C}_{36} - \bar{C}_{26})}{(\bar{C}_{33} - \bar{C}_{22})} \alpha_{z\theta} \Delta T r \quad (20)$$

where C_1 and C_2 are constants of integration to be determined.

Next, multi-layer analysis for a N layered multi cylinder imposes continuity of radial stress and displacement at the N-2 lamina interfaces and including the boundary conditions, allows the constants C_1 and C_2 (and subsequently $C_3, C_4, \dots, C_{2N}$) to be solved. Thereafter, the thermoelastic strains $\varepsilon_\theta, \varepsilon_z, \varepsilon_r$ & $\varepsilon_{z\theta}$ can be obtained directly.

To determine the effective thermoelastic constants α_θ, α_z & $\alpha_{z\theta}$ which are required for the analysis, Pipes & Hubert adopted a relaxation method by first expressing the desired resultant torque and force in terms (via influence coefficients A, B, C & D) of axial strain (w_0) and shearing strain/radius (v_0)

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{Bmatrix} v_0 \\ w_0 \end{Bmatrix} = \begin{Bmatrix} \tau_{step} \\ F_{step} \end{Bmatrix} \quad (21)$$

where the effective thermal torque τ_{step} and force F_{step} per temperature step change ΔT is

$$\tau_{step} = 2 \int_{R_0}^R \sigma_{z\theta} \pi r^2 dr, \quad F_{step} = 2 \int_{R_0}^R \sigma_z \pi r dr \quad (22)$$

Next by setting v_0, w_0 and ΔT to appropriate values, the influence coefficients are determined,

$$\begin{aligned}
A &= \tau, & \text{with } v_0 &= 1, & w_0 &= 0, & \Delta T &= 0 \\
C &= F, & \text{with } v_0 &= 1, & w_0 &= 0, & \Delta T &= 0 \\
B &= \tau, & \text{with } w_0 &= 1, & v_0 &= 0, & \Delta T &= 0 \\
D &= F, & \text{with } w_0 &= 1, & v_0 &= 0, & \Delta T &= 0
\end{aligned} \tag{23}$$

The effective CTEs are then obtained

$$\alpha_z = \frac{w_0}{\Delta T}, \quad \alpha_\theta = \frac{u_0}{R\Delta T}, \quad \alpha_{z\theta} = \frac{v_0 R}{\Delta T} \tag{24}$$

The total recovered torque at a certain temperature is then

$$M_{rec} = \int_{T_0}^T \tau_{step} dT \tag{25}$$

Yang and Li's analysis is more exact than Shafer's as each concentric cylinder is constrained at the interfaces while the latter allows the layers to deform independently from each other. However, the analysis is complex and involves many parameters.

Abbas and Zhao [27] proposed a simpler, and more direct derivation for M_{rec} . The primary assumption is that axial contraction is negligible compared to radial expansion and is thus ignored, so the Aziz formulation forms the basis for their analysis. Applying torsion mechanics (where J is the 2nd moment of inertia of the twisted fibre, γ is the shear strain and σ is the shear stress)

$$\gamma = \frac{d\Delta\phi}{2l}, \quad \sigma = \frac{d\tau}{2J} \tag{26}$$

to Hooke's Law and Eqn. 5, leads to

$$M_{rec} = \frac{GJ\phi_0 \left(1 - \frac{d_0}{d}\right)}{l} \tag{27}$$

with d being the only unknown. By utilizing the effective transverse CTE for the twisted fibre,

$$\alpha_{trans} = \left(\frac{d}{d_0} - 1 \right) \Delta T \quad (28)$$

and substituting into Eqn. 28, leads to

$$M_{rec} = \frac{G \phi_0 \pi d_0^4 (1 + \alpha_{trans} \Delta T)^3 \Delta T \alpha_{trans}}{32l} \quad (29)$$

which is a more direct expression for fibre torque, requiring only the effective shear modulus G and effective transverse CTE to be known beforehand.

With the thermally activated fibre torque M_{rec} known, the final stage of analysis is to translate this torque M_{rec} into TCP coil contraction/extension, which gives the actuator stroke at load.

From the spring mechanics theory for open coil springs (Wahl [52]), deflection of the helical coil due to an axial load is computed from the deflections accruing from the torsion and bending moment of each wire element that makes up the helix. Integrating the element term over the length of the wire gives the expression for coil deflection.

$$\delta = PR^2 s \left(\frac{\cos^2 \alpha}{GI_p} + \frac{\sin^2 \alpha}{EI} \right) * \beta \quad (30)$$

$$\text{where } \beta = l + \frac{3 \left(\frac{d}{2R} \right)^2}{16 \left[l - \left(\frac{d}{2R} \right)^2 \right]}$$

For a close coiled spring where bias angle is small, Eqn. 30 reduces to the well known

$$\delta = \frac{64 Pr^3 n}{Gd^4} \quad (31)$$

Eqn. 31 predicts that as the shear modulus G falls with increasing temperature, the spring should extend further. However, a TCP is able to counteract this extension and even contract due to massive fibre untwist on heating.

As the TCP is constrained from rotating during thermal actuation, the cumulative fibre untwist along the entire length of the fibre generates an opposite reaction moment equal to M_{rec} at both ends of the TCP. Therefore, the TCP coil is subjected simultaneously to an axial force and axially directed torque. Using the approach described by Dym [53], Yang and Li [25] applied Castigliano's second theorem to solve for the TCP deflection.

Figure 3.4 (A) Left : TCP loaded with applied force F and recovered torque M_{rec} . Right: kinematic relationship of TCP. (B) The coordinate systems of coiled spring model [25]

Referring to Fig. 3.4, the complementary energy reflecting torsion, bending normal to centreline, transverse shear and axial tension, is given by

$$U^* = \int_0^{L_c} \frac{M_z^2}{2GJ} + \frac{M_\theta^2}{2EI} + \frac{F_z^2}{2EA} + \frac{F_\theta^2}{2GA} dl \quad (32)$$

and as the stress components are constant along the coil,

$$U^* = \left(\frac{M_z^2}{2GJ} + \frac{M_\theta^2}{2EI} + \frac{F_z^2}{2EA} + \frac{F_\theta^2}{2GA} \right) L_c \quad (33)$$

Rearranging,

$$U^* = \frac{1}{2} f_{11} F^2 - 2 f_{12} F M_{rec} + \frac{1}{2} f_{22} M_{rec}^2 \quad (34)$$

where $\bar{E}$ and $\bar{G}$ are the effective moduli of the twisted fibre, and

$$f_{11} = \frac{8n}{\pi^3 d^4} \left(\frac{L_c}{n}\right)^3 \frac{\cos^4 \alpha_c}{\bar{G}} + \frac{8n}{\pi d^2} \left(\frac{L_c}{n}\right) \frac{\cos^2 \alpha_c}{2\bar{G}} + \frac{8n}{\pi^3 d^4} \left(\frac{L_c}{n}\right)^3 \frac{2\sin^2 \alpha_c \cos^2 \alpha_c}{\bar{E}} + \frac{8n}{\pi d^2} \left(\frac{L_c}{n}\right) \frac{2\sin^2 \alpha_c}{2\bar{E}} \quad (35)$$

$$f_{12} = \frac{8n}{\pi^2 d^4} \left(\frac{L_c}{n}\right)^2 \frac{\cos^2 \alpha_c}{\bar{G}}$$

$$f_{22} = \frac{32}{\pi d^4} \frac{L_c}{\bar{G}}$$

Applying Castigliano's second theorem,

$$\begin{Bmatrix} \delta \\ \phi \end{Bmatrix} = \begin{bmatrix} f_{11} & f_{12} \\ -f_{12} & f_{22} \end{bmatrix} \begin{Bmatrix} F \\ M_{rec} \end{Bmatrix} \quad (36)$$

Therefore TCP deflection

$$\delta = f_{11} F - f_{12} M_{rec} \quad (37)$$

3.2 Dynamic Models of TCP

Tracking the TCP state over time requires the use of dynamic models. The most common approach to modeling the real time behaviour of TCP is illustrated in Fig. 3.5.

Figure 3.5 Dynamic response of TCP actuators

The accepted baseline thermo-mechanical model for TCP control is a linear time invariant 2nd order ODE incorporating a spring, mass and damper, as shown in Fig. 3.6(B).

$$mx'' + bx' + k(x - x_0) = F \quad (38)$$

where F is the actuator generated force.

Figure 3.6 (A) Force temperature relation at different strains. (B) Thermomechanical model of actuator under load [30]

First adopted by Yip and Niemeyer [30], this format is amenable for frequency domain analysis of the actuator dynamic response. By observing that the force versus temperature profile is approximately linear and consistent at different strains as illustrated in Fig. 3.6(A), Yip proposed a linear expression of force generated by the TCP, in terms of temperature. The value of c is extracted from the mean value of the experimentally derived force-temperature slope.

Force balance is thus

$$F = k(x - x_0) + c(T - T_0) + b\dot{x} \quad (39)$$

The TCP is treated as an isotropic spring of stiffness k and a (temperature dependent) force generating device, which is convenient for envisioning the deflection of the actuator as two independent modes of action.

In reality, the stiffness of the TCP coil is inextricably linked with the state of twist of the anisotropic twisted fibre at all temperatures. Even if the molecular chains were to exhibit no contraction, the classical spring mechanic equations which were developed for isotropic wires cannot be applied without modification to the twisted anisotropic fibre. However, for control system analysis and design purposes, such black/grey box models are convenient for predicting actuator response.

Next, an electrical analogous thermoelectric model can be constructed by treating the actuator as a capacitor for storing and discharging thermal energy. The RHS represents the heating input and heat flux between the actuator and ambient environment.

$$C_{th} \frac{dT(t)}{dt} = P(t) - \lambda(T(t) - T_{amb}) \quad (40)$$

where C_{th} is the thermal mass of the actuator, $P(t)$ is the heat applied, λ is the absolute thermal conductivity, $T(t)$ is the actuator temperature, and T_{amb} is the ambient temperature. For Joule heated TCP, $P(t)$ will simply be i^2R .

λ represents the overall transfer coefficient accruing from conduction, convection and radiation. For the TCP, convection is the primary and dominant mode of heat transfer with the environment.

3.3 Viscoelastic Behaviour of TCP

TCP actuators exhibit definite viscoelastic behaviour, inheriting these properties from its polymeric constituents. Eqn. 38 adopts a basic Kelvin-Voigt model with a parallel spring and a damper which simulates the flow of a viscous fluid. Actual viscoelastic behaviour, which is time, temperature and rate dependent, is far more complex. A typical deformation of the viscoelastic solid in response to a step change in load is shown in Fig. 3.7.

The same basic spring and damper models used in Eqn. 38 can be combined in various ways to model complex elastic recovery and viscous energy dissipation patterns associated with polymer strain. Particularly for position control applications, hysteresis must also be modeled and catered for.

Figure 3.7 Deformation of a linear viscoelastic solid, [12]

Haines et al. [4] mentioned the need to train or condition the TCP before it can produce repeatable behaviour. Little information is available on why this training is necessary or what condition it addresses, or even how it should be performed.

In his 1941 Thesis, Leaderman [54] described mechanical conditioning of filamentous materials as the process of eliminating secondary creep. Leaderman noted that on the first loading of a nylon filament and subsequent removal of the load, creep recovery is slow and a sizable residual strain will remain

even after 24 hours. Repeating this creep and recovery test however resulted in the subject recovering to its starting length at the beginning of the second test. Further tests at the same or lower loads produced no further residual deformation.

The first or initial tests that are required to eliminate the variability in residual deformation is called the mechanical conditioning process. It must be performed at the highest operating load, in order that subsequent equal or smaller loads applied will allow the filament to consistently recover to its pre-cycle resting length.

In rubbers and rubber like materials, a stress softening effect is experienced whereby the material undergoes a significant softening upon the first loading, as described in Diani et al. [55]. This effect has been known for decades and was first studied extensively by Mullins and co-workers; hence the name ‘Mullin’s Effect’. Li et al. [56] found in their work on tyre cords that nylon 6,6 also exhibits a similar behaviour, which is described as follows :

1. Under cyclic loading, the loading and unloading curves are never coincident; appearing as typical hysteretic stress-strain loops.
2. When strained maximally, significant softening is reported. Most of this softening occurs on the first loading. Subsequent cycles see a convergence of these stress-strain loops and the loading-unloading cycle becomes stable.
3. When a new maximal load exceeding the historical maximum is applied, the material again traverses further up the main stress-strain curve for monotonic loading before experiencing further softening.

Fig. 3.8 illustrates this effect. Residual deformation clearly increases with maximum cyclic stress.

The common theme in Leaderman’s observations and the Mullin’s effect, is the mechanical conditioning that occurs on the initial cycles that stabilizes the material stress-strain behaviour.

Figure 3.8 Monotonic and cyclic loading of nylon 6,6 tyre cords [56]

TCPs exhibit a perplexing phenomenon where anytime the load on the TCP is increased and upon the first heating/actuation cycle, the TCP will assume a longer loaded resting length. Subsequent heating cycles at the same load does not alter the resting length further. However, when the load is reduced, the TCP will shorten its resting length upon the first initial actuation. Again, subsequent actuations produce no more changes.

This means the resting length will continuously vary depending on the loads encountered. If a consistent, or predictable actuator resting position is required then the above behaviour presents a design challenge. This phenomenon is best visualised with actual numbers from ascending/descending loading (see Table 3.1) and random order loading (see Table 3.2) tests of TCP actuators.

Table 3.1 Ascending/Descending loading of TCP fabricated from 0.3 mm nylon 6,6

Load (g)	Initial Resting Length upon loading (mm)	Resting Length after 1 st heating/actuation cycle (mm)	Resting Length after 2 nd heating/actuation cycle (mm)
34	39	40	40
68	43	47	47
87	51	54	54
106	54	55	56
87	54	52	52
68	52	49	49
34	48	43	43

Table 3.2 Random order loading of TCP fabricated from 0.3 mm nylon 6,6

Load (g)	Initial Resting Length upon loading (mm)	Resting Length after 1 st heating/actuation cycle (mm)	Resting Length after 2 nd heating/actuation cycle (mm)
100	47	52	52
50	50	47	46
100	48	54	55
34	51	43	43
84	46	53	53
103	54	55	56

In conclusion, while these non-linear effects cannot be completely mitigated or explained currently, it is evident that the mechanical conditioning or training of polymer actuators at their maximum working load, or even after each load change is critical to ensuring repeatable stress-strain behaviour.

This principle is adhered to in all testing procedures of the TCP actuator performed in this work.

Chapter 4 EXPERIMENTAL SETUP

4.1 Precursor Monofilaments

Although a number of semi-crystalline thermoplastics can be used to make functional TCP actuators, nylon 6 and nylon 6,6 filaments provide the best actuator performance with nylon 6,6 gaining the edge due to its higher temperature limit and stroke. Both materials are widely available commercially as monofilaments for use as fishing lines or sewing threads.

However, such commercial filaments often contain additives and are processed differently, resulting in variations in mechanical and thermal properties across brands. Additionally, commercial nylon 6,6 monofilaments above diameters of 0.3 mm are not widely available for sale in small quantities.

Two monofilaments from the list of monofilaments used in Haines et al. [4] were acquired – a 0.3 mm nylon 6,6 sewing thread and a 0.46 mm nylon 6 fishing line.

In addition, a generic non branded monofilament made from Dupont nylon was found in fishing shops, with a melting temperature close to that of nylon 6,6. More importantly, these filaments are available in a range of sizes from 0.1 mm up to 1.5 mm. Without the uncertainty of unknown parameters such as proprietary processing and material blends, different sizes of this series of filaments can be tested against each other to better understand effects of draw ratio and filament diameter.

Short of possessing the capability to extrude and draw the monofilaments in the lab, this option presents the most economical and practical manner of acquiring a greater range of suitable samples for testing. However, the composition of these filaments need to be ascertained first, which will be focus of the next section.

At this point, a naming convention is introduced to identify the various test filaments. The generic Dupont monofilaments will be identified as GN66-XX, where XX represents the diameter (in multiples of 10 microns).

Table 4.1 Precursor lines used for the fabrication of TCP

P/N	Precursor monofilaments	Commercial source
TRI6	Nylon 6 fishing line 20 lb test (0.46 mm)	Berkley Trilene, 20 lb monofilament
TX66	Nylon 6,6 sewing thread (0.3mm)	Thread Exchange monofilament
GN66-XX	Dupont nylon 6,6 fishing lines 0.35 mm (8 lb), 0.45 mm (10 lb), 0.46 mm (12 lb), 0.5 mm (15 lb), 1.5 mm 65 lb test	Generic non-branded fishing monofilament made from Dupont nylon.

4.2 Characterisation and Identification of Precursor Filaments

This section documents the tests performed on the filaments listed in Table 4.1. As explained in Chapter 3, the primary fibre properties of Young's modulus (axial and transverse), shear modulus as well as CTE (axial and transverse) are often needed in mathematical models used to predict TCP deflection. The GN66 filaments will also be referenced against Dupont's Zytel 101NC010 PA66 resin, which is the likely constituent.

(A) Storage Modulus

A TA Instruments DMA800 Dynamic Mechanical Analyzer was used to measure the storage modulus and loss modulus of 6 test specimens.

1. TRI6 (0.46mm)
2. TX66 (0.3mm)
3. GN66-45
4. GN66-45 dry
5. GN66-46
6. GN66-46 dry

Dry specimens were prepared by heating the filament at 70°C in the convection oven for 24 hours. The results are plotted in Fig. 4.1. The dry specimens display higher storage modulus than their equivalent non-dry samples.

Figure 4.1 Storage modulus (top) and Tan Delta (bottom) data from Dynamic Mechanical Analyzer (DMA) testing

The storage moduli of GN66-45 and the TX66 (0.3mm) are practically indistinguishable while the tan delta profiles are close. TX66 is a known nylon 6,6 monofilament supplied by a commercial sewing thread supplier, so this is further confirmation the generic Dupont nylon filaments are likely made from nylon 6,6.

(B) Draw Ratio

Other than the precursor resin, the draw ratio of oriented filaments also influences the eventual modulus. A number of studies [15], [16], [57], [58] have been performed correlating draw ratio of nylon 6,6 to the moduli, and their studies are summarized in Fig. 4.2.

Figure 4.2 Axial Young's modulus vs draw ratio

The studies in Fig. 4.2 show different axial modulus at draw ratio 1, which is undrawn filament equivalent to isotropic nylon 6,6. This is to be expected given the different nylon 6,6 sources, moisture content and testing regimes. However, the slope of the axial modulus versus draw ratio plot is consistent across all studies at approximately 1 GPa/Draw ratio. Based on this, a predicted curve for GN66 filaments is constructed, with the line crossing the Y axis at 1.4 GPa (which is the modulus of isotropic Zytel nylon 6,6, given per [59]).

The draw ratio for four GN66-XX filaments will be projected from their Young's Moduli using this curve. Young's Moduli of these 4 specimens were measured on an Instron 5569 Tensile Machine, using a strain rate of 10 mm/min up to a maximum load of 5 N. Environmental conditions were 26.5C and 55% RH. The moduli and predicted draw ratio and transverse moduli are summarized in Table 4.2.

Table 4.2 Predicted draw ratio and transverse modulus for GN66 monofilaments

Specimen	Young's Modulus (MPa)	Draw Ratio	Transverse Modulus (MPa)
GN66-35	3075	2.7	1520
GN66-45	1588	1.2	1360
GN66-46	3169	2.8	1540
GN66-50	2125	1.7	1300

(C) Transverse Modulus

The transverse modulus of the GN66 filaments is estimated from experimental data published by Leung et al. [16], corrected for Zytel PA66 and reproduced in Fig. 4.3.

Figure 4.3 Transverse modulus of nylon 6,6

The Poisson's ratio of Zytel is 0.4, taken from Dupont specifications [60]. For the orthotropic filament, the shear modulus can be calculated from

$$G = \frac{E}{2(1 + \nu)} \quad (41)$$

(D) Coefficient of Thermal Expansion (CTE)

From the 1 Hz DMA frequency tests, the thermal expansion data of the filaments are extracted and plotted in Fig. 4.4. The data shows that the dry filaments exhibit lower thermal contraction than the equivalent wet filaments. In fact, the dry GN66-45 filament actually expands (axially) up until 140° C.

This observation agrees with the theory that it is the stretched tie molecules that are responsible for the entropically driven negative thermal expansion in drawn fibres. With the estimated low draw ratio of 1.2 almost approaching that of isotropic nylon, GN66-45 has a much smaller negative thermal expansion than GN66-46 with its estimated draw ratio of 2.8.

The coefficient of thermal expansion (CTE) in the axial direction can then be determined from the derivative of the thermal expansion curves from the DMA tests.

Figure 4.4 Fibre thermal expansion in axial direction

With the GN66 filaments, the largest diameter available was 1.5 mm so the thermal expansion was measured directly with a Mitutoyo Micrometer (resolution 0.001mm). A heat gun was used to heat the filament while the filament temperature was measured with the Optris infrared thermometer. The results of this test are plotted in Fig. 4.5. The data points are fitted with a quadratic curve and the estimated CTE varies linearly with temperature.

Figure 4.5 Fibre thermal expansion in transverse direction

At this point, it is possible to derive the primary mechanical and thermal properties of both GN66-45 and GN66-46 filaments. The parameters for the non-dry specimens are summarized in Table 4.3. The effect of water content of the nylon on TCP performance is significant. Dry nylon has a much higher tensile modulus, higher loss modulus and lower thermal contraction along the axial direction. This suggests the hygroscopic absorption of water may in fact be beneficial, or at least not detrimental for TCP performance. This fact is pertinent, as any nylon exposed to the laboratory or outdoors will in time acquire a sizable moisture content.

Table 4.3 Summary of properties of GN66 filaments and Zytel PA66 resin

	GN66-45 Monofilament	GN66-46 Monofilament	Dupont Zytel PA66 Resin
Tensile Modulus	1588 MPa	3169 MPa	1400 MPa
Transverse Modulus	1360 MPa	1540 MPa	1400 MPa
Shear Modulus	567 MPa	1132 MPa	
Draw Ratio	1.2	2.8	Isotropic
CTE (Axial)	-66 (10 ⁻⁶ /K) @40° C -174 (10 ⁻⁶ /K) @100° C -264 ((10 ⁻⁶ /K) @150° C	-9 (10 ⁻⁶ /K) @40° C -369 (10 ⁻⁶ /K) @100° C -669 (10 ⁻⁶ /K) @100° C	100 (10 ⁻⁶ /K)
CTE (Transverse)	100 (10 ⁻⁶ /K) @30° C 128 (10 ⁻⁶ /K) @100° C 148 (10 ⁻⁶ /K) @150° C	100 (10 ⁻⁶ /K) @30° C 128 (10 ⁻⁶ /K) @100° C 148 (10 ⁻⁶ /K) @150° C	110 (10 ⁻⁶ /K)
Melting Temperature	258° – 265° C	258° – 265° C	262° C

The tensile modulus, CTE and melting temperature of the GN66 filaments are close to Zytel PA66. It is reasonable to conclude that the GN66 fibres are indeed pure nylon 6,6 extrusions.

The shear modulus increases with tensile modulus, based on Eqn. 41. However, Wakelin et al. [57] found that shear modulus is weakly correlated to draw ratio and suggested that drawing increases the shear modulus at the core and not at the surface. Their measured shear modulus for nylon 6,6 at draw ratio 1 is 510 MPa, which is close to the value for GN66-45.

4.3 Twisting and Coiling Setup

TCP coils used in this work are made by the twist insertion method. The twist insertion equipment comprises a lab stand with a vertically mounted motor. The filament to be twisted is clamped at the motor chuck and tied to a linear bearing free to slide on a chrome rod, but unable to rotate (see Fig. 4.6). The bearing weighs 105 g and serves as the minimum coiling load.

During twist insertion, the motor is operated at 60 rpm. This twists the filament in the form of a left-handed helix. The twist insertion load must be large enough to prevent premature snarling of the fibre, but not so large it breaks the fibre during coiling. Weights are attached to the linear bearing as needed.

On completion of coiling, the TCP will uncoil when released from the tether. To relieve the residual stress induced by the twisting and set a permanent helical coil, the TCP is annealed in a Binder ED23 convection oven by heating to 150°C and cooling gradually (< 2 C per minute) to below 100°C.

Figure 4.6 Test stand for fabricating TCP

4.4 Tensile Actuator Characterisation Rig

To characterise the behaviour of filaments and fabricated TCPs, an experimental test rig was constructed. It incorporates measuring instruments listed in Table 4.4. This rig is designed for the following functions :

1. Isotonic testing of TCP muscle stroke.
2. Isometric testing of TCP blocked force at various preloads.
3. Isothermal TCP force – displacement, hysteresis curves.
4. Measurement of coefficient of thermal expansion of fibres.
5. Viscoelastic characterisation of creep and stress relaxation.

Table 4.4 Instrumentation list

	Equipment	Specifications
1	Tensile Actuator Test Rig (TATR)	-
2	Panasonic HG-C1100 Laser Displacement Sensor	Repeatability 70 microns
3	Optris LS infrared thermometer	Measurement spot 1mm@62 mm Resolution 0.1° C, Accuracy $\pm 0.75^\circ$ C Response time 0.15 sec
4	HP-5 Force Meter	Resolution 0.001 N Accuracy ± 0.025 N
5	NI Data Acquisition USB6001	ADC 14 bit, Max sample rate 20kS/sec

Temperature measurements of the TCP are made with the Optris infrared thermometer, which has a close focus mode that allows a 1 mm temperature measurement spot at an exact focal length of 62 mm.

Friction and stick-slip behaviour of the linear guide can severely affect the accuracy of test rig. The linear guide was completely disassembled and adjusted to minimise friction. Eventual deviation (due to friction) between a loaded weight and the force meter readout is less than 0.05 N.

Fig. 4.7 shows the assembled tensile actuator test rig. The laser target is mounted on a linear guide. It is connected via stiff Kevlar fibres to the TCP on one end and to the tensioning weight on the other. Extension or contraction of the object under test is translated into a corresponding displacement of the laser target. The laser displacement sensor is positioned to measure the displacement of the laser target.

Figure 4.7 Test rig for characterising tensile actuators

4.5 Winding Insertion of Heating Element

In this experiment, the TCP is heated by electrical Joule heating. The heating element is a 100 micron nichrome 80 wire. To ensure proximity of the heating element with the TCP without impeding its deformation, the heating element must be wound around the fibre. This can be accomplished in 2 ways : twisting/coiling a pair of monofilament and heating wire in parallel, or first winding the wire around a straight monofilament before mounting on the twist insertion rig for coiling.

To wind the heating element, a heating element winding rig, shown in Fig. 4.8, was constructed. It comprises 2 reversible worm-gearbed 12V DC motors that are mounted facing each other. By supplying opposite polarity power, the motors rotate the attached filament about its own axis.

Figure 4.8 Heating wire winding rig

4.6 Evaluation of Winding Method

In the research literature, no mention is made of the pitch angle when winding the heating element around the straight filament, or the effect of this parameter on the performance of the eventual TCP. A test was designed to shed some light on this issue by testing TCP wound at different pitch angles, as well as TCPs produced simply by forced twisting the wire and filament in parallel.

The filament used in this test was TRI6 (0.46mm) nylon 6. By varying the insertion pitch angle of the heating element, 5 TCP specimens with different element wrapping patterns were produced, as shown in Fig. 4.9. The properties of the specimens are shown in Table 4.5.

Figure 4.9 TCP coils – (A) Bare TCP, (B) Directly twisted and coiled with heating wire, (C) 45° insertion, (D) 50° insertion, (E) 60° insertion.

Table 4.5 Specimen properties for heating element winding tests

Specimen	Description	Heater pitch	Result
A	Bare TCP		Reference
B	Filament/Heater twisted in parallel		Gnarly coils, irregular winding
C	30° feed angle of heater wire	2.4 mm	Minimal distortion of coil
D	50° feed angle of heater wire	1.2 mm	Visible distortion of coil
E	60° feed angle of heater wire	0.8 mm	Gnarly and compacted coils

During twisting specimen E broke repeatedly. The compactness of the heating wire winding likely overstressed the nylon during final writh formation. During the heating test, specimen B failed prematurely at around 7 V of applied voltage.

The unloaded length of specimen C = 32 mm and specimen D = 31 mm. To attain a roughly equivalent power input of approximately close to 4.5W, a 13.6V and 15V square wave DC voltage was supplied respectively to specimens C and D, and the results plotted in Fig. 4.10.

Figure 4.10 Isometric comparison test with specimen C (top) and specimen D (bottom)

Next, the 2 specimens were tested for contraction stroke test under isotonic load (186 g). Results are shown in Figs. 4.11 and 4.12.

Figure 4.11 Contraction stroke for specimen C

Figure 4.12 Contraction stroke for specimen D

Specimen D achieved a slightly better blocked force than specimen C under isometric tests. Under isotonic loading, specimen D produced a maximum stroke of approximately 4.5mm versus 3mm for specimen C, at the same temperature. The response of specimen C was also slower with a lag of about 4 sec. when power was removed.

A more compact winding of the heating element achieved better heat transfer efficiency with a better actuator stroke, which agrees with intuition. However, the upper limit for the heating wire feed angle appears to be around 50-55 degrees, beyond which the coils were compacted, stiff and more likely to fail during the coiling process.

Based on the results of this experiment, all further TCP produced in this work are wound with heating elements fed at a 50 degree pitch angle.

4.7 Summary of Chapter

The properties of a generic monofilament (GN66 series) made from Dupont nylon were identified and found to be very similar to Dupont's Zytel PA66. These nylon 6,6 monofilaments can now be used for further experimentation without doubts about their composition.

To support the fabrication and characterisation of fibres and TCP, a twist/coiling rig, a heating element winding rig and a tensile actuator test rig were constructed and used for all the TCP characterisation exercises described in this research.

Finally, the optimal heating element insertion method was identified and implemented in all the heated TCP actuators fabricated in this work.

Chapter 5 CHARACTERISATION OF TCP ACTUATOR

This section describes the experimental work performed on the TCP actuator to characterise its primary properties. By using 2 precursors of roughly similar diameter in GN66-45 and GN66-46, the size effect is disregarded and the effect of draw ratio of the fibre on the behaviour of the TCP can be studied in isolation.

TCP design rests, first of all, on selecting the right polymer fibre with the most appropriate anisotropic thermal expansion profile. Next, the spring index (defined as the ratio of TCP coil to fibre diameter) can be used to increase actuator stroke at the expense of force, and vice versa. Lastly, fibre diameter scales with actuator force but it is difficult to coil fibres of diameters above 0.5 mm into TCP. Draw ratio is an important parameter of oriented polymers but there has not been any research on its effect on TCP performance. This study aims to obtain a preliminary understanding of draw ratio on TCPs.

Two reference TCP actuators are fabricated under conditions listed in Table 5.1. The manufactured actuators are shown in Fig. 5.1. Test conditions in the laboratory are ~ 25-26° C and 50-60% relative humidity.

Table 5.1 Parameters of the two reference specimens

Parameters	Test TCP 1	Test TCP 2
Precursor filament	GN66 (0.45 ±0.003 mm)	GN66 (0.46 ±0.005 mm)
Filament Draw Ratio	1.2	2.8
Length	200 mm	
Heating element	0.1 mm Nichrome 80 wire	
Coiling Load	215 g (13.25 MPa)	215 g (12.68 MPa)
Turns to coil	173 (865 T.m ⁻¹)	158 (790 T.m ⁻¹)
Annealing Load	209 g	
Annealing temperature	150° C for 30 mins, cool to 100° C @ -1° C/min	
Post anneal unloaded length	46 mm	43 mm
Spring index	2.2	2.2
Fibre bias angle	~ 30 degrees	~30 degrees
Coil Modulus	60 MPa	80 MPa
Conditioning	Exposed to RH% 78 for 12 hours before testing

Figure 5.1 (A) GN66-45 fibre bias angle (magnified 100X), (B) GN66-46 fibre bias angle (magnified 100X), (C) Fully coiled GN66-45 TCP, (D) Fully coiled GN66-46 TCP

5.1 Actuator Stroke versus Temperature

The first task in characterising the TCP actuator is to establish the displacement stroke over the working temperature range. The TCP are conditioned at each load change by loading and unloading the weight 2 times before the eventual loaded length is set. This length is used to compute the stroke. The load is varied always in the ascending order, as changing the order will result in a different reading.

To illustrate the importance of conditioning the polymer, the difference in performance of a non-conditioned and conditioned TCP actuator is shown in Fig. 5.2. After just one cycle of conditioning the GN66-45 (test 2) shows vastly improved stroke.

After annealing, the TCP will have had substantial moisture expelled from the fibres, so each TCP actuator is conditioned by exposing to it outdoor humidity (>70% RH) for 12 hours prior to testing. Fig.

5.2 shows the maximum stroke attainable by heating the TCP up to 200° C. Water has a plasticizer effect on nylon, which appears to be similar to that of increasing the spring index.

At nominal stresses (wrt fibre diameter) below the minima (maximum contraction), the stroke of the TCP actuator is limited by coils contacting. Both specimens show nearly identical stroke profiles in this range. The maximum stroke of ~27% is achieved at ~10.5 MPa. The key difference is that GN66-45 levels off to a near constant stroke of 22% while GN66-46 is able to maintain contractions of 25%.

Figure 5.2 Left - Contraction (stroke) of TCP actuator at different loads. Right – Variation of contraction profile vs load with spring index, from [4]

What is not shown in Fig. 5.2 is that GN66-46 is able to maintain this stroke at up to 16.5 MPa or higher without suffering permanent deformation while the GN66-45 will yield at this load. The maximum stress was limited to below 14 MPa to avoid damaging the reference units.

Nylon 6,6 has a melting point of 262° C so heating the TCP up 230°-240° C is possible, but it is easy to subject the TCP coil to irreversible deformation at the higher temperatures (and loads) so a temperature limit of 200° C was set for this test. This implies that even greater strokes than 27% are possible for this TCP had it been driven to the limit.

Fig. 5.3 shows the variation in contraction of the TCP actuator at different temperatures. The nominal stress applied was 10 MPa (163g for GN66-45 and 170g for GN66-46). Both GN66-45 and GN66-46 behave similarly in generating most of the working stroke (20%) from 100° to 200° C. From room temperature to 100° C, the TCP contracts only about 5 %.

It is no coincidence that the negative thermal (axial) expansion and the positive transverse expansion of the nylon fibre also begins to increase significantly above 100° C. The thermal expansion data from section 4.2 is reproduced in Fig. 5.3, next to the TCP contraction chart. The correlation between TCP working stroke and fibre axial contraction and transverse expansion is clear.

Figure 5.3 Left – Contraction over working temperature range, Right – Thermal expansion of nylon in axial and transverse directions.

Interestingly, although the GN66-46 fibre itself has a much stronger axial contraction due to its higher draw ratio, its eventual TCP contraction is lower than that of GN66-45. Recalling the work of Aziz (Eqn. 5), Shafer (Eqn. 12) and Swartz (Eqn. 14), Aziz considers only transverse expansion while Shafer and Swartz adds the axial and transverse expansions in equal measure, for the untwist computation.

5.2 Dynamic Response Tests

GN66-45 and GN66-46 specimens are tested for their dynamic response, as well as the effect of assisted convection cooling (by a fan). The GN66-46 TCP actuator will be used as the baseline for comparison; its time response to a step input voltage of 10V is shown in Fig. 5.4.

Figure 5.4 Time response of GN66-46 TCP actuator

The response speed of GN66-45 and GN66-46 is compared by loading both actuators at 10 MPa and heating with a 3 sec square wave pulse of 15 V. Cooldown time is 30 sec. Results of this test are shown in Fig. 5.5.

Figure 5.5 Stroke vs Temperature plots for GN66-45 and GN66-46

The GN66-46 specimen is able to attain a higher maximum temperature, although both actuators were heated from the same starting temperature. More importantly, the stroke and response time are very similar between both specimens.

5.3 Effect of Forced Convection Cooling

Next the thermal response of the TCP is studied, by testing the GN66-46 specimen in still air against forced convection cooling supplied by a CPU fan located 10 cm from the specimen. As expected, the still air unit reached a higher maximum temperature of 120° C versus 100° C for the fan cooled unit as shown in Fig. 5.6. The results summarized in Table 5.2.

Figure 5.6 GN66-46 Stroke and temperature attained with and without convection cooling

Forced convection cooling slows temperature rise but significantly reduces the cooling time constant by almost 50%. The critical limitation of thermal actuators is its cooling time so assisted cooling will be important requirement for such systems.

Table 5.2 *Temperature response of GN66-46 with and without convection cooling*

	Fan off	Fan on
Starting temperature	28° C	25° C
Max temperature reached	118.8° C	100.8° C
Temperature rise	90.8° C	75.8° C
Time taken	3.1 sec	3.2 sec
Time required to cooldown to 36.8% of temperature rise	10.6 sec to cool from 118.8° C to 61.4° C	4.9 sec to cool from 100.8° C to 52.9° C

5.4 Isometric Blocked Force

The maximum blocked force generated by both GN66-45 and GN66-46 under isometric conditions was measured using the tensile actuator test rig. Different levels of starting pretension were set by locking the position of the laser target which anchors one end of the test subject, and adjusting the position of the force meter, onto which the other end of the TCP is attached.

Some variance in the temperature reading from the Optris infrared thermometer occurred every time the pre-tension on the TCP was changed. Unfortunately, due to the small size of the filament and heating elements, the drift could not be eliminated.

The results of the test are shown in Fig. 5.7 (GN66-45) and Fig. 5.8 (GN66-46). It is here that the greatest divergence in performance between the lower and higher draw ratio filament is seen. Both specimens demonstrate improved blocked force with greater pre-tension, however the GN66-46 is not only able to sustain a higher pretension stress at equivalent extension to the GN66-45 but achieves a much higher blocked force. The blocked force at each pretension is summarized in Table 5.3.

Table 5.3 *Isometric blocked force attained by GN66-45 and GN66-46*

GN66-45		GN66-46	
Pre-tension	Blocked force	Pre-tension	Blocked force
0.26 N	1.43 N	0.45 N	2.38 N
0.65 N	2.03 N	0.81 N	2.95 N
0.80 N	2.27 N	1.11 N	3.46 N

Figure 5.7 GN66-45 - Blocked force at different pre-tension levels

Figure 5.8 GN66-46 - Blocked force at different pre-tension levels

5.5 Creep Behaviour of TCP Actuator

The creep behaviour of GN66-45 and GN66-46 TCPs is measured at nominal stress of 10 MPa. The results are plotted in Fig. 5.9.

GN66-45 reached onset of secondary creep at 3.5% elongation after 1848 sec (30 min 48 sec). Equivalent figures for GN66-46 are 3.0 % elongation after 1815 sec (30 min 15 sec). Time taken to reach 63.2% of transition from primary to secondary creep is 88 sec for GN66-45 and 103 sec for GN66-46.

Figure 5.9 Creep behaviour of GN66-45 and GN66-46 at 10 MPa nominal stress

5.6 Discussion of Findings

In the fabrication of the 2 reference specimens, GN66-45 (draw ratio 1.2) required 865 turns.m^{-1} and GN66-46 (draw ratio 2.8), 790 turns.m^{-1} to coil. Aziz et al. [22] measured the effect of inserted twist on fibre generated torque and stroke, as shown in Fig. 5.10. Both torque and stroke are positively correlated to inserted twist. Intuitively, a lower draw ratio fibre is less stiff and will require more turns to generate writhing formation, which in turn supports better TCP performance.

Figure 5.10 Torsional actuation test of nylon fibre at constant diameter - (A) Isotonic stroke (rotation) (B) Isometric generated torque [22]

On the other hand, the higher draw ratio GN66-46 filament has a better negative thermal expansion than the GN66-45. This correlation between draw ratio and CTE is supported by studies by Choy et al. [61], as shown in Fig. 5.11.

Figure 5.11 (A) Temperature dependence of thermal expansivities for dry nylon 6,6. (B) Effect of water on thermal expansivities of nylon 6,6 (dash curves denote wet nylon) [61]

Stroke and response speed is fairly similar between both reference TCP but GN66-46 is capable of a much larger blocked force under isometric testing. The addition of forced convection airflow greatly enhances TCP cooling and recovery, as have been observed by other researchers such as Yip and Niemeyer [30]

To summarise, this chapter presents the findings of comparative tests in the following areas –

1. Maximum TCP stroke at different loads.
2. TCP stroke versus temperature (room temperature to 200°C).
3. Dynamic response test (Isotonic condition).
4. Effect of active convection cooling.
5. Isometric blocked force.
6. Creep response.

At lower loads where TCP contraction is not impeded by coil contact, both GN66-45 and -46 produce almost equivalent maximal strokes. However, at higher loads beyond the point of coil contact, GN66-46 TCP performs significantly better in isotonic and isometric tests.

It is clear the draw ratio plays an important role in defining TCP behaviour, and this is an area that needs further examination. A shortcoming of this study is the limited availability of filaments of a full range of draw ratios for comparative testing. Ideally, this would be addressed by having access to equipment that can extrude and draw the filaments from the polymer resin.

The GN66 nylon 6,6 filaments are available in a range of sizes, but the spread of draw ratios is limited. Moreover, practical dimensions for testing are between 0.3 – 0.5 mm. Smaller diameter filaments are increasingly affected by the presence of the heating element, and it is challenging to measure their temperature as their coiled diameter is smaller than the 1 mm spot size of the infrared thermometer. Larger diameter filaments experience high failure rates during twist/writhe insertion and can only be mandrel coiled, with an accompanying higher spring index. At this point, four GN66 filaments with draw ratios 1.2, 1.7, 2.7 & 2.8 have been identified as suitable candidates for further draw ratio tests.

Chapter 6 INTEGRATED TCP ACTUATION

6.1 Application of Linear Muscles

Conventional articulated link robots are typically driven by motors situated at the revolute joints. An obvious disadvantage of such an arrangement is that the weight and inertia of the motors have to be borne by the robot during operation, as illustrated in Fig. 6.1(A).

Alternatively, the motor or power drive can be located at the base of the robot and motion transmitted to the distal links via a system of cables and pulleys. For fully actuated serial chain robots with a large number of degree of freedoms, the design of cables and pulley drives can be a complex undertaking, as shown in Fig. 6.1(B).

Figure 6.1 Robotic Designs - (A) Conventional industrial robot, (B) Cable driven robot [62]

The motors in Fig. 6.1(A) can also be classified as intrinsic actuators while the cable driven robot in Fig. 6.1(B) is extrinsically powered. An analogy can be found in the physiology of the human hand, shown in Fig. 6.2.

Figure 6.2 Intrinsic and extrinsic muscles of the human hand. (<http://slideplayer.com/slide/4156732/>)

Most of the viable artificial muscles operate as linear drives, similar to animal muscle fibres. However, the planar form of the dielectric elastomer actuator and the bulk of the McKibben actuator render them unsuitable for use as intrinsic muscle drives. Only the SMA and TCP actuators approach the slender aspect ratio of natural muscle.

However, while natural muscle can achieve strains of up to 40%, SMA and TCP actuators cannot yet achieve this performance and still deliver a useable force. Particularly for SMA actuators where the typical strain is only ~5%, long lengths of wire are required to generate the required stroke. The length can easily exceed the dimensions of the mechanism, which means the excess wire must be spooled and stowed outside the robot as extrinsic muscle as shown in Fig. 6.3. This imposes an added housing requirement which penalizes a robot's mobility and adaptability.

Figure 6.3 SMA actuator with spools to take up length of wire [63]

A solution for inadequate strain performance is to form the tensile muscle into a helical coil. This amplifies strain at the expense of stress. A nylon 6,6 TCP muscle can consistently achieve 20-30% strain. While still short of the 40% strain in natural muscle fibres, it is sufficient to allow TCP to function viably as intrinsic muscle in some applications.

To gain insight into the process of designing such a transmission system, we look to nature for readymade blueprints of efficient designs. For instance, the human musculoskeletal system may be a complex machine, but its functions can be basically distilled into 4 primary groups.

1. Balancing multiple forces.
2. Force amplification.
3. Range of motion/speed amplification.
4. Alter direction of applied forces.

Type 1 functions are accomplished through the use of class 1 lever arms, while type 2 & 3 functions are executed by way of class 2 & 3 lever arms. Pulleys allow the redirection of forces (type 4 function). Examples of motion amplification devices are shown in Fig. 6.4.

Figure 6.4 Linear actuator amplification devices. (Top) – Lever displacement amplifier, (Bottom L) – Flexure bridge amplifier, (Bottom R) – Leaf spring amplifier [64]

Compliant mechanisms can also be used generate high degree of freedom motions that are beyond the capabilities of conventional rigid link mechanisms. Man-made compliant mechanisms are widely available and can be further subdivided into 2 usage groups.

The first group comprises devices designed to provide maximum precision and repeatability of motion. These are mechanisms designed to overcome the problems of friction and backlash in conventional machines but must still possess sufficient stiffness to provide the requisite precision. Examples of such applications include precision stages for manufacturing, nano/micro scale devices and MEMs.

A second class of compliant mechanisms are used for applications requiring less precision and exploited for their ability to produce complex motions or replace conventional mechanisms. Their use can be found in many commercial applications like crimping mechanisms, bi-stable latches and braking lever mechanisms.

Soft robotics and compliant devices like grippers are another potential application area for this type of compliant mechanisms. Most compliance mechanisms are passive devices reacting to extrinsic actuation. The discovery of light weight muscles like the TCP opens up new possibilities of designing intrinsic and distributed actuation for multi input compliant mechanisms, as illustrated in Fig. 2.21.

Existing attempts at embedded actuation compliant mechanisms generally involve piezoelectric stacks incorporating displacement amplification to generate the required displacements. Other than certain implementations of morphing structures, there have not been any research into macro scale compliant mechanisms capable of compounded motions from a network of integrated actuators.

6.2 Compliant Gripper Mechanism Powered by TCP Actuators

To demonstrate the versatility of TCP actuators integrated closely with an adaptive structure, a compliant gripping demonstrator was designed and 3D printed in PETG. The gripper was synthesized via the building block method and deforms by means of fully distributed compliance.

Key considerations for this design are –

1. Fully intrinsic actuation.
2. No discrete joints or flexures.
3. Demonstrate the concurrent use of beam bending and tilt buckling in an adaptive mechanism.
4. Use of force/displacement amplifiers to match output to load.
5. Fully harness the size advantages (thin profile) of TCP actuators for use in restricted envelopes.
6. Utilise elastic energy stored in compliant structure to generate the gripping motion.

The culmination of the above deliberations is a multi-mode gripper design pictured in Fig. 6.5.

Figure 6.5 Isometric view of complaint gripper, showing mounting holes for actuators

Figure 6.6 Compliant Gripper with TCP actuators numbered 1 to 5.

The operating features and actuation for the gripper is illustrated in Fig. 6.6. Each actuator (group) can comprise multiple constituent TCP muscles installed in parallel. The number of TCP muscles used is shown in Table 6.1. Each actuator group can be powered individually to create various gripper poses.

Table 6.1 Actuators in Compliant Gripper

Actuator	TCP Actuator	Constituent TCP quantity
1	GN66-45, 45 mm unloaded length	6
2, 3	GN66-45, 45 mm unloaded length	3 each
4, 5	GN66-45, 28 mm unloaded length	2 each

6.3 Features and Operation

TCP actuators (and similar high aspect ratio devices like SMA coils) are much longer in length than their width or thickness. To produce transverse motion required for a gripper, the TCP actuator possesses sufficient stroke to directly pull the jaws together but this would result in a mechanism with a wide ungainly profile. This is not desirable for the manoeuvrability of grippers where a slim form factor is preferred.

Chen [65] and Belfiore and Pennestri [66] published extensive compendiums of linkage type robotic grippers. Verotti et al. [67] compiled an equivalent atlas for compliant grippers, albeit catering more for micro-sized designs. A common technique for producing transverse motion from a linear actuator is by using bridge type amplifiers/transmitters. A typical compliant gripper driven by contractive linear actuators pulls the input ends of the amplifier apart to close the gripper jaws. Conversely, pulling the input ports together generates an outward output motion. The principle of operation is shown in Fig. 6.7.

Figure 6.7 Bridge type amplifier (LH) with classical rotation joints. (RH) Analytical quarter model of amplifier [68]

Lobontiu and Garcia [68] analysed the bridge type amplifier and derived the amplification ratio a as

$$a = \frac{\sqrt{l^2 \sin^2 \alpha + i(2l \cos \alpha - i)} - l \sin \alpha}{i} \quad (42)$$

In the full bridge amplifier, the moment at the output cancels due to symmetry. With a half bridge amplifier, a residual moment is generated at the output when the input is displaced. This moment can generate unwanted deformations in a compliant frame but in this design, this moment is put to good use, as will be described in the next paragraphs.

Unlike the compliant grippers described earlier (actuate to close), the gripper in this work utilizes actuators to pull the half bridge amplifier inputs inward and open the jaws wide enough to fit around the object to be gripped (actuate to open). Gripping is achieved by relaxing the primary actuators and allowing the deformed compliant frame to elastically return to its close position. 2 secondary assistive gripping (group 4 & 5) actuators are used to stiffen the jaws against deflection and provide additional positive clamping force.

The added advantage of this design is that the entire length of the TCP actuators can be accommodated entirely within the boundary of the gripper. The gripper also does not require any power to maintain its grip, which is sustained primarily by the elastic frame.

The compliant gripper is designed for multi-mode operation with 2 pairs of jaws. Jaw 1 is a parallel opening/closing jaw. Jaw 2 features a rotating jaw which allows the gripper to encapsulate larger objects. Both jaws can be used simultaneously in a double pinching action, with the jaw 1 grasping the object while the jaw 2 restrains the object. Jaw 2's rotary motion is extracted from the flexion point of a fixed guided beam element, which is shown in Fig. 6.8(A).

Figure 6.8 (A) Fixed guided beam with a flexion point at the mid-section [69]. (B) A serpentine spring with parallel guided boundary conditions [70]

Since there is no physical feature to produce the guided constraint in the gripper; the output from the half bridge amplifier is used instead to provide the requisite moment M_0 . By carefully adjusting the lengths of the fixed guided element and half bridge amplifier, a pseudo guided constraint motion can be reproduced. This design feature is used to generate the near parallel opening/closing of jaw 1.

Next, the rotating jaw motion is tapped from the flexion point of the fixed guided beam. Generally, the angle between the flexion point and the beam ends will be too small to produce a practical rotating movement. In order to magnify this rotational movement, a serpentine spring section is used in place of the fixed guided beam, as depicted in Fig. 6.8(B).

A search of the literature revealed prior work in MEMs design using S shaped or serpentine 2D springs for both in plane or out of plane motions. Of particular interest, Liu et al. [70] analysed the variation of stress and stiffness and geometrical parameters of the serpentine spring under parallel guided boundary conditions.

This data is extracted from Liu's work and replotted in Fig. 6.9.

While the serpentine spring is used purely to magnify deformation in this work, it can also function as an elastic energy storage and release device. For example, snap release and ballistic motions could be produced for use with multi-stable mechanisms or jumping robotic applications

Figure 6.9 Variation of serpentine spring stiffness with different parameters [70]

The integrated serpentine spring and its deformation in the compliant gripper is shown in Fig. 6.10. While it is possible to generate even larger deflections by varying the spring parameters, it comes at a price as the stiffness is reduced accordingly. As the rotating jaw essentially rides on the end of a lever arm, any force applied at the rotating jaw is magnified.

Therefore, the design of the spring is a careful balance between maximising gripper range of motion and retaining sufficient stiffness for gripping.

Figure 6.10 Deformation of serpentine spring in Compliant Gripper.

Completely decoupled from the half bridge amplifier and serpentine spring elements, the outer arms (of jaw 2) can be independently deformed by tilt buckling via actuators 2 & 3 (opening) and bending via actuators 4 & 5 (clamping and stiffening). Refer to Fig. 6.6.

Chaudry and Rogers [44] carried out extensive analytical work on tilt buckling for shape control of beams. To understand tilt buckling motion, consider a cantilever beam with an actuator attached to the clamped and free ends of the beam. Refer to Fig. 6.11. The direction of the actuator force changes, and unlike a follower force, it passes through a fixed point (clamped end). This force is conservative.

Figure 6.11 Geometry of the tilt-buckling configuration [44]

The actuator is eccentrically loaded from the neutral axis by an offset distance d , which causes a tip moment equal to $P*d$. The governing equation of the beam is

$$EIw'''' + Pw'' = q \quad (43)$$

Boundary Conditions,

At $x=0$

$$w, w' = 0 \quad (44)$$

At $x=l$

$$-EIw'' = -Pd, \quad -EIw''' - Pw' = -V - P\frac{w}{l} \quad (45)$$

General solution –

$$w(x) = A (\sin kx - kx) + B(\cos kx - 1) + \frac{qx^2}{2P} \quad (46)$$

where

$$A = \frac{1}{\sin kl} \left\{ \frac{ql^2}{2P} - \frac{Vl}{P} - \left[\frac{q}{Pk^2} + \frac{Vl}{P} - d - \frac{ql^2}{2P} \right] (\cos kl - 1) \right\} \quad (47)$$

$$B = \frac{q}{Pk^2} + \frac{Vl}{P} - d - \frac{ql^2}{2P} \quad (48)$$

$$k = \sqrt{\frac{P}{EI}} \quad (49)$$

Ignoring for the moment the transverse load q , the general solution of transverse displacement can be simplified to the following -

$$w(x) = d \left\{ \frac{\cos kl - 1}{\sin kl} (\sin kx - kx) - \cos kx + 1 \right\} \quad (50)$$

For the beam tip ($x=l$), deflection

$$w(l) = d \frac{kl(1 - \cos kl)}{\sin kl} \quad (51)$$

Fig. 6.12 shows the tilt buckling response of external actuators compared to the tip moment response which arises from an actuator offset through the same distance d from the neutral axis.

Figure 6.12 Tilt buckling behaviour compared to tip moment response [44]

The tilt buckling of a 3D printed PETG beam by TCP actuators, is shown in Fig. 6.13.

Figure 6.13 Tilt buckling of beam by TCP actuators. Top – Resting state, Bottom - Buckled

6.4 Gripper Tests

Once the TCP actuators are installed under tension, the gripper settles into its equipped resting (unpowered) position with both jaws slightly apart. Before the gripper can be used, gripping pads will be attached to allow the jaws to close fully in the resting position.

(a) Range of Gripper Jaw Motion

Before the pads are installed, the maximum travels of the parallel and rotating jaws are first measured.

Figure 6.14 Compliant gripper jaws' range of motion. (A) Initial unpowered state, (B) Actuator 1 switched on, (C) Actuators 2 & 3 switched on, (D) Actuators 1, 2 & 3 switched on. Refer to Fig. 6.6 for actuator numbering.

By selectively powering the TCP actuators as shown in Fig. 6.14, different degrees of jaw opening can be attained. Heating of the TCPs is limited to 200° C.

Parallel jaw travel is measured at 3.4 mm. Rotating jaw opening is 13.7 mm for the bridge amplifier (actuator 1), 9.2 mm from tilt buckling (actuators 2 & 3) and 19.6 mm for combined actuation (actuators 1, 2 & 3).

By using larger diameter and/or higher draw ratio nylon filaments, the jaw motion range can be further enhanced. Alternatively, increasing the number of TCPs in a parallel bundle is another way to improve the force output from such artificial muscles. This versatility stems from the TCP muscle's extremely high aspect ratio and its scale invariant characteristics.

(b) Gripper Poses

Next, the gripping attachments are attached, which allow the jaws to close with a slight positive clamping force when the gripper is unpowered in its rest state. The gripper is now fully assembled and ready for gripping tests.

With the 5 actuators, a number of different gripper poses can be produced, as shown in Fig. 6.15. Additional clamping force to grip the object is provided by actuators 4 & 5. These clamping actuators (4 & 5) can be powered in an asymmetrical manner in relation to the opening actuators (2 & 3) to allow the gripper to assume various differential poses.

This permits the jaws to not only grip the object but also to perform minor adjustments of the item in its grip. This ability to generate complex multiple DOF motions and deformations is also a hallmark of true compliant adaptive structures.

Figure 6.15 Compliant Gripper poses with gripper attachment installed

(c) Gripping Strength

Next, the gripping strength of the device is investigated by performing a series of gripping tests with common household items (listed in Table 6.2).

Table 6.2 Gripping test objects

Item number	Description	Weight
1	Credit card	5 g
2	Smooth Brass plate	83 g
3	Weight set with hook	79 g
4	Cereal sachet	30 g
5	Creamer sachet	6 g
6	Bostik glue	33 g
7	Araldite tube	28 g
8	Metal part (round)	26 g

This multi-mode gripper features a parallel jaw and a rotating jaw. Both jaws can be operated individually, or in tandem to create different object gripping and cradling behaviours. The parallel jaws work primarily by pinching a thin object or section between the gripping attachments, as shown in Fig. 6.16. As the gripping strength depends on the stiffness of the PETG frame, the design of the gripper is a trade-off between greater jaw motion versus gripping force. In this test, the parallel jaws successfully gripped and held objects weighing up to 83g.

Figure 6.16 Parallel opening/closing jaws pinching tests

The rotating jaws possess dual functionality, namely pinching and cradling. With pinching, the greater jaw opening allows larger objects to be held, albeit with a much lower gripping force. The rotating jaw can also be operated in conjunction with the parallel jaw to perform a double pinching grip on larger objects, as shown in Fig. 6.17.

Figure 6.17 Rotating jaws pinching operation

The gripper can also cradle larger objects within its jaws, as shown in Fig. 6.18. By selectively powering/depowering the 5 actuators, the gripper can perform limited dexterous manipulations like shifting and rotating of the object cradled in the jaws.

Figure 6.18 Rotating jaws cradling tests

(d) Gripper Opening/Closing Response Speed

An important criterion for an effective gripper is a quick grip/release cycle. Recall Fig. 5.5 (p. 60), where a 3 sec duration 15V square wave pulse was sufficient to heat the TCP to 120 °C. Wu et al. [32] used an even shorter pulse of high electrical power to produce full contraction of the TCP within 1 sec. Therefore, rapid heating of the TCP to required operating temperatures is easily achieved. On the other hand, the time required for the TCP to cool down to its initial temperature often exceeds 30-45 sec as heat transfer is constrained by the low thermal diffusivity of standing air. Using forced convection cooling reduces this time by as much as 50%, as seen in Fig. 5.6 (p. 61)

The above figures refer to the response speed of the TCP muscle itself. To investigate the closing/opening speed of the gripper with coupled TCP muscles, the time taken for the rotating jaws to complete one cycle of opening/closing is measured (with convection cooling). Two tests are performed. The first test utilises bridge amplifier action (actuator 1) while the second test uses tilt buckling motion (actuators 2 & 3) to drive the rotating jaws. The results shown in Figs. 6.19 and 6.20

Figure 6.19 Response time of rotating jaws when operated by bridge amplifier actuator 1

Figure 6.20 Response time of rotating jaws when actuated by tilt buckling actuators 2 & 3

A complete opening/closing cycle requires approximately 15 sec for the bridge amplifier actuator and 20 sec for the tilt buckling actuators. More importantly, the jaws recover (cooling phase) from fully open to closed in 8-11 sec for the bridge amplifier and 9-11 sec for the tilt buckling actuation.

This means that the gripper mechanism recovery time is faster than the 15 sec required for the TCP to stretch back to its resting length under isotonic load (with forced convection cooling). As TCP muscles exhibit slow thermal fall times, the ability to harness the elasticity of the coupled compliant structure to improve the recovery speed of TCP actuated mechanisms is another benefit of integrating TCP muscles with compliant mechanisms.

6.5 Summary of Compliant Gripper Demonstration

The compliant gripper with integrated TCP muscle actuators was fabricated and its performance tested for :

- a) Sufficiently large jaw opening, which determines the size of objects that can be handled.
- b) Adequate dexterity to generate multi-mode gripper poses.
- c) Useful gripping strength.
- d) Quick grip/release cycle.

An ideal gripper would possess both a large jaw travel and a high gripping force. In this work, the compliant gripper was designed to close when unpowered so sufficient stiffness of the frame is needed to maintain the necessary positive gripping force. Ultimately, the final design was a compromise between jaw travel and gripping strength.

In summary, the gripper achieved a 3.4 mm opening for the parallel jaw and a 19.6 mm opening for the rotating jaw, whilst being able to grip items up to approximately 80 g in weight. The gripper also achieved various asymmetric poses as envisaged in the original design. Finally, the gripper opening/closing cycle was timed at approximately 15-20 sec, which is an acceptable performance for a thermal actuator powered device.

This work demonstrates the viability of using a network of TCP muscles to actuate gripping mechanisms with multi-mode capabilities. Although the design and analysis of the compliant mechanism itself is not the focus of this project, the use of a half bridge amplifier in tandem with a serpentine spring to create a gripper with concurrent parallel and circular jaw motions is a first for gripper designs.

Lastly, the interaction of the compliant frame with the TCP muscles resulted in a faster spring back of the muscles to their resting position(s), compared to a TCP lifting a constant load. This is another benefit of integrating soft TCP muscles with compliant mechanisms.

Chapter 7 CONCLUSIONS AND FUTURE WORK

7.1 Discussions and Conclusions

The TCP fabrication equipment produced more than a hundred TCP actuators in the course of this research, with the proper quality required for experimentation. TCP actuators thus produced achieved a maximum stroke of 27%, which is amongst the highest figures achieved for Joule heated TCP. The tensile actuator test rig performed to specifications, with no failures to date. One area for possible enhancement is the stiffness of the tensile test rig, which should be many orders of magnitude higher than the test object. While the existing rig is sufficient for testing TCP coils with their low spring modulus, a more rigid rig and attachments will increase accuracy, particularly for measuring the properties of precursor filaments.

Measuring the temperature of the TCP posed a challenge. Even with an infrared thermometer that is designed for close up pinpoint measurements, deviations in the temperature arose whenever the TCP was shifted. Even laboratory personnel walking past the test rig created sufficient draft to affect the temperature readings. However, compared to the use of thermocouples, thermistors or even thermal imaging cameras, the 1 mm measurement spot of this thermometer is still the more reliable option for measuring real time temperatures of the TCP.

The characterisation of the primary properties of TCP actuators yielded data that compared well with existing research. The preliminary study on the draw ratio showed that while stroke was roughly equivalent for different draw ratios, the blocked force was significantly higher with greater draw ratio. Although it is not possible to draw any further inferences from the limited test and sample size, it is apparent that there is a strong need for additional research in this area. The logistical problem of obtaining a proper sample size of varying draw ratio filaments must first be addressed, before a more detailed investigation of draw ratio can be performed.

Currently, TCP researchers are using off the shelf filaments manufactured with properties relevant to their respective commercial applications. Not all of these properties are useful, while some are actually detrimental to TCP functionality. The next stage in the development of the TCP muscle will be to discover or synthesize polymers with even better performance than nylon 6,6, at present the most effective TCP precursor. Concurrently, the processing parameters of the filament must also be specified and optimised for maximal anisotropic thermal expansion profiles.

Finally, the compliant gripper was successfully 3D printed and assembled with its component actuators. With the integrated actuators heated to 200° C, the parallel jaws maximum opening was measured at 3.4 mm (from its resting position). The equivalent maximum opening of the rotating jaw was 19.6 mm. The gripping action generated from the elastic spring back of the compliant frame, after the TCP actuators had opened the gripper jaws, was sufficient to grip items weighing up to 83 g.

By using only 5 actuators, the compliant device successfully demonstrated dexterity in effecting complex multi degrees of freedom motions. This is a robust proof of concept for integrating TCP artificial muscles with adaptive structures, and a first and important step to constructing more advanced and complex shape changing and motion generating structures.

Although the initial performance figures are modest, it is not the overriding priority at this stage. In any case, actuator force can be scaled up by parallel installation of more TCP, or simply by using larger diameter and/or higher draw ratio precursor filaments. The small diameter of the TCP is readily apparent on paper, but it is only by building a demonstrator that one truly appreciates the advantage of extremely thin muscles which can be bundled in proximity with little penalty to performance.

7.2 Future Work

The first generation tensile test rig will be upgraded for improved dimensional accuracy, stiffness and ease of use.

A search will be initiated for a suitable source of filaments to support further experiments on the fibre draw ratio.

Further investigations will be carried out on the viscoelastic behaviours described in section 3.3, in relation to the theories of Leaderman and Mullin's effect.

Derivation of a more general mathematical model that accounts for the effect of draw ratio on thermal expansivities in both the axial and transverse fibre directions.

Work on the Gen 2 TCP Compliant Gripper, with improved gripping range, strength and dexterity will be initiated.

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