Development of an Artificial Muscle from Coiled Polymer Fibers for Humanoid Robotics Applications

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Abstract:
Humanoid robotics aims at developing anthropomorphic robots able to move in environments and to manipulate tools that are designed specifically for human beings. The high number of DOFs required in a humanoid robot demands for compact and high power-to-weight ratio actuators. Among all the possible technologies, artificial muscles have the additional advantages to be flexible, lightweight, and to provide linear movement suitable for a human-like robotic system. Existing types of artificial muscles used in robotics and other automated systems are expensive and technically limited due to hysteresis, scalability and performance efficiency. Inspired by a recent discovery of artificial muscles made of common twisted fishing line, the goal of this study is to develop a low-cost thermally controlled actuator suitable for humanoid robotic applications. The experimental setup consists of a twisted fiber of nylon with a diameter of 1mm pre-tensioned and connected in series with a force sensor. The material is heated up thanks to a NiChrome (NiCr) wire inserted axially into the polymeric fiber. The temperature is measured and controlled thanks to a small NTC thermistor kept in contact to the NiCr wire. Different experiments were conducted in order to measure the dynamic response of the artificial muscle as well as the force-temperature characteristic in static conditions.

Keywords: Polymer Actuator, Artificial Muscle, Humanoid Robotics

I. Introduction

Artificial muscles have a wide range of possible applications. They can be used in rehabilitation and medical devices [1], in wearable exoskeletons and actuated suits [2], in the aerospace and energy industry [3], in bio-inspired robotic systems [4], in humanoid robotics [5], and in many other fields where a compact and human-like actuation system represents a good alternative to an electric motor. There are different possible technologies and materials that can be used to implement such a kind of actuation. Among of them: McKibben Pneumatic Artificial Muscle (PAM) [6], Shape Memory Alloys (SMA), Electroactive Polymers (EAPs) [7], Carbon Nanotubes (CNT), Electrorheological Fluid, and the most recent one, twisted polymeric fibers [8]. PAMs are made of an inner rubber tube covered by a braided mesh shell. The working principal is as follows: when the pressure of the gas inside the tube is increased, it causes the tube to expand radially; this creates in the shell an axial force that causes the contraction of the muscle [9]. Owing to their advantages, such as lightweight, flexibility, high power-to-weight ratio, and cheapness, PAMs are widely used in robotics. Shape memory alloys, in turn, are the class of materials, which has the ability to "memorize" some shape and return to it, when heat is applied [10]. Some problems with SMAs, such as slow response and erratic movements, are preventing their mass usage. However, some of the SMAs (for example, NiTi) have a very useful characteristic: they are biocompatible and, thus, suitable for biomedical applications. Electro-active ceramics are made of crystals endowed of piezoelectric properties. When they are exposed to a mechanical stress, they generate an electrical charge. They can also work as actuator, i.e. generating force when stimulated by an external electrical voltage [11].

Development of artificial muscles made of coiled fishing lines of different shapes and sizes is a recent discovery that can be utilized in the development of humanoid robots, prosthesis, exoskeletons and automated systems that require high load capabilities. Imitating human muscles, this kind of actuators can expand and contract generating up to 5 kilowatt of mechanical power per kilogram [12].

According to the study conducted by Haines et al. and reported in a recent number of *Science* [8], high-strength and low-cost nylon occurred to be the most appropriate material for fabrication of polymeric twisted fibers. In addition, the helical structure of coils provides contraction from 4% to 34% by rising the material temperature from 20 to 240 °C. Such systems with high range of temperature control can be used for humanoid robots to make fast and at the same time precise movements, where both, stiffness and tensile actuation, are important.

The aim of this work is to develop and study an

artificial muscle suitable for humanoid robotics applications able to reach a tensile stroke up to 30% of its length. Thus, exploiting volumetric controlled thermal expansion with different fibers configurations while working in a range of temperatures between 20-80°C.

The rest of this paper is organized as follow: **Section II** introduces the methodology we followed to prepare the twisted fibers and reports the main components of the test-bed. **Section III** describes the initial experiments we performed on the developed prototype and reports its characteristics. Finally, **Section IV** brings the conclusions and indicates some possible future developments.

II. Methodology

Fibers Preparations

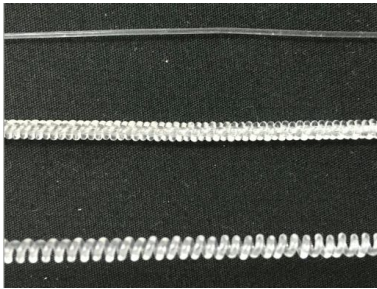Different fibers were prepared from inexpensive polymer fishing line of 0.5mm, 0.8mm and 1 mm in diameter.

Fig. 1: **Nylon Fiber**: *untwisted, coiled at rest, and coiled stretched.*

Even though, untwisted straight polymer fibers exhibit contraction and expansion properties under heating, in the twisted form (helical structure) these properties considerably enhance. The team from Texas University [8] made the fibers by attaching the upper end of the fishing line to the tip of a power drill and attaching to the other end a load of appropriate mass. Thus, twist insertion was introduced vertically. Unlike this strategy, we twisted the fibers fixed on both ends by inserting the twist horizontally. Keeping the constant tension helped to adjust the speed of rotation. After the drill was powered up and started spinning, we arranged the speed to be high for the fishing line to be twisted along its length faster, around 250-300 RPM. Once the twisting limit was reached, we decreased the speed to approximately 200-250 RPM to allow the fiber to form equal coils. Noticeably, fibers twisted from the line of 0.5 mm were found more susceptible to mechanical stress, i.e. they deform and easily untwist if large tension is applied. In contrast, thicker fibers (0.8 and 1mm in diameter) are stronger in the capability to keep original structure and coil configuration when exposed to mechanical impact. Therefore in our final

experiments we decided to use fibers of 1mm. When the fiber is heated up, length contraction and diameter enlargement occur, therefore, causing fiber untwist. Since in nylon fibers negative axial expansion and positive radial expansion take place, they together contribute to untwist, that is why nylon is considered to be ideal for actuation purposes. Untwist, in turn, produces torque that reduces the inter-coil separation. The spring index has some effect as well. It is defined as the ratio of the coil diameter to the fiber diameter. Different spring indexes give the opportunity to tune actuation stroke and stress. Coiled fibers with spring indexes close to one have high stiffness, while coils with high spring indexes can contract and elongate to access high range of coil bias angles (approximately from 0 to 90 degrees). The spring indexes for our fibers having diameters 0.5, 0.8 and 1mm are C=2.6, 2.7 and 3.125 respectively.

Heating Element and Preliminary Tests

For feasibility reasons in our setup we decided to use electrically conductive heating elements instead of hot water or air. Large availability and the conductive properties of copper wires led us to trials of its insertion inside the polymer fiber coils. However, its low resistivity required a too high voltage in order to generate the necessary amount of power to heat the fiber. Therefore, further considerations and survey have shown that NiChrome (NiCr) is the most suitable material for our application. The current supplied to the wire must be balanced with enough resistance to produce heat. The resistivity of the NiCr [13] is approximately 100 times higher than that of a copper wire of the same size, though copper is a good conductor. For our purposes we chose a NiCr wire of 0.3 mm in diameter and having a resistivity of $\rho= 115 \times 10^{-8}$ Ω/m. To provide power to the NiCr wire we used a controllable DC power supply able to generate a maximum of 5A at a voltage of 6V.

Initial tests with one fiber at rest (coiled fiber with an internal NiCr wire) showed that it could contract up to 14%. However, after cooling it was not retrieving its initial position (e.g. initial length - 48.7 mm, heated length - 42.0 mm, final length after cooling - 43.2 mm.). A possible reason for that can be the increased friction between the twisted fiber and the NiCr wire on micro level. When the twisted fiber is in contact with highly heated wire, it starts to melt, thus partially 'solders' to the wire. From here the necessity to precise regulating the temperature of both the Nylon fiber and the heating wire in the following experiments we conducted.

Experimental Setup

The test-bed we developed (see Fig. 2) allows to pretension the coiled fibers by mean of an adjustable mechanism that can slide horizontally. This in turn is

attached to an ATI-nano-17 sensor that can measure the static force generated by the fibers with a resolution of 0.318g. The coiled fiber in one side is attached to the force sensor by an inextensible wire of Dacron and in the other to the metal structure of the test-bed by using a terminal connector that serve also to realize an electrical contact with the internal NiCr wires. It is important to notice that the NiCr wire, in order to avoid blocking the fiber extension/contraction, should be able to slide. To allow this we developed in SolidWorks a special holder that is capable to mount up to four fibers in parallel. Specifically, it consists of four parts connected together with screws and is realized in a modular way to allow the mounting and detaching of the fibers once at time. This is possible by disassembling the three upper parts from the bottom one.
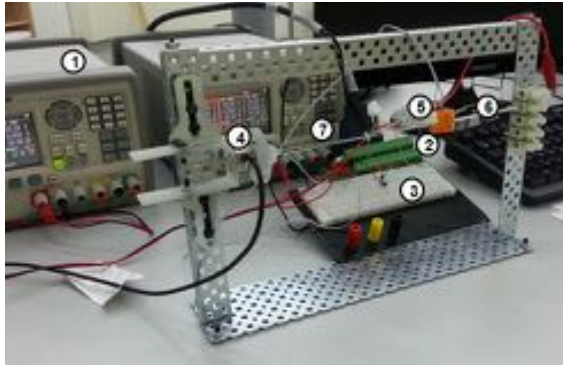

Fig. 2: Final Test-Bed Set-Up: *1- DC Power Supply; 2- Data Acquisition Connector; 3- Voltage-Divider Circuit for the Thermistor; 4- Force/Torque Sensor and adjustable holder; 5- Thermistor; 6- polymer fiber with inserted NiCr wire; 7- Dacron Fishing Line.*

In order to grasp properly the fibers without squeezing them, in one of the sides of both the upper parts and the bottom part there are semicircle horizontal holes. Furthermore, additional vertical holes of bigger radius are added to attach the load.
To measure the temperature of the NiCr wire we used a negative temperature coefficient thermistor, the NTC 100 kΩ F04675.

III. Experiments

All the software to conduct the experiments was developed in LabVIEW due to its convenient interfacing with different instruments we used. The DC power supply was connected to the PC via a USB cable; while the force sensor and the thermistor were connected trough two different DAQs' analog inputs channels. To configure and control the voltage and the current of the DC power supply we used the IVI driver and the NI-VISA library. The DAQmx and the DAQ assistant blocks were used to establish the connection with the sensors.

With a first experiment we wanted to measure how fast the fiber can cool down from an initial defined temperature. At first we increase slowly the temperature till we reached 50°C then we let the fiber cooling down naturally. As in Fig. 3 the heating phase occurs in 58 seconds, while the cooling phase requires 561 seconds. Since cooling the fiber takes more time than warming it up, for the final artificial muscle development will be necessary to think to a system to force the cooling. A possible solution is to pump cold distilled water around the fibers. From the plot of Fig. 3 it is possible also to observe that if the fiber is warmed up starting from 37°C and cooled down to the same temperature the two time intervals are comparable.
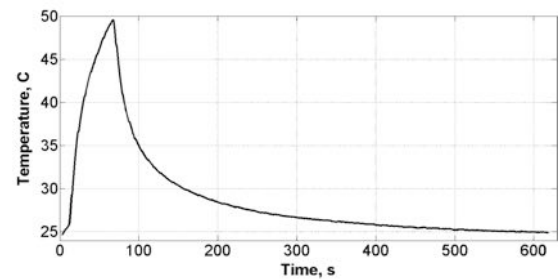

Fig. 3: *Temperature-time relationship*

The purpose of a second experiment was to measure the force-temperature characteristics of a single fiber of 1mm in diameter. A current was supplied to the NiCr wire until a maximum isometric force of 3N was reached. After, the current was turned off and the force was measured until the temperature of the fiber returned to its initial value. The experiment was repeated three times as reported in Fig. 4. As we expected the characteristics is represented by a hysteresis loop typical for elastic and rubber materials.
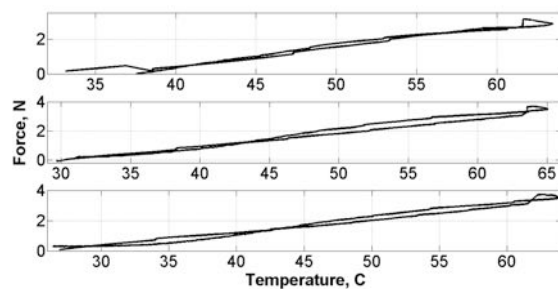

Fig. 4: *Force-temperature relationship*

In the third experiment, following the considerations from the first experiment, we pre-warmed the fiber until reaching a temperature of 40°C, after that we supplied a current of 1A as a square wave with a period of 16 seconds. Then we increase the temperature of the fiber till 60°C, we let the fiber cool down till 46°C, and finally we warm up it till 64°C. The temperature-time relationship is shown in

3

the Fig. 5. With 70mm length and of 2.5mm diameter coiled fiber we reached 2.2N at a temperature of 48°C. The average power consumed for a single fiber during the warming up phase was 1.53 Watts.
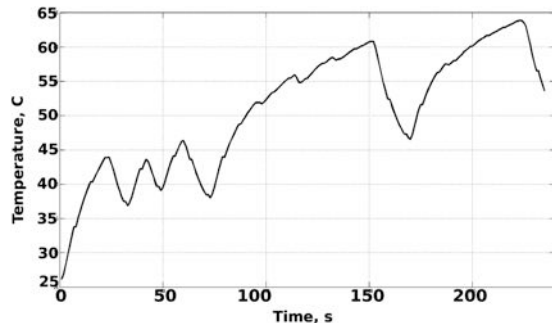

Fig.5: *Experiment results with pre-warmed fiber*

IV. Conclusions

Artificial muscles made of polymer fishing lines represents a low-cost alternative to existing bio-inspired actuation systems. The feasibility study we conducted has shown that the behaviour of the artificial muscle is highly dependent on the materials' properties and physical factors like the diameter of the fiber and its spring index. After testing different mechanical configurations and various preliminary experiments, a test bed was developed that allowed us to measure the force-temperature characteristic of a single coiled nylon fiber in static condition. Our experimental work confirmed the idea that artificial muscle made of materials like Nylon can be used in various fields like humanoid robotics, prosthetic limbs, and artificial exoskeletons. As future work we intend to test more fibers connected in parallel. A position sensor will be required to measure the change in length of the fibers when heated up. Furthermore, it will be necessary to implement a control system to control the isometric force generated by the fiber.

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