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A Device for Producing Artificial Muscles from Nylon Fishing Line with a Heater Wire*

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***Abstract*— The paper introduces a device "Artificial Muscle Twister" (AMT) used for producing artificial muscles from nylon fishing line with a heater wire. AMT is assembled from common electronic and mechanical components, while the case is printed on the 3D printer. The device is used for winding wire onto a nylon monofilament and twisting followed by coiling threads to form helical springs. The paper presents the main characteristics of the muscle samples created by AMT, differing in source fiber diameter and process of manufacturing. The produced muscles are actuated by applying voltage to the wire wound around the nylon fiber through the MOSFET keys of the 12 volt power supply. The proposed device can be used in small-scale production of artificial muscles in research and practical use. The assembly and operation circuit, as well as the 3D models will be available as open source.**

I. Introduction

Biological muscles have several properties that make their technical counterparts preferable to use in zoomorphic and anthropomorphic robotic devices. As examples of such properties, we can point out flexible form, extensibility and elasticity, the ability to shrink in size to do work, lability or the recovery rate of functionality and muscle strength [2].

In the studies of artificial muscles, i.e. actuators having the above mentioned properties of biological muscles, various materials are used: shape memory alloys (SMA) [3], shape memory polymers (SMP) [4], electroactive polymers (EAP) [5, 10], bundles of carbon nanotubes [6]. These materials have the ability to shrink or grow in size when exposed to electricity, light, temperature, chemical action. Typically, the quantity of deformation amounts to a small percentage of the material's original size, so a composition of such elements is used for larger quantities of deformation. A wide spread of artificial muscles is hampered by various technical difficulties, such as low efficiency, weak electromechanical and thermomechanical coupling, high input voltage and so on.

A group of researchers from the University of Dallas suggested a promising solution to the basis for artificial muscles: to use ordinary nylon fishing line twisted into a tight helical spring [1, 7]. This material has some properties inherent to biological muscles. Namely, it has a similar shape (flexible elastic fibers), and the ability to expand or contract performing useful work when affected thermally. At the same time there are a number of challenges on the way to the mass use of this approach. For example, the problem is the implementation of heating and cooling the nylon fiber which would effectively match the biological muscle form factor. For example, to heat up the fiber, we can use metal coated nylon surface which is heated by electrical current [7, 8]. Many tasks involving muscles require fast heating or cooling of the muscles, which requires a separate solution due to the inertia of the heat transfer processes.

Currently, scientists search for practical applications of twisted and coiled polymer actuators [12-16]. In these studies, the creation of muscle samples based on polymer fibers plays an important role. For example, in [14] equipment was developed to keep the fabrication conditions and to produce identical muscles. As they examined muscles fabricated with silver-coated nylon sewing threads (multi-filament fiber), the equipment design was intended only to control twisting of the fibers with a suspended load. According to [15] muscles made of mono-filament fiber are expected to have a better contraction than those made of multi-filament fiber. To actuate muscle with mono-filament fiber we can utilize metal (Nichrome or Copper) wire wound around fiber. Therefore, one of the immediate tasks is to automate the manufacture of artificial muscle samples with a metal heater wire.

The aim of this paper is to describe the study and development of manufacturing technology of artificial muscles, created by twisting a nylon thread wound by metal wire. The machine (Figure 1) proposed in this paper allows to make samples of muscles with identical characteristics. The paper also presents the basic characteristics of the artificial muscles, produced with the help of the suggested technology. We consider only the artificial muscle contraction effect during heating.

Figure 1. The device "Artificial Muscle Twister" for creating artificial muscles made of polymer fibers with a wire heating element.

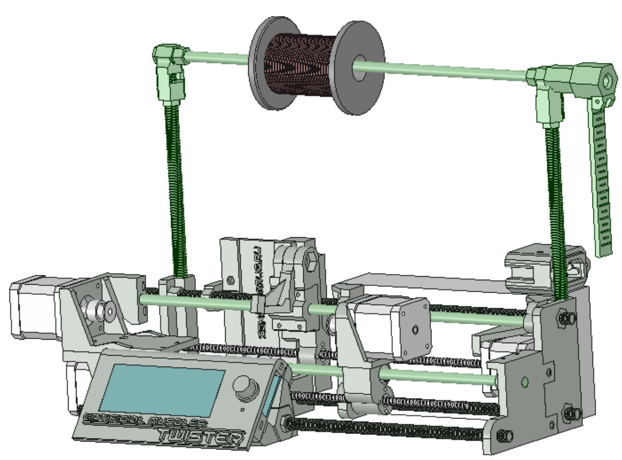

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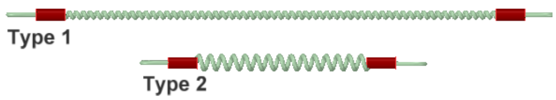
Figure 2. Prefabricated artificial muscle. Type 1 - polymer fiber twisted into a tight helical spring, Type 2 – fiber twisted until the formation of coils



and wound on a rod of a certain diameter.

II. Theoretical and Experimental Methods

In [1] it was demonstrated that inexpensive polymeric filaments, such as usual nylon fishing line, can be used as a basis for artificial muscles. To create muscles, mono- or multifilament fibers are variously twisted into a helical spring, which thermally expands or contracts, depending on the production method.

In subsequent studies of artificial muscles based on twisted polymer fibers, nylon thread with conductive silver coating is used most commonly [7, 8, 9]. The usage of silver coating significantly increases the resulting cost, moreover, some authors [9] mention a small lifetime of such fibers (about 7000 cycles) when exposed to electricity necessary to heat the artificial muscle.

In our experiments we used a polyamide based fishing line with a diameter of 0.5 mm and 0.8 mm (Klinskaya new fishing line®) without any coating, with the corresponding marking Nylon 6. To heat the fiber, a copper wire 0.14 mm thick was used.

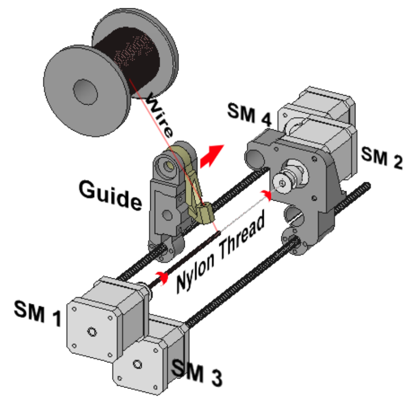
Using a copper wire as the heating element requires rapid heating of the prepared artificial muscle, so the surface of the polymer fiber should contact with this wire as extensively as possible, without deteriorating the dynamic properties of the muscle. This is possible if the wire is wound with a small pitch on the original polymer fiber. Next, the fiber should be twisted into a spiral, as described in [1]. This is usually done with one end fixed in the electric motor chuck and the other one attached to a load which is sufficient to coil the fishing line into a uniform spiral. In the process of twisting, the load goes up, since the fiber is reduced in length, and at a certain point the speed of movement of the load increases, and the line starts to coil into a tight spiral.

As a result of this manipulation, polymer undergoes a strong plastic deformation, and after the removal of the rotating force, the helix uncoils only slightly. In some studies the resulting coiled fiber is stretched up to 130% of its original size and is heated for some time before the polymer melting temperature is reached, to obtain the desired form [9].

Two types of muscle can be identified (Figure 2), created from a nylon thread by twisting. The first type of muscle is obtained by the method described above, when the twisting is performed until the moment when all the original polymer fiber is converted into a tight helical spring. The second type of muscle is made when the original fiber is twisted until the formation of coils, and then wound on a rod of a certain diameter. The result is also a helical spring, but with a larger diameter and different artificial muscle properties.

In general, the process of winding the wire on the fiber and subsequent spiral twisting is not trivial. Furthermore, to have best characteristics of the finished artificial muscle, all the above mentioned manipulations should be performed as accurate as possible because the coils of the helical spring must have the correct shape and be the same throughout the working length of the muscle. This cannot be achieved if done manually. To solve this problem, we developed a device “Artificial Muscle Twister”, presented in Figure 1.

Figure 3. Reel mode - winding a metal wire on the polymer fiber.



III. A Device for Creating Artificial Muscles

One of the goals of this paper is to suggest a technology that facilitates the massive use of artificial muscles based on twisted nylon thread which are inexpensive to produce. This can be achieved following the approach described in [11], that is, by providing full open-source scientific hardware and software. Therefore, the device for creating this type of muscles should be built from common or easily constructed components available for Do-It-Yourself developers. An example of this kind of device is RepRap machine [17].

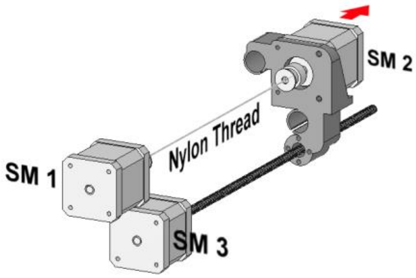
A device suggested here for creating muscle with a wire heating element - hereinafter AMT (Artificial Muscles Twister) - uses electronic and mechanical components similar to ordinary RepRap. Namely, four stepper motors NEMA 17 (holding torque at least 44 N cm); Arduino Mega 2560 controller and expansion card RAMPS 1.4; four stepper motor drivers A4988; three mechanical limit switches; Smart LCD Controller with a four-line LCD screen, controls (angular sensor and buttons), SD card reader, shield cable to connect to RAMPS 1.4; PSU 12 volt 20 amp. The case of the device is 3D printed.

There are two basic modes of operation of the device: winding the wire on the polymer fiber and twisting the fiber into a helical spring. There are also a few auxiliary functions and operations, which are available through the control panel in the corresponding menu items.

The device uses two slide parts (Figure 3): a guide for wire (labeled as Guide in the figure) and stepper motor SM2. After powering-up, they are set to the left starting position (procedure Home).

To create a maximally long artificial muscle, the nylon thread needs to be prepared before putting it into the device. To do this, a piece of thread 30 cm long is cut, and fixing loops of 10 mm are made at the ends of it. Loops are fixed with the help of pieces of copper pipe, 2 mm diameter and 5 mm long, which are clamped with pliers. Thus, the working length of the sample thread is about 23 cm.

Figure 4. Stretch mode - stretching the sample of polymer fiber.



The loops of a polymer fiber sample are fixed on the chucks of stepper motors SM1 and SM2. Then, Stretch procedure should be applied (Figure 4) - after the start, SM2 motor begins to move to the right, stretching the thread. The exact moment to stop the movement is determined by the operator of the device depending on the degree of fiber tension.

The next phase of creating a muscle is winding the wire on the polymer fiber (Figure 3). The Guide head is moved to the leftmost position. The wire goes from the reel, through the guide, and is fixed on the chuck of motor SM1.

From the menu of the device, Reel procedure should be chosen, which winds the wire on the fiber. Motors SM1 and SM2 are rotated in the same direction, and the Guide moves slowly to the right, thereby forming a uniform winding of the wire on the polymer thread. If the sample is shorter than the maximum possible thread length, the process should be stopped manually, otherwise it is done automatically. After the winding procedure, the wire should be cut off. A small length of wire should be left for later application of an electric voltage to the muscles.

Final stage is the twisting the filament with a wire into a tight helical spring (see Figure 5). The device has two modes: automatic and controlled by the operator. Generally speaking, the result of coiling fibers depends on many physical parameters: initial fiber diameter, its chemical composition, the diameter and metal of the wire wound around it, twisting speed, temperature of the sample, the rigidity of the entire construction. During the twisting, motors SM1 and SM2 rotate in opposite directions. Also, SM2 motor appears to rotate in the opposite direction with respect to the previous mode of winding the wire, otherwise the wire breakage would occur.

Figure 5. Twisting mode - twisting polymer fiber into a tight helical spring.

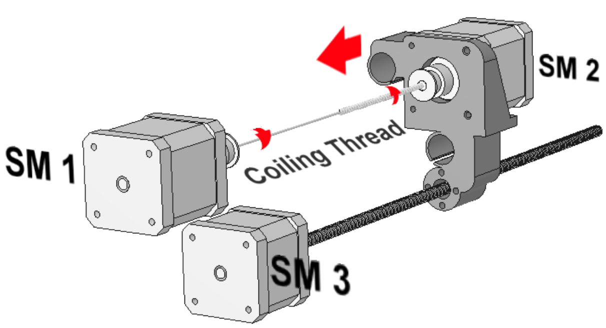
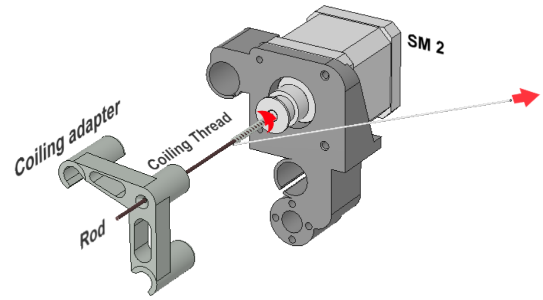


Figure 6. Coiling mode – coiling the twisted polymer fiber around the rod.



Since twisting a nylon thread implies its shrinking in length, and the formation of coils rapidly increases the length change rate, the operator's task is to control the speed of moving motor SM2 to the left. All the operator’s controlling manipulations on the motor SM2 shift speed are stored in memory. Thus, the optimum shift mode for a particular sample type of polymer thread and the parameters of wire are to be found experimentally. The optimal mode data obtained in this way can be written to the non-volatile memory of the device, with the stored data automatically available for possible further use.

The artificial muscle, prepared this way, should be stretched on a special wire frame and placed in an oven and heated slowly for half an hour up to a polymer melting point, which is about 180 degrees Celsius for nylon. This annihilation process is needed to ensure that the helical spring would not untwist under load.

Now let us consider the process of manufacturing the artificial muscles of the second type using the AMT device. What makes it different from the above process of creating the first type of muscle, is that this time during the Twisting mode it is necessary to stop the twisting of the polymer fibers before the formation of coils starts. The end of the fiber is detached in the stretched state from the stepping motor SM1. On the guiding axis of the device, a special adapter with the rod of the required diameter is installed, for example, in the form of stiff wire (Figure 6). Coiling mode is switched on, during which only the stepping motor SM2 rotates making the twisted fiber coil around the rod. The process of coiling is stopped manually. By changing the direction of motor SM2 rotation when winding the thread onto the rod we can get the muscles contracting or expanding.

IV. The Main Characteristics of the Prefabricated Artificial Muscles

Many studies mention the need for “training” the muscle before it starts to contract in the maximum value [8, 9]. The muscle is suspended vertically and the load attached to the lower end of it. Then the voltage is applied. The initial heating causes the elongation of the muscle under the gravity force of the load. After several iterations, the value of the muscle contraction under the electrical current stabilizes and becomes constant at a predetermined heating temperature. The value of the initial elongation of muscles depends on the weight of the load.

Figure 7. Various types of artificial muscles made using the AMT device

In this work, we used the AMT device to fabricate both types of muscles described above (Figure 7), whose repetitive characteristics have been studied (Table I,II,III). A nylon 6 monofilament with diameter of 0.5 mm and 0.8 mm was used as precursor fiber. Characterization of thermally-activated artificial muscles based on this type of nylon was deeply considered in [19].

TABLE I. CHARACTERISTICS OF MUSCLE SAMPLES MADE USING THE AMT DEVICE

Parameter name	Muscle Samples		
	Sample 1	***Sample 2***	***Sample 3***
Type of muscle	Type 1	Type 1	Type 2
Nylon thread diameter	0.5 mm	0.8 mm	0.8 mm
Working part length of the muscle twisted into a helical spring	5.8 cm	5.3 cm	3 cm
Rod diameter used for coiling	-	-	1.5 mm

TABLE II. CHARACTERISTICS OF THE MUSCLE WITH A SUSPENDED LOAD OF 300 G

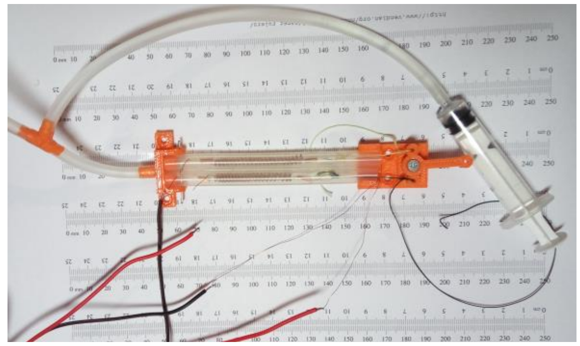
Parameter name	Muscle Samples		
	Sample 1	***Sample 2***	***Sample 3***
Working part length of the muscle with a suspended load after "training"	8.5 cm	6.5 cm	6.5 cm
Maximum contraction displacement with the load	7 mm	10 mm	16 mm
Heating time to reach maximum muscle contraction	400 ms	1300 ms	1300 ms

TABLE III. CHARACTERISTICS OF THE MUSCLE WITH A SUSPENDED LOAD OF 200 G

Parameter name	Muscle Samples		
	Sample 1	***Sample 2***	***Sample 3***
Working part length of the muscle with a suspended load after "training"	7 cm	6 cm	5 cm
Maximum contraction displacement with the load	10 mm	7 mm	14 mm
Heating time to reach maximum muscle contraction	625 ms	1300 ms	1000 ms

Let us refer to the fragment between metal fixtures of muscle loops as a working part of the muscles. In our experiments initial polymer thread length was 30 cm, heater copper wire diameter was 0.14 mm. Heater wire resistance on each muscle was 2.2 Ohm, electrical voltage applied in heating process was 12 V. To control the electrical voltage on the studied artificial muscle samples we used pulse width

Figure 8. Water injection into air-pumped silicone tubes for muscles cooling.



modulation (PWM), a controller Arduino Mega 2560 and the keys on the MOSFET transistors.

At room temperature, the minimum period of cooling after the contraction of the muscles (Sample 1) was 19 seconds. Forced cooling by an air pump (4 lpm), with the muscles being placed into the air-pumped silicone tubes, reduced the cooling period to 3 seconds. For cooling Sample 3 water injection into air-pumped silicone tubes was used (Figure 8).

The actuator on the basis of muscle differs from our usual actuators, which are rigid, have non-deformable structure and require transmission system for driving various units [9]. These muscles can be viewed as springs with changing stiffness coefficient which depends on the temperature changes while the current passes through the heater wire [1, 18, 20]. The parameters shown in the tables allow us to estimate the maximum distance and speed which we can get while lifting the load suspended from the lower end of the muscle. In this case the muscle is exposed to the constant force of gravity of the load. A more interesting case is the combination of two muscles operating in the opposite directions. Each muscle, while contracting, will increasingly be resisted, which will result in sharp decrease in displacement value. To improve the displacement in this situation it is advised to use a longer muscle [8, 14]. Also, under the condition of a loss in the power, a larger displacement is obtained with the muscles of Type 2 [1]. In our experiments (Figure 8, supplementary video to this paper) we got a larger displacement value by using a combination of two muscles of Type 2, with one of them contracting, and the other expanding under the current. Thus, when heated, the former increases the stiffness while the latter decreases it, thereby reducing the resistance force of the contracting muscle and making the displacement value dependent only on the load applied to the actuator. In combination with the development of position controllers [15], this approach seems promising in search of practical application of these muscles.

V. DISCUSSION AND CONCLUSION

The paper introduces a device "Artificial Muscle Twister" (AMT) used for producing artificial muscles from nylon fishing line with a wire heater. The architecture of the device implies using common components and 3D printed case. The software of the device enables producing muscles based on nylon fibers twisted into a spring that can be coiled with or without a rod. The produced muscles can contract or expand under Joule heating.

The main problem solved by the device is the implementation of Twisting mode, which ensures the proper tension of the twisted thread and creation of a tight helical spring. At the same time, the fiber should be covered with coils of a wire heater, which can be done in the Reel mode. Unlike in the off-the-shelf wire winding machines, SM2 component is movable and controlled by a microprocessor to maintain the tension of the twisted fiber. Moreover, manufacturing muscles requires a specific combination of operation modes of the motors of the device, controlled via the on-board microprocessor.

Further work on the AMT device involves the development of a mathematical model that will allow calculating the automatic operation of the device in the Coiling mode depending on the specified characteristics of the precursor polymer fiber. It is also possible to improve the hardware to be able to obtain longer muscle samples.

The paper presented several muscle samples, differing in source fiber diameter and process of manufacturing. The results of the sample study are consistent with the results presented in the currently available literature.

The foregoing suggests that the proposed device can be used in small-scale production of artificial muscles according to the described above technology for further research into the applicability of this type of muscles, and also in a variety of practical applications including in the framework of the movement Do-It-Yourself.

Appendix

This paper is accompanied by a video that shows the proposed device in action. The full stage of twisting the filament with wire into a tight helical spring is presented in the video (preparing muscle sample 2). We also show the muscles prepared by AMT in action: applying Joule heating for muscle contraction, and cooling by water injection into the air-pumped silicone tubes for muscle relaxing.

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