Optimal Design of Shape Memory Alloy Wire Bundle Actuators

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Abstract:
This research studied the optimal design of Shape Memory Alloy (SMA) muscle wire bundle actuators. Current literature describes the use of multiple muscle wires placed in parallel to increase the lifting capabilities of an SMA actuator, which however, is limited to wires of like-diameter. A constrained optimization problem was formulated, with constraints on the maximum number of wires, voltage applied, and SMA bundle length and cross-sectional area, that explored the use of several different diameter wires for the development of an optimal SMA bundle actuator that will be able to apply maximum force. As a case study, the optimal design of SMA bundle actuators for the Rutgers robotic hand is presented.

Introduction

The need for lightweight robotic devices has prompted the use of compact, smart material based actuators to power the robot joints [1], since traditional forms of actuators have a major drawback in that the system necessitates the use of large and heavy supporting apparatus. The interest in these types of actuators evolved from the promising results in force and motion development shown by many of these materials, specifically in micro-robotic systems [2, 3]. In this project we studied the optimal design of Nickel Titanium Shape Memory Alloy (SMA) based actuators, which possess the ability to undergo shape change at low temperature and retain this deformation until they are heated; at which point they return to their original shape.

Though SMA muscles have a high force to weight ratio, the maximum force that each wire can apply is approximately 0.3 kilograms (this varies according to wire diameter). Because daily weight lifting requirements for the robotic hand, used as the case study here, are greater than 0.3kgs, it is proposed that many muscle wires be "bundled", just as muscle fibers are in humans, to form a muscle with greater lifting abilities. Bundling wires of like diameter to reach this goal has been done thus far [4]. Figure 1 shows an example of a like-diameter wire bundle. Generally, the construction of the bundle consists of running the wires in parallel attached to a bracket by crimps at the ends of the wires, to preserve the wire shape change properties. Since these wires contract in length, the bundles are then attached to the device via a small cable or tendon at both ends. One end is stationary and the other moveable, so that with a temperature change in the wire (when voltage is applied) the device is moved.

The main goal here was to design SMA bundle actuators with various diameter wires (100 µm, 150 µm, 250 µm, and 300 µm) with the objective of maximizing the force capabilities under certain constraints. In general, while the smaller diameter wires have a faster cycle time (faster cool time), the larger diameter wires provide more force. It is proposed that by combining smaller and larger diameter wires placed in parallel an actuator could be made that will benefit from the higher cooling speeds of the smaller wires while obtaining a higher force from the actuator. A constrained optimization problem was formulated where the goal is to calculate the number of wires with different diameters and the applied voltage, based on a specified wire length, so that the total SMA bundle force is maximized under particular constraints determined by the maximum number of wires per bundle, the acceptable ranges for the bundle length, the voltage applied, and the maximum cross-sectional area of the bundle. As a case study, the optimal design of SMA bundle actuators for the Rutgers robotic hand is presented.

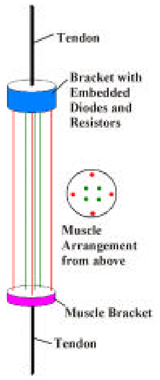

Fig. 1: *Structure of a Muscle and its Fibers*

Problem Formulation

A SMA bundle actuator, as the one shown in Figure 1, is considered. The actuator consists of several

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different diameter SMA wires placed in parallel, attached between two brackets. The number of SMA wires having the same diameter k is denoted by N_k. The index "k" represents the wire diameter values of, either 100 µm, 150 µm, 250 µm, or 300 µm. It is assumed that the same voltage V_{in} is applied to all wires. The goal is to calculate the number of wires N_k and the input voltage V_{in}, given a certain wire length L, so that the total SMA bundle force F is maximized under constraints determined by the maximum number of wires per bundle N_{max}, the acceptable ranges for the bundle length, the voltage applied, and the maximum cross-sectional area A_{max} of the bundle.

The maximum power $P_{max,\,k}$ required to actuate each wire to its maximum force $F_{max,\,k}$, in *one second* is calculated by:

$$P_{max,\,k} = (i_{max,\,k})^2 * R_k * L \tag{1}$$

where: $i_{max,\,k}$ is the current required for each wire to attain its maximum force in one second; R_k is the resistance in each wire per unit length.

The efficiency ? is defined as the ratio of each wire's input power $P_{in,\,k}$ to $P_{max,\,k}$. $P_{in,\,k}$ is determined by the applied voltage V_{in} and the current $i_{in,\,k}$ needed to actuate each wire without causing overheating.

$$\eta = \frac{P_{in,\,k}}{P_{max,\,k}} = \frac{V_{in} * i_{in,\,k}}{(i_{max,\,k})^2 * R_k * L} \tag{2}$$

The efficiency indicates the fraction of $P_{max,\,k}$ that is being input to each wire. This in turn indicates the fraction of the maximum force that is being output from the wire (one second actuation speed). It is important to note that given enough time each wire will attain its maximum force. By multiplying both sides of Equation (2) with $F_{max,\,k}$ Equation (3) is obtained:

$$F_k = \eta * F_{max,k} = C_k * \frac{V_{in}}{L} \tag{3}$$

where: F_k is the output force from each wire (one second actuation speed). Constant C_k contains all known information for each SMA wire and can therefore be calculated using NiTi actuator wire properties tables [5, 6]. The maximum power requirement per unit length $(i_{max,\,k}{}^2 * R_k)$ for each wire, the maximum force achievable by the wire $F_{max,\,k}$, and the input current $i_{in,k}$ make up C_k:

$$C_k = \frac{F_{max,\,k} * i_{in,\,k}}{(i_{max,\,k})^2 * R_k} \tag{4}$$

The total bundle force F is found from:

$$F = -\left[N_{100}C_{100} + N_{150}C_{150} + N_{250}C_{250} + N_{300}C_{300}\right] * \frac{V_{in}}{L} \tag{5}$$

Equation (5) is our optimization objective function. The minus sign indicates the minimization of Equation (5), where the goal is to find V_{in} and N_k given the specified constraints listed below:

a) The number of wires N_k, which are non-negative:

$$N_{100} \geq 0,\quad N_{150} \geq 0,\quad N_{250} \geq 0,\quad N_{300} \geq 0 \tag{6}$$

b) The total number of wires, which is equal to the sum of all N_k, and is less than or equal to a maximum number of wires N_{max} that is selected by the SMA bundle designer based on the bundle application:

$$N_{100} + N_{150} + N_{250} + N_{300} \leq N_{max} \tag{7}$$

c) The bundle length L is constrained between a minimum and a maximum value L_{min} and L_{max} respectively that are imposed from the geometry of the application:

$$L_{min} \leq L \leq L_{max} \tag{8}$$

d) Due to power considerations and the SMA wire's fatigue life, there is a maximum acceptable value V_{max} for the applied voltage V_{in}:

$$0 \leq V_{in} \leq V_{max} \tag{9}$$

e) The total area of all SMA wires, which is the sum of the products of each wire's cross-sectional area A_k times N_k, should be less than an acceptable maximum area A_{max}. A_{max} can be found by considering the application of the SMA bundle actuator, the area of each wire and the associated area needed for crimps (the mechanism used to attach the wires to the device), and the space for airflow. It is suggested here that the larger diameter wires require a greater space between them for heat dissipation, so an incremental factor based on the wire diameter (approximately three times the wire diameter) was used to determine the area. The final constraint equation is:

$$N_{100}A_{100} + N_{150}A_{150} + N_{250}A_{250} + N_{300}A_{300} \leq A_{max} \tag{10}$$

Thus the design of a SMA bundle actuator has been formulated as a constrained optimization problem and classical optimization techniques were used to solve it.

Discussion / Results

To demonstrate the application of the methodology of the last section, the SMA bundle actuator design as dictated by the Rutgers Hand prototype currently being developed in our laboratory [7, 8] was used. Utilizing the MATLAB® Optimization Toolbox function *CONSTR*, which finds the constrained minimum of a function of several variables, Equation (5) was solved using constraints (6) – (10). Two different values for N_{max} equal to 10 and 15 wires were considered. The length L was constrained to lie in the range from 0.1524m (6") to 0.2032 m (8"). The maximum voltage was selected to be 7 V, while the maximum acceptable area A_{max} was calculated as 0.56 cm^2 (10 wires) and 0.60 cm^2 (15 wires). Two different possible wire configurations were considered: *Group 1*; 100 µm, 150 µm, 250 µm, and 300 µm and *Group 2*; 150 µm, 250 µm, and 300 µm.

The summary results of the optimization are shown in Table 1 for just the 0.1524m length, since this is the ideal length for the Rutgers Hand. Note that the force provided does not increase with the length, but the power requirement does. The length of the actuators can be varied depending on the task. Since the contraction length achieved by these actuators is based on 4% strain of the wire, the longer the wire the greater the distance traveled in linear motion or the greater the rotation in angular motion. See [9] for tables that show the force and power data for varying lengths of all the wires for the bundle actuators. The tables can be used for quick reference for actuator construction.

Table 1: *Summary of Optimization Force and Power Results for Different Diameter SMA Bundles (0.1524 m length)*

Number of Wires / Type			*Power*	*Force*
	100 µm	250 µm	(W)	(N)
10 Wires	5	5	5.83	16.21
15 Wires	13	2	8.75	22.65
	150 µm	250 µm		
10 Wires	7	3	12.48	34.01
15 Wires	12	0	14.98	38.81

The optimal solutions for both bundle configurations were formed using a combination of the smallest diameter wires along with the 250 µm diameter wires. Neither program chose to use the 300 µm diameter wires, because the force capabilities of these wires drops due to the material properties. Additionally, the values for the bundles found here with varying wire diameters were compared with bundles of same diameter wires (Table 2) [5, 6]. According to the optimization routine, the bundles that use varying diameter wires produce better results (i.e., higher force and lower power) than same diameter wire bundles. A comparison of the 0.1524m (6") length wire sample values found in Tables 1 and 2 will show this. Note that due to the constraints put on the area, the bundle consisting of 15 wires of the 150 µm and 250µm diameter, was formed with only 12 of the 150 µm diameter wires, so there is no difference in power or force as compared with the manufacturers data (Table 2).

Table 2: *Force and Power for Multiple Same Diameter SMA Bundles (0.1524 m length)*

Number of Wires / Type			*Power*	*Force*
	100 µm	150 µm	(W)	(N)
10 Wires	10	-	8.89	14.70
10 Wires	-	10	14.22	32.20
15 Wires	15	-	13.34	22.05
15 Wires	-	15	21.24	48.45

Three of the actuators shown in Table 1 were fabricated and experimentally tested to verify the computational results. The actuators tested were those constructed with: 1) 5 – 100 µm diameter wires and 5 – 250 µm diameter wires, 2) 13 – 100 µm diameter wires and 2 – 250 µm diameter wires, and 3) 7 – 150 µm diameter wires and 3 – 250 µm diameter wires. The bundles were tested for: minimum voltage (power) requirements for actuation, optimal voltage (power) requirements to obtain the optimal actuator, confirmation of the optimization routine capabilities, and any possible excess force attainment. These tests were accomplished by placing the bundles vertically in a test apparatus above a mass tray. Voltage was applied to both ends of the bundle while the displacement, force applied, voltage, and amperage were observed and recorded. The third actuator (7 – 150 µm diameter wires and 3 – 250 µm diameter wire) is shown in Figure 2.

Fig. 2: *10 SMA Wire Bundle Actuator (7-150 µm and 3-250 µm)*

The results of the actual experimental tests are presented in Table 3. The minimum power is what was required to just actuate all the wires. This test was run with a minimum mass attached as well as the amount as dictated by the optimization routine. The maximum power is what was required to provide a much larger force (approximately double) than that suggested by the optimization routine for a contraction time less than one second. The optimal power is what was necessary to lift a mass above that given by the optimization routine in a reasonable amount of time (one second).

Table 3: *Summary of Experimental Force and Power Results for Different Diameter SMA Bundles (0.1524 m length)*

	Minimum		***Maximum***		***Optimal***	
	Power (W)	Force (N)	Power (W)	Force (N)	Power (W)	Force (N)
1	6.72	7.85	-	-	23.52	19.61
	6.72	15.69				
2	10.55	7.85	22.26	41.19	20.20	22.56
	10.27	22.56				
3	15.40	7.85	30.89	63.74	12.97	41.19
	12.50	34.32				

Note: The numbers above refer to the following actuators; 1) 5 – 100 µm diameter wires and 5 – 250 µm diameter wires, 2) 13 – 100 µm diameter wires and 2 – 250 µm diameter wires, 3) 7 – 150 µm diameter wires and 3 – 250 µm diameter wires.

From these results, it can be seen that the optimization routine provides the minimum power requirements to actuate the bundle, which is not necessarily the optimum power. This is consistent with previous results found in [9]. This is due to manufacturers data being used in the optimization routine, which is more conservative in its reporting of the abilities of the SMAs. The manufacturers take into account the longevity of the SMAs and it is true that for longer actuator lifting life, it is best to not overly stress the wires by using excessive voltage or having excessive force expectations. However, for faster response times it is necessary to increase the power. More importantly, an increase in voltage is necessary for the smaller diameter wires to fully actuate.

Some important notes for these actuators are: actuator #1 required such a high voltage to actuate all the 100 µm wires that it was impractical, and since the 250 µm wires were primarily providing the force, it makes more sense to just use a bundle of 5-250 µm wires; actuator #2 was the most impractical actuator for similar reasons given above, however adding the 250 µm wires did provide higher lifting capabilities than just the 100 µm wires could do alone; and actuator #3 was the best combination as it could lift an excess of weight beyond what the optimization routine gave at close to the power requirements (however, slower than at maximum power), which is more force than the 150 µm wires alone could provide. All the bundles displaced the expected 4% of the wire length.

For these unlike diameter wire bundle actuators, exceeding the voltage limits of the bigger diameter wires to the minimum voltage required for the smallest diameter wires results in the performance of the actuator occurring as predicted (i.e., the actuator lifts more weight faster), provided this voltage does not over stress the wires. The user will have to balance the advantages of speed vs. power demand.

Conclusions / Future Work

The design of SMA bundle actuators consisting of several single heterogeneous diameter wires placed in parallel was presented in this paper. Such SMA bundle actuators possess high payload to weight ratios and can be very useful in applications combining high lifting requirements with small size constraints. The specific problem studied here was to calculate the number of wires with different diameters and the applied voltage, with a given wire length, so that the total SMA bundle force was maximized under certain constraints determined by the maximum number of wires per bundle, the acceptable ranges for the bundle length, the voltage applied, and the maximum cross-sectional area of the bundle. As a case study, the optimal design of SMA bundle actuators needed for the Rutgers robotic hand was presented. This optimization routine is useful for large numbered SMA wire bundles where the possible configurations would be far too many to calculate otherwise.

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