2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

Optimization of Parallel Spring Antagonists for Nitinol Shape Memory Alloy Actuators

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***Abstract*— While there has been a steady progression of research in robotic and mechatronic systems that utilize nickel titanium alloy (Nitinol) as an actuator, the design of the antagonistic element for the inherently "one-way" technology has not been thoroughly investigated and described. In this paper, we discuss the properties of Nitinol-based shape memory alloy actuators as they relate to the design of passive spring antagonists. We describe the major classes of design goals as they relate to the choice of properties of the antagonistic element, and present techniques for optimizing parallel antagonists through passive linear springs in order to maximize the generally most desirable property of the actuator - the maximal repeatable strain of the antagonist pair.**

I. Introduction

Active material actuators, where applied control signals and power lead to developed force and/or strain across the material, are desirable for a number of reasons. Unlike devices that are comprised of heterogeneous parts, material actuators are not assemblies (in contrast to common Lorentz force actuators, for example, which generally require bearings, magnets, and a physical or electronic means of commutation between coils) and so more easily lend themselves to miniaturization. Adding further to the simplicity, the powering schemes generally involve simple application of current (such as Joule heating) in order to reach a phase-change point in the material. Of the existing options, which include electroactive polymers [1] and piezoelectric materials [2], nickel titanium alloys (Nitinol) show the largest achievable strain and greatest durability of material actuators [3]. Therefore, despite its limitations in terms of thermodynamic inefficiencies and achievable bandwidth, Nitinol has been the most commonly used material actuator in robotics research.

One of the drawbacks of Nitinol SMA as an actuator is its inherently unidirectional action. When heated to initiate the shape-memory effect, the material will remain in that configuration until it is mechanically strained. Considering that nearly all actuation applications would require more than "one-off" single use of the material, some type of antagonist actuation must be provided. This is generally done with either a second SMA element (e.g. [4–7]), or with passive mechanical springs, which can be placed either in series (e.g. [8], [9]) or parallel (e.g. [10]) with the active element.

In this paper, we describe the considerations involved in designing a Nitinol/passive spring antagonist pair in which

Research supported by United States Air Force Office of Scientific Research under Grant #FA9550-11-1-0093.

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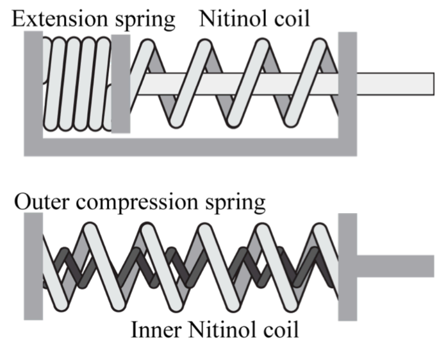

Figure 1. Types of linear Nitinol mechanisms

the spring is placed in parallel, for the purposes of maximizing the achievable strain that can be repeatedly obtained during actuation. Optimization of the Nitinol mechanism requires both an understanding the kinematics of the mechanism structure, as well as the material properties of the constituent components. This paper aims to present a complete picture of the parameters available to the designer and how these choices affect the basic functionality of the device. In particular, the equilibrium between the SMA element and the antagonist spring must be considered, which is made challenging due to the fact that the stiffness of the Nitinol component cannot be modeled as a simple linear spring: the internal stiffness changes as the metal is heated and the crystalline lattice of the alloy is varied from fully-martensitic to fully-austenitic.

The most common configuration of linear Nitinol devices includes a Nitinol element (either straight wire or coiled "spring") in *series* with a bias/return spring. Series mechanisms are attractive because both elastic elements are generally in tension at all times. However, the length of the pair will be fairly long to achieve a specific force, recoverable strain, and stiffness property [11]. An antagonistic spring in parallel, alternatively, allows for a much more compact system. However, it requires consideration of other important issues, such as buckling, to be explained more fully later.

While a fairly large number of research projects have implemented passive springs as antagonists for SMA elements, they have nearly always done so without substantial justification for the associated design choices. The most relevant work along those lines involves a discussion of the optimization of the SMA element for a given antagonist series spring. This paper, alternatively, focuses on the analysis and optimization method for choosing the properties of an antagonistic spring, including rest-length, spring constant, diameter, etc., placed in parallel with a given SMA element, with the goal of optimizing the repeatable strain of the actuator pair.

We begin the remaining portion of this paper with a description of the basic mechanical properties of Nitinol as it changes phase to create a strain, followed by an introduction to the desired properties in an antagonist (section II). We then describe the details of the considerations involved in optimizing an antagonist spring placed in parallel with the NiTi element, including discussing the role of the geometrical properties of the SMA and the spring, for the purposes of maximizing the achievable repeatable strain of the system (section III). Finally, we present conclusions and future work extensions of the work presented here (section IV).

II. Nitinol SMA Actuator Properties

In order to be able to describe the requirements for the design of a mechanical spring antagonist, we must first lay out the relevant mechanical properties of the active Nitinol actuator element. We begin by describing the basic material and mechanical properties of the alloy (section II.A.), then describe the primary ways in which an antagonist can bias the behavior of the active element system (II.B.), and conclude with a discussion of the effects that a popular strain-magnifying form factor of the NiTi (coiled "springs") affects the element properties (II.C.)

A. Basic Mechanical Properties of Nitinol

When Nitinol is used as an actuator, which is its most common use in the robotics literature, systems are exploiting the shape memory effect of Nickel Titanium (NiTi) Shape Memory Alloys (SMA). SMAs have the distinct advantage of being highly compact and requiring little overhead in drive electronics, and the direct electrical interfacing and ease of integration makes them attractive for many applications, specifically when simplicity and small size is prioritized. NiTi, the most widely-available SMA, can develop high stresses (approximately 100 MPa in the martensitic phase and 560 MPa in the austenitic phase) in wires of less than 0.5 mm thickness [12]. Conversely, many other active material actuators, such as electro-active polymers and piezoelectric cells, allow either limited stresses or very low achievable strains, making them less suitable for widespread use in a wide range of applications. Furthermore, NiTi is durable and inexpensive, in addition to its ability to achieve large strains when heated.

NiTi shape memory alloys have their own inherent limitations, however. The mechanism by which they actuate stems from a phase change phenomenon in which the crystalline lattice of the metal transitions from austenitic structure to martensitic structure on cooling. Heating causes the crystalline domains to transition to the more compact austenitic lattice form, inducing a strain in the material. In commercial NiTi SMAs, this strain is currently limited to approximately 4% for straight drawn wire in tension. Additionally, SMA is a unidirectional actuator – an external restoring stress must be applied to strain it to its detwinned state. The SMA must then be heated to revert back the more-dense austenitic lattice (see Fig. 2). Despite these limitations, however, it is the most reasonable option for many robotics applications.

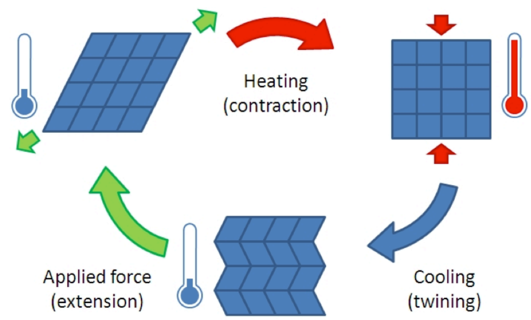

Figure 2: SMA activation cycle

B. Bias forces for One-Way Nitinol Elements

Similar to the way in which an active antagonist can be controlled in order to modulate the impedance characteristics of the actuator, the properties of the antagonist spring can be chosen in order to give a variety of behaviors. We categorize these into "constant force", strain-optimized, and stiffness-optimized antagonist springs (Fig. 3).

In the first of these categories, a constant-force spring or biasing element is used. Fig. 3A (left) shows the force/deflection curves of the martensitic (light blue) and austenitic (dark blue) phases of the NiTi element, with a constant force bias shown in turquoise. While a constant-force element would theoretically allow for the largest net strain of an SMA actuator (taken as the difference in the horizontal axis intercepts between the antagonist element and the martensitic and austenitic NiTi phases), it is very difficult to implement in practice. Constant force springs, such as those used to power mechanical watches, generally take up a large amount of physical space and are limited to fairly small forces. Another option would be through the use of a load mass, such as used in mechanical clocks. The negatives there are obvious, including the variation with orientation with respect to gravity, travel limits in the coupling of the mass to the mechanism, as well as the net added mass and size to the

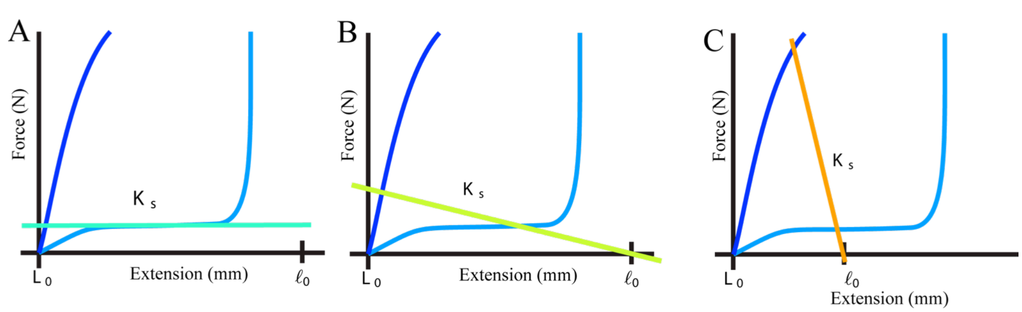

Figure 3. One-way Nitinol element can be biased by constant forces, linear springs, or non-linear elements. Shown here are biasing forces that optimize strain with a constant force (A), optimize strain with a linear spring (B), and optimize strain variability with a linear spring (C).

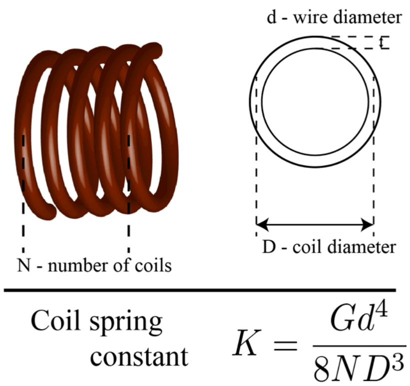

Figure 4: SMA cell stiffness tuning through spring geometry.

system.

The second major option is the implementation of a linear spring (with a constant, non-zero force/deflection curve), as shown in Fig. 3B. All mechanical springs will have a certain amount of deflection associated with an applied force. The idea with this option would be to find a spring with as low stiffness as possible while allowing for the desired deflection, which puts an upper limit on the practical stiffness due to the yield strength properties of the spring material (typically a steel formulation). Designs of this type will maximize the repeatable strain of the antagonistic pair, which is the goal of the proposed work.

The last class of passive antagonist seeks to maximize the stiffness variation in the stiffness (Fig. 3C). While not addressed in this paper, this concept rest upon the ability to maximize the *difference* in stiffness between martensitic and austenitic phases of the SMA element. Since the spring and active element are in parallel, the best designs involve the choice of springs that are impedance-matched to mean stiffness of the Nitinol phases.

C. *Nitinol Coil Characteristics*

The typical form-factor for commercial Nitinol is simple extruded wire. While this gives the largest attainable force, commercial straight-drawn Nitinol wire has a maximum recoverable strain limit of approximately 4%. However, similar to the way that a typical gear-based transmission can trade off torque for speed of an electric motor, a greater amount of strain can be attained by coiling the wire, trading off applied force for increased strain.

We have been able to achieve linear strains of over 20% with coiled NiTi elements by "training" them such that their memory shape is in the form of a linear coil. In doing so, we can vary the contractile properties of the system by altering the geometry of the coil. Given a specific Nitinol alloy chemistry, the spring stiffness is proportional to the wire diameter and inversely proportional to the number of turns and the coil diameter. Fig. 4 shows an example coil, where d is the Nitinol wire thickness, D is the mean diameter of each coil, and N is the number of turns in the coil.

The effective "spring constant" of the Nitinol coil is a function of those parameters and the shear modulus G of the Nitinol in each phase. It will have two different shear moduli, G_A and G_M, while in the fully-austenitic and fully-martensitic crystal phases, respectively, and will vary

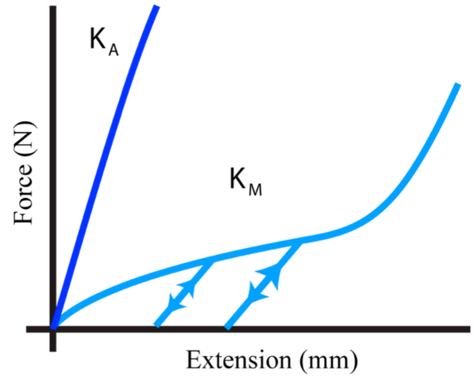

Figure 5. Force-displacement characteristics of a Nitinol spring, in contrast to that of straight drawn wire shown in Fig. 3.

between those during phase changes. The contractile and stiffness properties of the coil can therefore be controlled and tailored to the needs of a specific application by varying d, D, and N.

The stiffness model shown in Fig. 4 does not fully capture the contractile behavior of NiTi actuator coils, however, due in part to the material property variations with the phase change spectrum of the material, as well as to geometric effects from the coil form factor. As a result, a more complete analytical model [7] or experimental determination of the true mechanical behavior of a specific material chemistry and form factor (e.g. Fig. 5) might be used in the design optimization.

III. Parallel Spring Optimization

To optimize a bias spring (namely its rest length and spring constant) in order to maximize the amount of travel for a parallel mechanism, the designer must know several parameters and limitation of the mechanism under consideration. First, the limits of travel of the mechanism are critical, including the smallest amount of compression the device can make as well as the maximum extension. Often times the device will have physical stops that prevent the mechanism from traveling beyond the allowable bounds, but these limits are still important for computing the spring length and stiffness that maximizes travel. It also provides an upper bound on the percentage compression the bias spring will make. Second, the largest allowable diameter of the bias spring will play a role in determining the maximum length of the bias spring before buckling occurs, in conjunction with the percentage compression. The final consideration in finding the ideal bias spring is to find commercially available springs that satisfy the length and stiffness criteria. The optimization steps are performed as follows:

A) Characterize the Nitinol shape memory element by theoretically or experimentally identifying an analytical form for the force-displacement curves of the fully-austenitic and fully-martensitic phases (similar to those found in Figure 5)

B) Determine the maximum Nitinol extension before permanent plastic deformation will begin and the maximum stable bias spring length for the spring diameter and desired deflection.

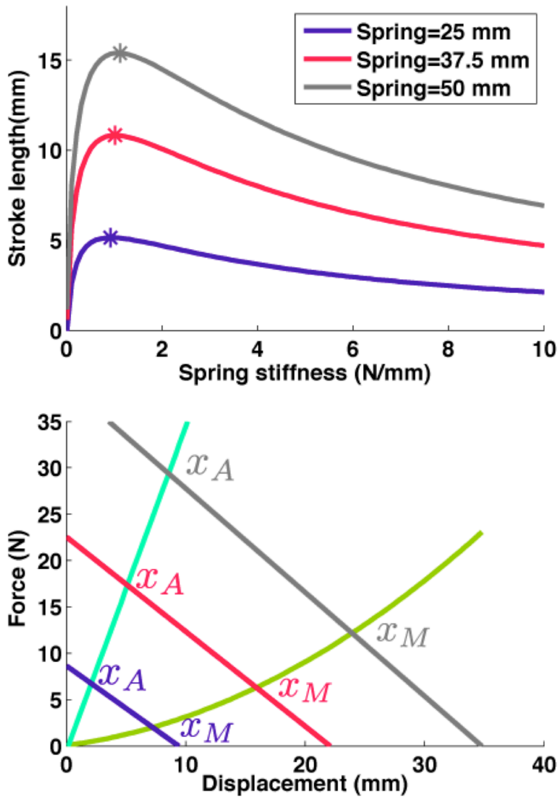

Figure 6. Optimizing the stroke length over stiffness for three lengths of bias spring (top). As expected, the total stroke length increases as the spring length increases. The optimal spring stiffness marked with a star on top is then plotted (bottom) for each spring length, where the Austenite stiffness (green) and the Martensite stiffness (yellow) are fitted from data from real devices we have made. The equilibrium displacement length for the three different bias spring lengths are indicated in the same color as the spring stiffness curve at the points where the spring stiffness curves cross the martensitic and austenitic Nitinol stiffness curves.

C) Compute the points at which the spring curve intersects the martensitic and austenitic force curves as a function of the bias spring rest length and spring constant.

D) Finally, perform a constrained optimization where the objective function is the difference in static two static equilibriums with the constraints for the spring length and the martensitic equilibrium determined in (B).

A simple form of the static equilibrium configurations can be derived when modeling the Nitinol coils as linear springs, where the equilibrium solutions are

$$\text{Austenite equilibrium} \quad f_{ext} + K_s(x_A - \ell_0) + K_A(x_A - L_0) = 0 \quad (1)$$
$$\text{Martensite equilibrium} \quad f_{ext} + K_s(x_M - \ell_0) + K_M(x_M - L_0) = 0,$$

and the optimum bias spring is computed as

$\{L_0{}^*, K_S{}^*\} = \text{argmax}_{L_0,K_S}|x_M - x_A|$.

Here, f_{ext} is any externally applied load on the device, K_s is the spring constant of the bias spring, K_A is the spring constant of the Nitinol when in the Austenite phase, K_M is the spring constant of the Nitinol when in the Martensite phase, ℓ_0 is the rest length of the bias spring, L_0 is the memory rest length of the Nitinol spring, and x_A and x_M are the Austenite and Martensite equilibrium displacement with respect to the memory rest length of the Nitinol spring.

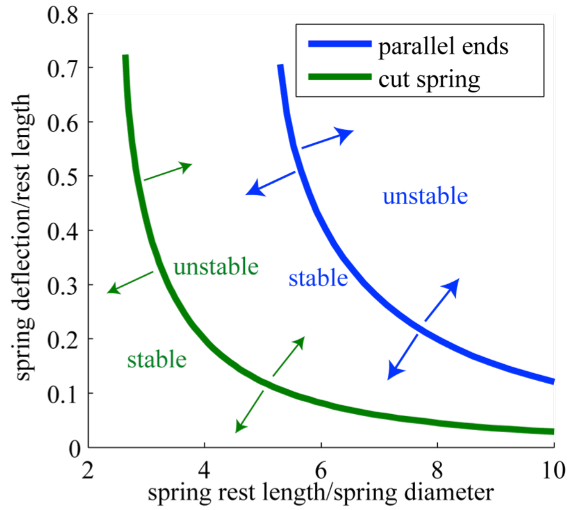

Figure 7. The stability of the bias spring in terms of the spring length, the spring diameter, and the amount of deflection.

In many respects, a constant force spring would be the ideal bias spring for maximizing displacement, though such springs are often not available at such small scales and they often have a low number of allowable cycles before failure.

In Fig. 6 (bottom), we show we see the Austenite (green) and Martensite (yellow) stiffness curves from fitted data. Fig. 6 (top) show that for each length, there is a distinct optimum stiffness of the bias spring. These optimum values are plotted in the corresponding color in Fig. 6 (bottom). Note that in this figure, we have not enforced any of the constraints given in Step B above. As such, the optimal spring constant is nearly the same for all of the spring lengths demonstrated. If there had been a constraint to prevent permanent plastic deformation, the longer springs would have necessarily been of lower stiffness to avoid over-straining the Nitinol coil.

Finally, in Fig. 7 and 8 we demonstrate the process of optimizing a bias spring for one of our manufactured coils. Fig. 7 is a graphical depiction of the spring buckling contraints that must be followed to ensure that the parallel bias spring does not buckle when the Nitinol transitions from the martensitic to austenitic phases. This particular design parameter is not present in a Nitinol actuator design where the bias spring is in parallel with the Nitinol element because the bias spring is always in tension. The advantage of a design utilizing a parallel bias spring is that the length of the device can be made much more compact, at the expense of ensuring the device is wide enough to meet the necessary spring rest length to spring diameter criteria shown as the X-axis in Fig. 7.

Fig. 8 (top) shows both the force-displacement characterization of the coil in the Austenitic phase (red) and the Martensitic phase (yellow). The Martensitic characterization was conducting by sequences of stress and release steps to identify the point at which permanent plastic deformation begins. With this set of coils that were 16 mm long, permanent plastic deformation begins after approx. 14 mm of strain. This bias spring was selected from commercially available low-pressure springs available from

Lee Spring (Lee Spring Ltd, Wokingham, England). In Fig. 8 (bottom), we plot the optimal length and stiffness for a 50 mm spring and the curves for the entire Lee Spring LP series springs. As a spring is cut down, its spring constant will increase, such that the stiffness will increase inversely proportional to the change in length. Here we see that there is a low pressure spring than nearly matches the optimal parameters, namely model LP 026GH 06S316 being trimmed to the 50 mm length. Some manufacturers sell cut-to-length springs where they specify a *spring rate* where the spring constant is given as the spring rate time the length.

These steps of identifying the Nitinol characteristics, delineating the constraints provided by the mechanism design, solving the constrained optimization for the length and spring constant, and finally finding a commercial spring that either satisfies or can be made to satisfy the optimal characteristic provides a straightforward method of quickly designing one-way Nitinol coil mechanisms.

IV. Conclusions and Future Work

In this paper, we described the analysis and procedure for designing a compact Nitinol-based SMA actuator utilizing a passive linear spring in parallel with the active element. We examine the active force/deflection behaviors of the two material phases (martensite and austenite), as well as describe the net behavior of common coiled NiTi wire as it relates to the choice of antagonist. The parallel architecture is more challenging to analyze due to the fact that the force on the two components is not explicitly equal and that the buckling of the elements must be considered, but is much more compact than the more common linear arrangement.

In terms of future work, the immediate extension is the consideration of the design of the antagonist pairs for the purposes of maximizing the stiffness variation of the actuator module between phases. While the representative plot shown in Fig. 3C shows the basic idea, the magnitude of the variation in stiffness is a complicated function of the stress/strain behavior of the SMA element (including implemented geometric considerations such as coiling) as well as how the intercepts of those curves with the passive spring element can be varied with slope (i.e. stiffness) and intercept (i.e. pre-load).

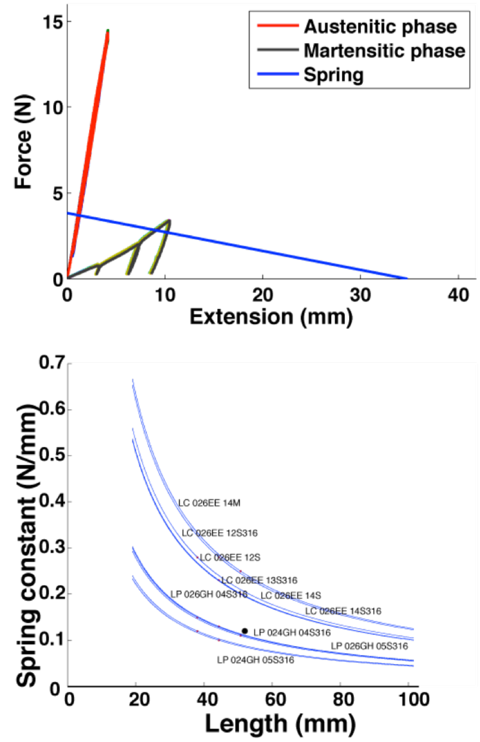

Figure 8. Bias spring optimization for experimentally characterized Nitinol coils used in an inchworm robot. The top shows the force-displacement curves for the prepared Nitinol coils when in the Austenite phase (red) and the Martensite phase (yellow). The Martensite characterization consisted of cyclic straining and relaxation of the coil, without heating to return to the memory length. These 16 mm coils were able to extend approximated 14 mm before permanent plastic deformation occurs; the characterization experiment stopped extending around 12 mm to prevent such damage.

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