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Novel bio-inspired mechatronic articulation with potential for use in space

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ABSTRACT

Joints are failure points for deployable systems and moving devices. Their reliability and efficiency are of great concern for space applications. In this paper we present a new biologically inspired joint for space applications that has a minimal number of parts and requires no bearings. Its principle is based on a compliant structure that changes shape with Shape Memory Alloy actuators. An experimental two degrees of freedom prototype joint is built and proves the concept. Analysis of a simple model of the joint shows that further optimization with respect to the motion envelope is possible.

1. INTRODUCTION

Joints are failure points for deployable systems and moving devices. Their reliability and efficiency are of great concern for space applications. Weight and dimensions must be reduced as much as possible since they have a direct impact on launch costs and thus on space mission budgets. New joint concepts that meet these harsh requirements are more than welcome.

Biology shows many clever designs and forms a huge potential pool of clever interesting mechanisms for robotic applications [1, 2, 3]. The number of species of insects is truly awesome, for example there are over 600,000 scientifically described species of beetles with at least twice that number remaining to be discovered and described and beetles are only one type of insect. To put that number into perspective, there are probably around 10,000 species of birds, and maybe 4,000 species of mammals. The total number of interesting mechanisms in insect species, birds and mammals is almost beyond imagination.

This paper is the result of a study focused on articulations found in nature. Both the joint layout, kinematics, actuation, and control levels were studied during the research study. It was found that:

a. hydroskeletons feature various muscle arrangements, generating different types of motion without a structural skeleton at all [4],

b. exoskeletons feature asymmetric joint activation (sometimes even based on hydraulic principles) with return spring mechanisms,
c. exoskeletons feature a closed skeletal structure that flexes on the point where joints are required (so there are no sliding elements),
d. endoskeletons feature clever mechanisms that facilitate energy storage, weight compensation, and muscle translocation, most of them serving dynamic movements tasks [5, 6],
e. mammals have a highly developed neuro musculo-skeletal systems that allows optimal and adaptive control [4].

Combining the findings mentioned above, the authors conceived a new compliant mechanism that can change shape, performing the flexion function of a rotational joint.

In this paper, we will investigate the possibilities of this active compliant structure. The scope of this paper will be on the investigation of the motion envelope of the joint, which is largely determined by the chosen joint geometry. The structure of the paper will be to start with the lay out and design of the joint along with some first experimental results. Next a simulation model of the joint will be built and consequently this model will be analyzed on its design parameters to verify if further design optimization is achievable.

2. JOINT LAY-OUT AND DESIGN

The principle consists of off-centered spring-elements (agonist-antagonist pairs) of which the agonists (inside) are the actuators, and the antagonist (outside) is the carrying and enclosing structure or exoskeleton of the joint. The joint lay-out is given in Fig. 1

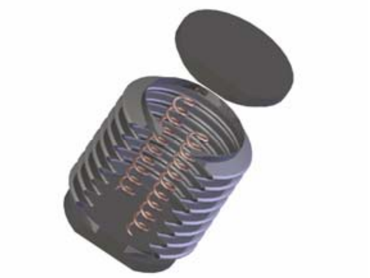


Fig.1 Artist impression of the joint lay-out.

The enclosing structure is a passive spring element and pre-tensions the inner springs. The latter are chosen to be Shape Memory Alloy (SMA) actuators. These have a high power density [7] and are space compatible. The mechanism is simple and compact without sliding elements. This reduces energy dissipation and the need for bearings or lubrication.

A first experimental test set up was constructed to see whether this concept could work. Fig.1 depicts a closed structure on the outside. This could be, for instance, a bellows-type of mechanism. For the sake of simplicity, the authors chose to have a helical compression spring on the outside instead. With three SMA actuators two degrees of freedom can be controlled, Fig. 2.

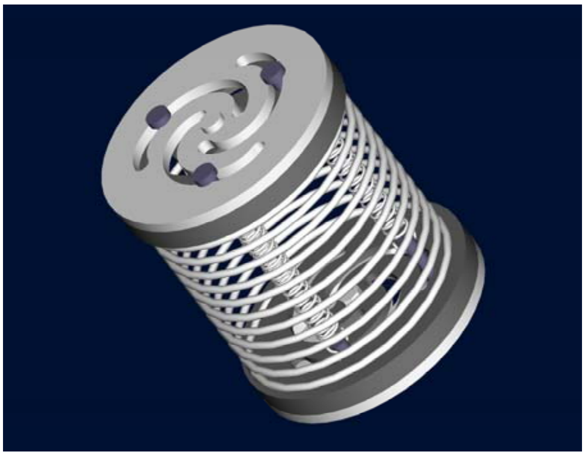
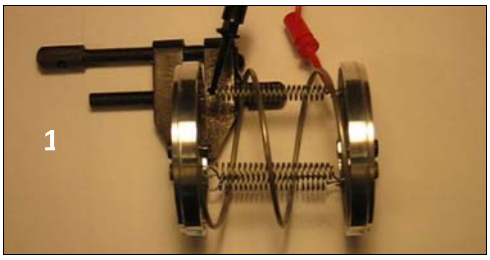
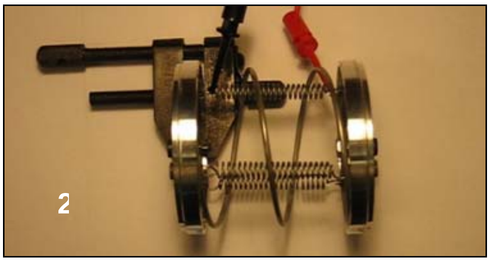


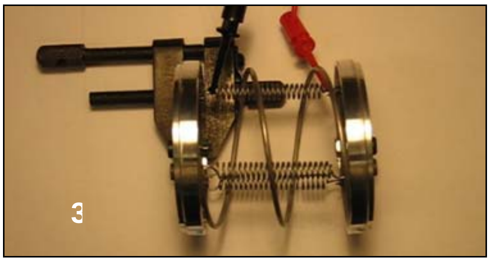
Fig 2. A drawing of an experimental test-set up of the joint. It has 3 helical wound NiTi SMAs, and a helical wound compression spring on the outside.

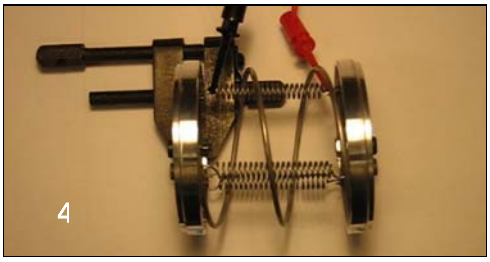
The SMA actuators are from Modotronics and have a maximum force approximately 4 [N] each. Their attachment points are from electrically isolating material (PVC) and can slide within the spiral grooves to adjust their distance to the joint center.

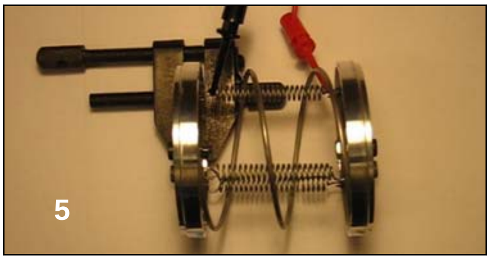
During the experiments one of the three SMA springs was heated with a 2 [Amp] current. Fig. 3 shows a movie strip with a 4 [s] time frame interval. The joint bends within the visual plane of the camera. Bending angles up to 10 degrees were obtained.

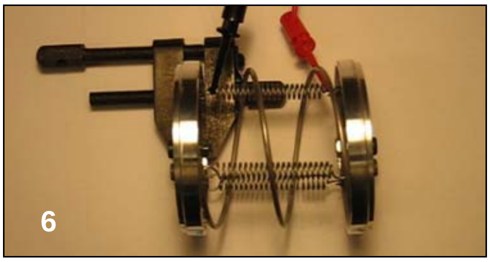












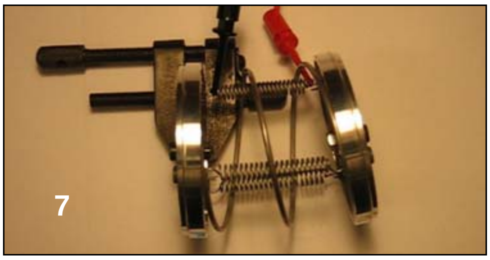


Fig. 3 A movie strip of the joint moving. The time frame interval is 4 [s].

3. JOINT MODELING

The motion envelope of the joint is largely determined by the geometry and compliance of the joint. There are opposing design criteria, such as:

- High outer spring stiffness limits the maximal bending angle, and provides joint stability.
- Low outer spring stiffness gives a large angular workspace by limits the joint stiffness and might provide insufficient pretension for the SMAs.

Similar opposing criteria can be found for parameters like outer spring diameter, and zero length. This suggests an optimum geometry of the joint with respect to its motion envelope. At the same time the workspace of the SMAs (strain and force) have to be respected. In order to make this joint work properly, a model was constructed to optimize its geometry

We started by assessing the performance of the SMA springs used as actuators for the proposed novel active joint. Cyclic force measurements were conducted as depicted in Fig. 4.

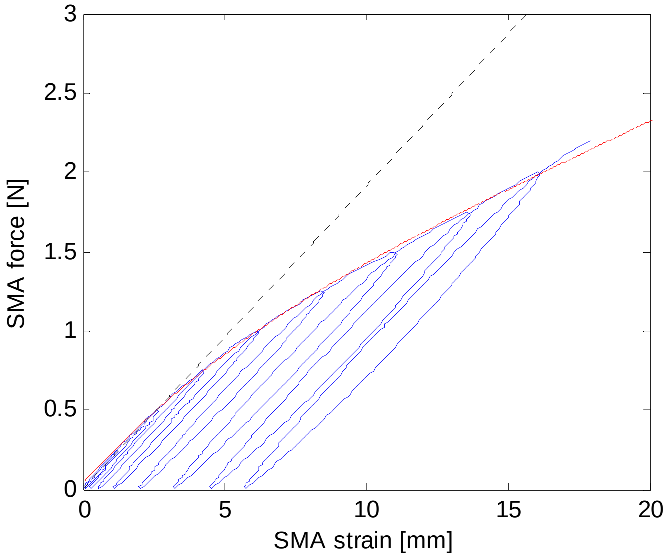


Fig. 4 Plot of the measured NiTi helix SMA. The black dotted line indicates a heated SMA, the cycles indicate the saturation and the deformation of a cool SMA. The red line is a 4th order polynominal approximate.

A Fourth order polynominal was used to approximate the measured force saturation curve of the SMA, depicted in Fig. 4. When heated the SMA was a near perfect linear spring, plotted in Fig. 4.

The joint itself was approximated as a planar system of 2 compression springs on the outside (each of half the spring stiffness) and 2 SMAs, see Fig. 5. Due to the fact that the system is a spatial structure, the non-active SMAs (nr.1 and 2) are lumped into one SMA on half the distance to the joint center with twice the stiffness, Fig. 5.

The equilibrium equations can be written as:

$$F_b^L + F_b^R - F_{sma}^L - F_{sma}^R = 0$$
$$F_b^L \cdot D_b - F_b^R \cdot D_b - R_{sma}^L F_{sma}^L + R_{sma}^R F_{sma}^R = 0$$

where: ***F*** is a force, index ***b*** indicates bellows (or out spring), index ***sma*** indicates SMA, index ***L*** indicates left side, index ***R*** indicates right side. ***D*** is the diameter, and ***R*** is the radius indicated in Fig. 5.

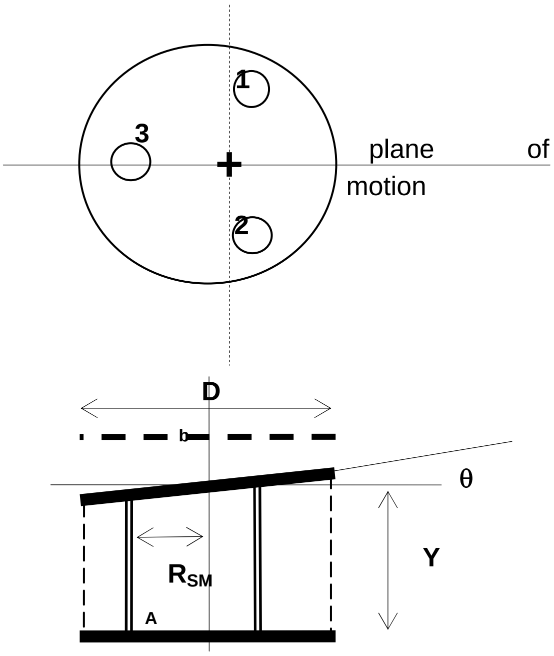


Fig. 5 The model is reduced to a planar model, within the plane of motion. SMA 1 and 2 are lumped to 1 SMA with twice the stiffness on half the distance to the joint center.

The forces can further be specified as:

$$F_b^L = \tfrac{1}{2} C_b \left(L_b^0 - y + \tfrac{1}{2} D_b \sin\theta \right)$$
$$F_b^R = \tfrac{1}{2} C_b \left(L_b^0 - y - \tfrac{1}{2} D_b \sin\theta \right)$$
$$F_{sma}^L = \tfrac{1}{2} C_{sma} \left(y - L_{sma}^0 - U_{off} - R_{sma} \sin\theta \right)$$
$$F_{sma}^R = \tfrac{1}{2} C_{sma} \left(y - L_{sma}^0 - U_{off} + R_{sma} \sin\theta \right)$$

where: L^0 is the zero length and U_{off} the offset of the SMAs (distance of the active coils with respect to their attachment).

The measured values of the parameters are shown in Table 1. The values for the bellows stiffness (***C_b***) and zero length (***L^0_b***) were varied.

symbol	**value**	**unit**
D_b	60	mm
R_{sma}	20 (high setting) 11 (low setting)	mm
L^0_{sma}	16.8	mm
U_{off}	22.2	mm
C_{sma}	0.1911	N/mm

Table 1 The measured values of the model parameters

4. MODEL ANALYSIS

With the model defined in Section 3, simulations were performed for various settings of the bellows/spring stiffness and zero length, plotted in Fig. 6.

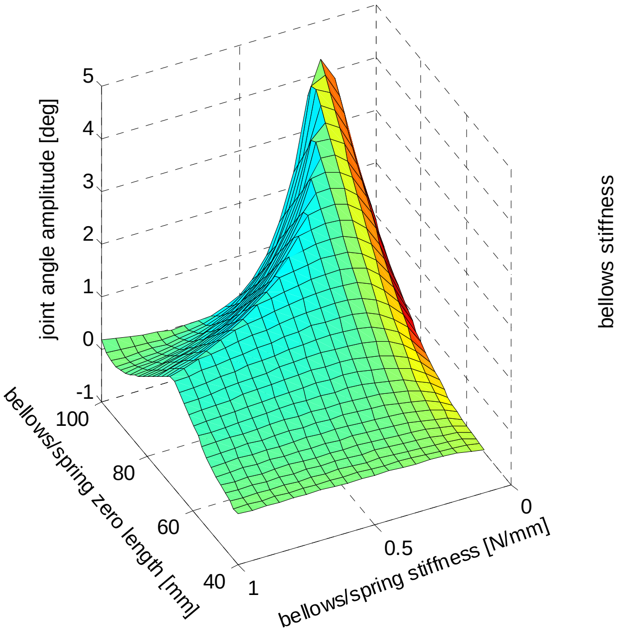


Fig. 6 A grid search plot for various setting of the spring/bellows zero length and stiffness. Clearly a narrow optimum exists.

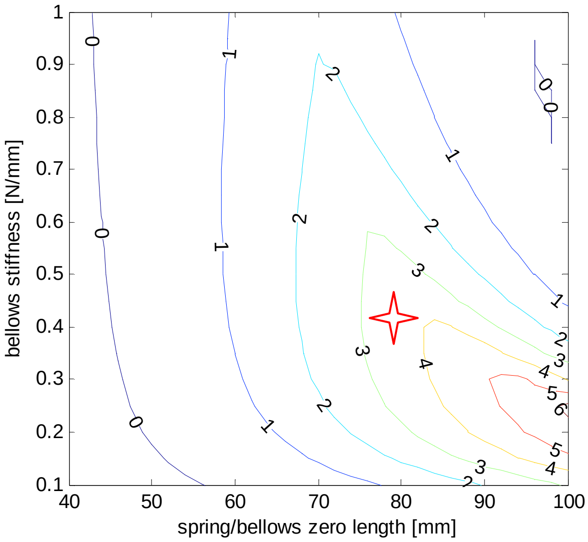


Fig. 7 Contour plot of Fig. 6 which shows the experimental test set up (star). Although the first prototype is close to a maximum, larger bending angles are to be expected for different settings of the bellows zero length and stiffness.

Varying the distance between the SMAs showed that the 'high setting' for R_{sma} was preferred. If bending angles get bigger, the spring might hit the bellows/spring outer structure.

The contour plot in Fig. 7 indicates the settings of the maximum achieved bending angle in the experimental set up. Although the measured angle was higher than predicted by the simulation, the figure clearly indicates that larger bending angles are to be expected for different spring/bellows settings.

5. CONCLUSIONS

Performed analyses and experimental tests proved that the bio-inspired concept of a compliant joint with SMAs works. The motion envelope of the joint depends on the geometry and compliance values of the structural frame. Simulations of a simplified model showed that the system can be largely improved and is potentially suitable for future realistic industrial implementation. Further work is needed in order to model and characterize the time response of the system in vacuum.

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