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Development of shape memory alloy actuators with inherent guidance function

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A B S T R A C T

Shape-Memory-Alloys (SMA) are suited for miniaturized drives since they possess a high specific workload and scalability. However, most SMA drives still require guidance to realize stiffness. But, there is a design approach for actuators which realize both. Here, the stiffness in the non-moving directions is achieved by the arrangement of the SMA as wire robot. This paper presents a general description of such actuators. Based on that the design of such actuators is formulated as a mathematical optimization algorithm providing a correlation between the variables for design and specification. In order to evaluate this approach, a rotary and a linear actuator are designed and experimentally investigated.

1. Introduction

Modern high precision machine tools for small work pieces are usually downscaled equivalents of macro scale machine tools. The dimensions of applied machine components such as drives, guidance elements and supports do not significantly differ. Hence the cross-section of such machines is related to their large counterparts. Due to the rather small workspace of these machines they are characterized by an extensive disproportion between workspace and cross-section. The dimension of the machine commonly exceeds the dimensions of the work piece by orders. This effect is mainly caused by two reasons. Firstly, the miniaturization of drives is limited because their physical principle necessitates minimum sizes. Secondly, guidance elements need a certain dimension to realize the expected stiffness. Due to their high specific workloads and relatively small spatial requirements, Shape-Memory-Alloys (SMA) possess an outstanding potential to serve as miniaturized positioning devices in small machines and numerous other applications [1]. However, most of the known SMA drive applications are still complex and necessitate additional guidance elements to realize a certain mechanical stiffness. There are only few known approaches where the solid state properties of shape memory alloys are consistently used for the function of combined actuation and guidance. A micro system actuator for realizing two-dimensional movements without requiring additional guidance is presented in [2]. Another approach, as shown in [3], describes a multi-staged approach using SMA sheet structures to realize solid state properties. However, all known solid state actuator principles are based on very difficult to manufacture SMA structures working as mechanical bending elements. There is currently no known approach for solid state actuators that use the advantages of contracting SMA-wires as described in [4]. In [5] a wire-based SMA actuator design which does not require additional guidance is presented. The stiffness in directions different from the moving direction of the actuator is realized by an offset angle of β between working direction and wire. Hereby the stiffness of an SMA-wire is split into a longitudinal and a transversal component. Thus the support of transversal loads is possible and no further guidance elements are required.

This paper presents a general description of such actuators. Based on that the design of such actuators is formulated as a mathematical optimization algorithm providing a correlation between the variables for design and specification.

2. Mathematical description of the design approach

2.1. General description of actuator kinematics

The actuator consists of two groups of n SMA-wires which are connected between frame and end effector as shown in Fig. 1.

Every group is responsible for one moving direction, resulting in an antagonistic wire configuration as presented in [6]. Since the presented approach uses SMA-wires as load-carrying and working

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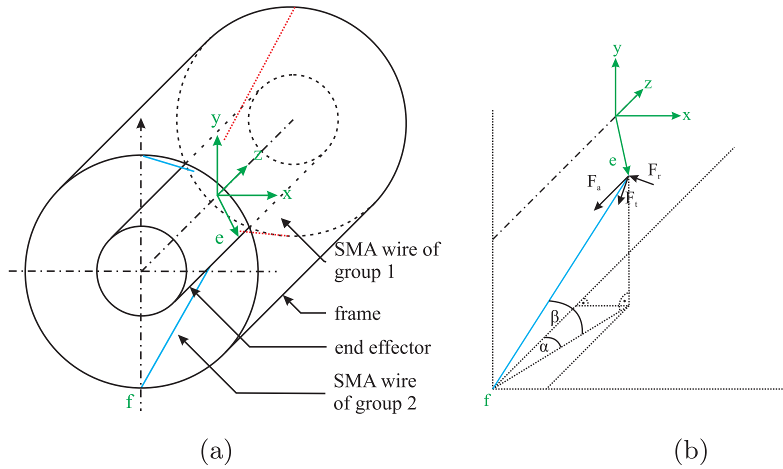

Fig. 1. (a) General actuator arrangement, (b) single wire arrangement.

elements, it can be described as a cable-driven manipulator as long as the diameter of the wire is magnitudes smaller than its length. If the actuator has at least four SMA-wires per group, it can be characterized as a redundantly restrained parallel manipulator (RRPM) [7,8] which means it can have a maximum of 6 degrees of freedom (DOF) if every wire is actuated separately. This results in stiffness in all directions.

In order to model the actuator a general mathematical description of the kinematic structure is necessary. For this purpose only one wire of the actuator is examined as illustrated in Fig. 1b. This wire is linked between the frame-point f and the end effector point e. The wire has two angular orientations: α projected in the x–z-plane being responsible for the type of motion and β defining stroke, force and stiffness. A value of $\alpha = 90^\circ$ results in a rotary workspace and a value of 0° in a linear one. Any value between 90° and 0° results in a spiral workspace. The force of the wire is split into three components, one axial, one tangential and one radial. If one wire group consists of n wires, which are rotated by $2\pi/n$ relating to the z-axis, and all wire forces $\boldsymbol{F}$ are equal, the resulting force and moment are determined by:

$$\boldsymbol{F}_{\mathrm{res}} = \sum_{\mathrm{i}=1}^{n} (\mathbf{R}_z(2\pi/n \cdot i)) \cdot \boldsymbol{F} \tag{1}$$

$$\boldsymbol{M}_{\mathrm{res}} = \sum_{\mathrm{i}=1}^{n} (\mathbf{R}_z(2\pi/n \cdot i)) \cdot \boldsymbol{e} \times \boldsymbol{F} \tag{2}$$

With the summation of $\mathbf{R}_z$ (rotation matrix) as shown in Eq. (3) $\boldsymbol{F}_{\mathrm{res}}$ and $\boldsymbol{M}_{\mathrm{res}}$ only have components in z direction.

$$\sum_{\mathrm{i}=1}^{n} (\mathbf{R}_z(\phi(n) \cdot i)) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & n \end{pmatrix} \tag{3}$$

This results in one DOF if all wires of one group are equally activated.

2.2. Modelling of the actuator motion parameters

The significant actuator motion parameters include the two aspects of blocking force or torque and the maximum load-free movement. Both values depend on the acceptable maximum values of stress $\sigma_{\max}$ and strain $\varepsilon_{\max}$, which are the essential design parameters considering the durability requirements. Assuming a maximum wire stress σ_{max} , the radius of the wire r, the preload force F_0 and Eq. (1), the blocking force can be obtained by:

$$F_{\mathrm{block}} = n\cos(\beta) \cdot (\pi^2 \sigma_{\max} - F_0) \tag{4}$$

The blocking torque can be calculated similarly:

$$M_{\mathrm{block}} = \|E\| n\cos(\beta) \cdot (\pi^2 \sigma_{\max} - F_0) \tag{5}$$

Eqs. (4) and (5) are only valid in case of a linear (Eq. (4)) or rotary (Eq. (5)) actuator. The calculation of the maximum load-free movement is based on the direct kinematic problem of the actuators. In general the direct kinematics of parallel structures cannot be determined analytically [9]. Thus only the two relevant special cases of linear and rotary actuators are examined. To calculate the load-free stroke $\Delta z_{\max}$ of a linear actuator, the single wire arrangement of Fig. 1a is projected into the y–z-plane which is visualized in Fig. 2. If the SMA-wires of one group are elongated (1) to $\varepsilon_{\max}$, the end effector is in position e. After the wires are completely activated (2), the end effector moves to point e‘. The maximum linear stroke $\Delta z_{\max}$ is defined as the difference between Z_0 and z‘, which can be calculated by the length of the contracted SMA-wire l_0 :

$$\Delta z_{\max} = \sqrt{(l_0 \cdot (1 + \epsilon_{\mathrm{rev}}))^2 - (\sin\beta \cdot l_0)^2} - l_0 \cdot \cos\beta \tag{6}$$

The maximum angle $\varphi_{\max}$ of a rotary actuator is based on the projection of the single wire arrangement of Fig. 1b into the x–y-plane, which is shown in Fig. 2. The actual position of the end effector point e (l) depends on the current length of the SMA-wire l. It can be calculated as the intersection of the two circles (3) and (4). Using this intersection point, $\varphi_{\max}$ can be determined:

$$\varphi_{\max} = \arctan\left(\frac{e_x}{e_y}\right) \tag{7}$$

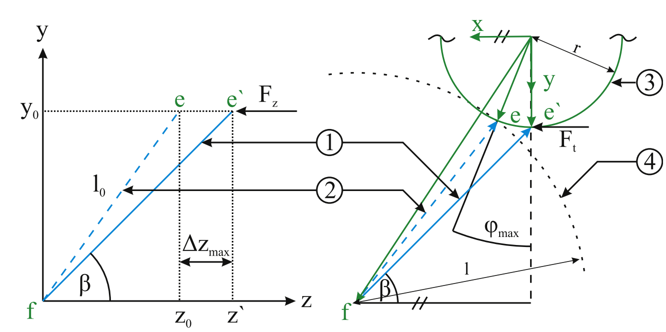

Fig. 2. Projections of linear (left), rotary actuator arrangement (right).