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Title(English)	Physical Compensation of Output Non-Linearity in Shape Memory Alloy Actuators
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論 文 要 旨

THESIS SUMMARY

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要旨（英文 800 語程度）
Thesis Summary (approx.800 English Words)

Shape Memory Alloy (SMA) actuator control, when using temperature as input, is challenging due to the SMA's nonlinear relationship with displacement and force output, often requiring compensation for effective control. In the literature, SMA models have been proposed as a way to provide this compensation, but this method has its drawbacks. The nonlinear output behavior of SMA changes due to various initial and state-dependent variables such as temperature, stress or strain, prestress, martensite fraction, alloy composition, etc., so the compensation may become inaccurate if any of those variables are not measured and taken into account by the model. An approach that could compensate for the nonlinearity of SMA without relying on its initial and state-dependent variables would be desirable. For this reason, the objective of this thesis is to devise a construction concept for SMA actuators that can improve their open-loop output linearity and to assess the effectiveness of the proposed concept by testing prototype actuators.

To enhance the output linearity of SMA without a model, a physical compensation approach is proposed. This approach substitutes the nonlinear temperature input variable with an 'activation ratio' that is linearly related to displacement and force, reducing the non-linearity of the actuator without requiring initial or state-dependent SMA variables. Two construction arrangements for this idea are explored: parallel and serial. Both configurations use SMA bundles and a fluid that transports the thermal energy to the SMA components, wet activation, as a common element.

For the parallel configuration, the number of parallel SMA wires (parallel activation ratio) replaces the temperature as the input control variable. Three prototypes using this concept, ZFMALA, CFSMALA, and CFSMALA-v2, in which the activation ratio was manually changed. Then, they were evaluated with isometric experiments to determine their capability to improve the linearity of force output and perform iterative improvement of the prototype and test bench, focusing on time response. For all prototypes, the results of the experiment showed improved open-loop linearity compared to a typical SMA temperature-controlled actuator. Moreover, the addition of forced convection heat transmission, a thermal liquid injected into the CFSMALA, reduced the actuator response time compared to the original ZFSMALA. By decreasing the size of SMA chamber of the CFSMALA-v2, further response

enhancement was obtained. Additionally, the differential wire mechanism tested on the CFSMALA-v2 was shown to reduce the impact on the output force of differences in the length of the SMA wire bundles, improving the force transmission efficiency. Due to the complexity of its automation, the parallel configuration was not paired with a controller.

For the serial configuration, a hot/cold water mix ratio replaces temperature as the input control variable. The mix ratio modifies the position of the inflection point of a temperature gradient that activates specific longitudinal sections of the SMA (serial activation ratio). An SMA chamber is presented that can generate and control the position of the inflection point of this gradient. The main idea is to use two input ports for hot and cold water, arranged longitudinally and antagonistically, coupled with uniformly spaced outlets on either side. By adjusting the flow rate ratio between the inputs, it is possible to control the position of the temperature gradient's inflection point in the SMA chamber, thus, the activation ratio of the actuator. Two actuators, GASMAA-F and GASMAA-D, were built and tested on this concept, with their chamber and SMA elements designed for force and displacement, respectively. Both chambers showed good performance controlling the actuator's activation ratio. Similarly to the parallel arrangement, the results of the serial configuration experiment showed improved open-loop linearity and enhanced time response compared to the temperature-controlled case and with good repeatability. GASMAA-F showed poor performance in covering the entire output range of the actuator, which was not the case for GASMAA-D. It was possible to control both actuators with a PID controller and output feedback, achieving good performance in terms of resolution and error.

This thesis addresses output non-linearity in SMA actuators via a model-free approach using physical compensation. Two configurations, parallel and serial, introduce an 'activation ratio' as a linearizing input variable. The prototypes validate the linear relationship between the activation ratio and actuator output. The parallel configuration proves the feasibility and offers design improvements. The serial setup, with an SMA chamber design that produces a temperature gradient, shows automation potential, simplifying SMA actuator control. Future work includes optimizing GASMAA geometry for enhanced performance, exploring arrays of actuators, and demonstrating GASMAA's application potential over traditional SMA actuators in specific applications.