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Shape memory alloy wire for self-sensing servo actuation

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ABSTRACT

This paper reports on the development of a straightforward approach to realise self-sensing shape memory alloy (SMA) wire actuated control. A differential electrical resistance measurement circuit (the sensorless signal conditioning (SSC) circuit) is designed; this sensing signal is directly used as the feedback for control. Antagonistic SMA wire actuators designed for servo actuation is realized in self-sensing actuation (SSA) mode for direct control with the differential electrical resistance feedback. The self-sensing scheme is established on a 1-DOF manipulator with the discrete time sliding mode controls which demonstrates good control performance, whatever be the disturbance and loading conditions. The uniqueness of this work is the design of the generic electronic SSC circuit for SMA actuated system, for measurement and control. With a concern to the implementation of self-sensing technique in SMA, this scheme retains the systematic control architecture by using the sensing signal (self-sensed, electrical resistance corresponding to the system position) for feedback, without requiring any processing as that of the methods adopted and reported previously for SSA techniques of SMA.

1. Introduction

Self-sensing (the ability of a transducer to sense its motion as it is being driven) has been demonstrated for electromechanical transducers such as moving voice coil loudspeakers and, piezoelectric distributed moment actuators [1]. In these devices, self-sensing was achieved dominantly by constructing a bridge circuit to extract a signal proportional to the transducer motion even as the transducer was being driven.

Self-sensing actuation (SSA) considers the possibility of using a single element as both sensor and actuator; thus avails/purposes/features shared sensing and actuation. SSA in intelligent material uses a single piece of piezoelectric/magnetostrictive/shape memory alloy (SMA) element that simultaneously performs as both a sensor and an actuator. This idea should be advantageous especially for control of flexible structures. Unlike piezoelectric or magnetostrictive transducers, SMA does not exhibit direct and converse (piezoelectric or magnetostrictive) effect of switching the functions between sensor and actuator; but SMA exhibits shared sensing and actuation functionalities by SSA or suitable mono-design for bi-functions.

SSA in SMA is through the SME; this transduction is inherently non-linear. The use of resistance as a sensor to realise self-sensing position control has been implemented [2–4,17]. It also acts as a high-resolution sensor, by replicating even the minute variations in its actuation (high precision).

When a single SMA wire is used as an SSA, it possesses many advantages over the use of two separate SMA elements as individual sensors and actuators. The concept of a self-sensing piezoelectric actuator was first developed and published [5]

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for vibration control; while SSA in SMA was first reported [6] for an active endoscope. SSA systems are lighter and less costly than non-collocated sensor/actuator systems because they employ a single element. Furthermore, the collocation of sensing and actuation allows the control signal to be applied at the point of measured response, thereby eliminating the coupling between the sensor and actuator element. Self-sensing allows actuating an SMA device while sensing its displacement (strain) and/or applied force (stress). The intrinsic technique may be further used in a closed-loop system without needing external sensors.

1.1. Antagonistic SMA actuated system: background

The two-way actuators/ antagonism/ differential type made of two SMA elements have the advantage of easier and faster control while the bias type actuators require less power, making them more desirable for internally powered devices. The bias type actuators can be very slow if there is an overshoot thus requiring cooling and the work of the bias spring for reverse actuation. Considerable research for antagonistic type control application has been made in the last few years. A novel SMA actuator [7] is designed comprising of 12 SMA wires in a helical arrangement that produced larger strains than long, straight SMA wires, but at the expense of reduced force outputs. Using the actuators in an antagonistic arrangement, they investigated the use of two-stage relay control, which is a form of Variable Structure Control (VSC). An antagonistic pair of actuators is presented to show that the SMA wires can control forces both rapidly and precisely. The results demonstrated fast and accurate force and position responses with 0.1 s rise times for large force steps of 7 N and position steps of 2.5 mm, as well as stable tracking of both 2 N and 1.5 mm amplitude sine commands at 2 Hz. One major problem they faced was the existence of limit cycles, or oscillations, due to the discontinuous switching of the relay controller. Grant and Hayward [8] managed to address this problem using a dead band controller in their control system under the 'no load' condition. Grant further extended this work in the presence of a load disturbance [9], and although the limit cycles had been reduced, they were not eliminated. A control scheme for angular position control of a rotary load using SMA wires in antagonistic configuration is presented [10]. The controller designed is based on partial feedback linearization and sliding surface concepts. Position control architecture using an actuator designed by an antagonistic pair of SMA wires is demonstrated [11,38,39]. The force control architecture consists of a differential controller, an anti-slack mechanism, a rapid-heating mechanism, and an anti-overload mechanism. The results showed fast and very accurate responses to force commands with no sign of limit cycles. They have obtained the results similar to Grant's, but by using simple PID controllers and ignored the nonlinearities of the system. The literature [12] has reported on differential type SMA actuators that were operated at a very low frequency but were not involving self-sensing. SSA techniques [2,6,13–16] have been adopted but come with certain limitations. The self-sensing techniques mainly have two approaches: mapping and modelling of SMA material properties. The mapping employs two methods, namely polyfit or curve fitting and neural networks (NN). The former is used to calibrate the electrical resistance variation (sensing signal) with the external physical sensor and establishes a polyfit function between them. In this approach, the accuracy is highly dependent on the accuracy of the external sensor used and the order of the polyfit equation; it is normally taken up to only 6 degree due to the limitation of the software computation (like in MS Excel/ MATLAB [6,17,18]. NN approach needs open loop experimentation that should be done off-line to implement the resistance-position mappings to train the algorithm [13]; the accuracy of the NN approach is highly dependent on its training using several sets of mappings obtained from the experiments. The modelling approach requires no measurement feedback but depends on any of the following mathematical modelling of SMA: stress-strain relation, mathematical heating models, hysteresis model, a constitutive equation relating the changes in temperature and mole fraction to the stress and strain induced in the SMA, as used in SMA actuated systems [19–24]. This approach mainly depends on the precise knowledge of the ambient temperature and material properties. At ambient temperature, the material properties remain mostly constant, and it becomes difficult in cases where this temperature experience unexpected changes [22]. So, this paper intends to overcome the limitations and is presenting a better self-sensing technique:

- A technique that requires no open loop experimentation and external physical sensor, which can used directly to the SMA wires for measuring the variation in electrical resistance of the wire.
- Which can be used for any self-sensing SMA actuated system, i.e., an approach that is system independent.

To meet the demand of the sensing technique, a simple solution to the self-sensing SMA actuated system is proposed by designing an electronic (sensorless signal conditioning) circuit that measures the variation of electrical resistance in SMA wire actuator (sensing signal) that acts as both, driving and sensing simultaneously. Without any open loop experimentation, this electronics measuring technique can be applied to the single wire to multi wire configuration. The method is system independent and compatible with any SMA driven system regardless of the dimension of wires used along with proper pretension. SMA wires are configured in antagonistic mechanism for rotary motion; also a relation between the angular rotations (degree) to the strain of the SMA wire is established. Even though most of the tracking applications use antagonistic setups, all of them are made to operate at low frequency undergoing full phase transformation. In particular, this bi-directional rotary self-sensing tracking has achieved higher bandwidth up to 2 Hz by proper design of the actuator configuration. The actuator design can vary the frequency of operation for any system and the factors affecting the angle of rotation of the manipulator is presented. This proposed rotary control is an ideal actuator for manipulators where stroke and power density, rather than speed, is of primary concern.