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Shape memory alloy with bi-functionality in the master system to control a slave

Josephine Selvarani Ruth D., K. Dhanalakshmi *

Department of Instrumentation and Control Engineering, National Institute of Technology, Tiruchirappalli 620015, India

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ABSTRACT

Application of a shape memory alloy (SMA) with bi-functionality, acting as a force sensor and as an actuator (***sens***or + h***aptics*** = '***sensaptics***') is proposed for the master side of a master – slave system. A 1-DOF master is instrumented with SMA wires to servo a 2-DOF slave. Antagonistic shape memory alloy wires employed in master system performs shared sensing and actuation; the operator's command to control the slave system is sensed by the variation in the differential electrical resistance of SMA and it functions as a haptic device to display the interactive force fed back from the slave to the master. From the haptic information the operator can make decisions and take appropriate action/correction in co-ordination with the requirement of the slave environment. The laboratory model of SMA based master – slave system is designed, developed and evaluated for its performance. The validity of the results proves the concept of shared bi-functionality.

1. Introduction

Master – slave is a dual robot system in which a remote slave robot tracks the motion of the master robot which is in turn commanded by a human operator. The tele-operation systems for medical applications were developed and have been studied by Melchiorri and Eusebi [1], Rosen et al. [2], Buttafuoco et al. [3] and Wang et al. [4]. The first commercial master – slave system was invented for robotic minimally invasive surgery (MIS) wherein, the surgeon's console provides visual feedback but no force or torque information about the surgical field. It was realized that a force-reflective console for the surgeon can counter balance the limited maneuverability of surgical instruments and restricted camera vision experienced in MIS. Incorporating force feedback into a robotic master – slave system calls for two devices: a force-reflective actuator in the master and a force sensor at the end-effector of the slave that can measure the tool–object interactions in the form of forces or torques. These interaction measurements at the slave's side are a prime cause for superior performance and fidelity that it can bring into haptics-based tele-operation, as opposed to position error based haptic tele-operation. Thus, the force tele-presence can provide the operator with interactive force information of the dynamic slave environment acting on the objects, and subsequently improve the operational performance as discussed by Sheridan [5], Matsuhira et al. [6], Ning [7] and Chen et al. [8]. Therefore, the master equipped with haptics is an ideal and efficient method for tele-control.

Shape memory alloy (SMA) exhibits a crystal transition between a high-temperature austenite phase and a low-temperature martensite phase. At low temperatures, an SMA exhibits a small Young's modulus and can be stretched easily; when heated, it contracts back to its original shape, overcoming almost twice its pulling force. The maximum recoverable strain of an SMA is a little over 4% of its original length. SMA actuators have been adapted for flexible and miniaturized applications and they are anticipated to play a pivotal role in future due to their high energy density, mechanical simplicity, compactness and clean operation. When a SMA changes its shape by metallographic transformation, the electrical resistance also undergoes a simultaneous observable change, and this is much more significant than the resistance change due to the alloy's shape as stated by Wang et al. [35]. This is an added advantage of SMAs as it leads to reduction in number of sensors and allows focus on miniaturisation. The only drawbacks of SMA are its low response rate and its non-linearity during the cyclic phase transformation. This work attempts to use the potential features of SMA for a highly dynamically responsive system by suitably handling the limitations with appropriate design and techniques.

* Corresponding author.
E-mail addresses: djsruth@gmail.com (J.S.R. D.), dhanlak@nitt.edu (D. K.).

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1.1. Literature on haptics for master – slave system

Master – slave systems have been applied to many areas since the 1960s when the first master – slave manipulator was developed by Geortz [15] and Sheridan [16]. Two types of actuation mechanism are common: passive and active type for force feedback in master slave system. The passive type is known to be safe; the active type using electric motor is widely used as a repulsive force or torque generating actuator. However, it has a complicated mechanism, safety problem and difficulty in continuous force control discussed by Pierrot et al. [17], Yamaguchi et al. [18]. Kerbs et al. [19]. have developed active (motor-driven) haptic device (MIT-MANUS) and conducted many clinical tests for upper limbs rehabilitation. However, the motor-driven robots basically require high-cost safety system compared to passive (brake-based) devices. In these systems, conventional power brakes were used as haptic generators. Generally, the response time of the power brake is more than 100 ms and it causes lack in quality of force feedback. To solve these problems, researches about haptic master using smart materials such as piezoelectric [20], electro rheological (ER) fluid, have been studied by Furosho and Kikuchi [21]. Two-types of actuators were developed using ER fluid, Kikuchi et al. [22]. designed an active-type ER actuator and passive-type ER brake as in Furosho and Kikuchi [21] for rehabilitation system. ER fluid is able to change their rheological properties such as yield stress by applying electric field. The fast response, simple mechanism, continuous force and high stability are the ideal properties for haptic master devices in which various different strengths of forces can be simulated. Due to the rapid response of ER fluids, the haptic device presented by Kikuchi showed good performance as a force display. ER fluid actuator-type system has high safety and good performance for haptic control, but it needs a lot of cost and size for actuator. On the other hand, ER fluid brake-type system is very compact and inherently safe; however, it has strong limitation of haptic varieties. Kikuchi et al. [23]. developed an active/passive switchable rehabilitation system called "Hybrid-PLEMO" with ER clutch/brake. To generate motion commands for the slave robot but also to generate the physical constraints of the slave robot to the surgeon a 4-DOF ER haptic master is designed by Oh et al. [24]. with encoder to sense the position commands to the slave. A controllable magneto rheological (MR) fluid based haptic master is made by Oh et al. [25]. to feedback function for a surgical robot and the performance is evaluated in the cyberspace that features virtual object.

1.2. Main contributions

The use of haptic feedback is advantageous in many applications, and that it is therefore appropriate to create lower cost master devices. The possibility of integrating sensorial capabilities into the actuators themselves is thus investigated. The focus of the work presented in this paper is to incorporate SMA for shared sensing and actuation in a haptic master; each SMA adopts 'sensaptics'. This SMA based master senses the human commands and sets the reference to the slave. The SMAs function as sensor and converts the hand motions into electrical signals (variation in differential electrical resistance). These hand movements are replicated in the remote site using a slave robot. Besides, the SMA wire acts as a haptic element by generating appropriate forces with respect to the contact with an object in the slave environment, by force feedback. This bi-functional haptic master acts as a human machine interaction (HMI) where the force stimuli can provide the human operator with interactive information of the dynamic slave environment. In order to validate the design of the SMA haptic master, a Proportional-Derivative (PD) controller is implemented to track the desired force/torque and position trajectories. The bilateral tracking control performance is hence demonstrated. This work is devoted to develop the principles and techniques needed to realize SMA wires to play the primary role as a sensor and, to act as a haptic generator when suitably required; thereby exhibiting bi-functional characteristic.

2. Design and working of the sensaptic master – slave system

Bilateral control is one of the control techniques to transmit kinesthetic sensation bi-directionally as discussed by several authors Sherman et al. [9], Ando et al. [10], Tavakoli et al. [11], Ohnishi et al. [12] Samur et al. [13], Bolopion et al. [14], Lawrence [26], Yokokohji and Yoshikawa [27], Leung et al. [28], Baier and Schmidt [29], Alfi and Farrokhi [30], Hokayayem and Spong [31]. and Alfi and Farrokhi [32]. In a bilateral tele-operator, there are primarily two design goals which ensure a close coupling between the human operator and the remote environment. The first goal is that the slave manipulator should track the position of the master manipulator, and the second goal is that the environmental force acting on the slave when it contacts an article/detects impact in the remote environment, be accurately transmitted to the master.

And, in this haptic master – slave system, the SMA haptic master plays two roles: firstly it acts as the reference input device to the slave and secondly as a force feedback display device from the slave environment to the operator. A force feedback from slave to the master representing contact information provides a more extensive sense of tele-presence. The specificness in this system is that a single configuration of antagonistic SMA plays the dual roles: to sense the operator movements (in place of traditionally used sensors like encoder, potentiometer or accelerometer) and concurrently generates force for haptic feel (in place of conventionally used motors, etc.).

2.1. SMA sensaptic master: SMA for shared sensing and haptics

A haptic master is proposed in this work which is custom designed and developed for 1-DOF operation, using SMA wires that function both as sensor (continuously) and actuator (conditionally on demand). The master is intended to perform two basic functions: (1) 'sense' the human command to control the slave (2) reflect/generate force/torque from the slave to the master ('haptics'); these functionalities are further explained in the Sections 2.1.1 and 2.1.2 respectively.

The technique/design of incorporating both sensing and haptics within oneself, thereby being bifunctional is referred to as 'sensaptics' (The name is suggested as 'sensaptics' = sensor + haptics).

The master is designed as a vertical structure with two parallel columns connected by a horizontal shaft at a height of 14 cm from the base. The handle of the master (master head) is attached at the center of the shaft that is similar to a joystick, an input device consisting of a stick that pivots on a base (the shaft) and reports its angle and direction to the device it is controlling (the slave). The one rotational degree of freedom of the master head is driven by a pair of sensaptic SMA wires (Flexinol® 0.015 cm φ, length 23 cm) spaced apart by 4 cm, is configured in antagonism. The master head rotates about the centrally hinged point of the shaft whose movement is brought by the operator (Table 1).

This SMA based master is configured to realize a mechanism for conversion between angular and translational movements. The SMA wires are accommodated in an assembly that is fixed axially to one end of the shaft (hence rotates along with the shaft) that drives the centrally hinged master head for bidirectional angular movement (Table 2).