Applied Soft Computing 32 (2015) 580–589

Contents lists available at ScienceDirect

Applied Soft Computing

journal homepage: www.elsevier.com/locate/asoc

Fuzzy based sliding surface for shape memory alloy wire actuated classical super-articulated control system

S. Sunjai Nakshatharan, K. Dhanalakshmi*, D. Josephine Selvarani Ruth

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

ARTICLE INFO

Article history:
Received 24 March 2014
Received in revised form 25 March 2015
Accepted 25 March 2015
Available online 18 April 2015

Keywords:
Fuzzy logic
Sliding mode control
Shape memory alloy
Antagonism
Ball and beam

ABSTRACT

This paper presents the experimental study on a system which is an interesting crossover between a standard benchmark control problem and a smart material. The study represents the effect of stress, strain and temperature over bandwidth of antagonistic shape memory alloy (SMA) and its relative performance in influencing the stability of the system. The experiment is implicated on an underactuated open loop unstable ball and beam system, designed and developed to be driven by SMA. A proportional derivative controller cascaded with sliding mode controller (SMC) based on simplified fuzzy adaptive sliding surface is considered to study the dynamics of the system. The designed simplified fuzzy based sliding surface controller is able to balance the ball and beam system around its equilibrium state, which as a control perspective shows that performance of this controller is better than the conventional SMC. Furthermore from smart material perspective decisive results are arrived to handle the issues like stability, speed of operation and performance of antagonistic SMA.

1. Introduction

Modern technology is in need of common requirements for actuators-designed for robotic, auto-motive, bio medical, aeronautic, and spatial applications. They are small size and weight, high performance, low cost and integration compatibility. Compared with traditional electrical or pneumatic other advanced piezoelectric, magnetostrictive, or electrostrictive actuators and innovative actuators based on the shape memory alloy (SMA) technology are now considered for various applications [1]. Among these SMA posses the advantages of high strain and the highest power density [2]. Other advantages offered by the SMA devices are their compliance with harsh environments, the simplicity of their actuation mechanisms, their silent and smooth motion, and their autosensing ability [3]. These factors make SMA a promising candidate among the actuators [4]. Especially SMA actuators are considered as interesting candidates for aeronautic applications, particularly for airfoil profile control systems [5].

There are hand full literatures avalible in application of SMA for aerospace applications. Robust control approach for a flap positioning based shape memory alloy actuator is addressed by Feng et al. [6]. New flap morphing mechanism that can change the wing shape smoothly devised to prevent aerodynamic losses was proposed by Kang et al. [5]. Tharayil and Alleyne [7] proposed modeling and control for smart mesoflap aeroelastic control. Wing shape control through an SMA-based device is discussed in [8]. Barbarino et al. [9] proposes a novel SMA based concept for airfoil structural morphing. Henry [10] discuss about the posiibility of using SMA for roll control for UAV of a variable span morphing wing. Morphing characteristics of a fiber metal laminate based on shape memory alloy skin and a carbon fiber reinforced epoxy composite is studied by Kuang et al. [11]. Wing morphing control with shape memory alloy actuators is discussed in [12]. Similarly many researchers have proposed the use of SMA for aerospace guidance control applications [13]. All the above work discuss the results of performance of the system in simulation or a prototype of the section alone. During a flight control operation, the real dynamics is much more complicated because of some attention grabbing nature of the system like issues regarding stability, non linear dynamics and more over an aerospace system behaves like an underactuated system. It is necessary to study the behaviour of SMA under these perceptions. Hannen et al. [32] introduces an indirect intelligent sliding mode controller (IISMC) for shape memory alloy (SMA) actuators.

Likewise other systems that have similar dynamics are tasks such as transporting objects using robotic arms, walking of legged robots and vertical take off of rocket, choppers etc. These systems are unstable, under actuated and nonlinear and need some special techniques and complicated mathematical derivation in conventional control methods. The vital problem that arises in the study of stability of such real, unstable systems, is that they cannot be analysed dynamically in the laboratory. In this case a simple analogical system is usually considered that has simplistic design and dynamic characteristics that could replicate the real dynamics of such systems. The ball and beam system is one such system and also a famous control problem. The system is known to be the benchmark for both classical and modem control techniques.

This paper proposes the same old ball and beam system but with a new face i.e., it is completely driven and controlled by shape memory alloy wire actuators. This system is widely used because of its simplicity to understand as a system and provides the opportunity to analyze the control techniques. The ball and beam system is also called 'balancing a ball on a beam'. It can usually be found in most university control labs. It is generally linked to real control problems such as horizontally stabilizing an airplane during landing and in turbulent airflow. There are two degrees of freedom in this system. One is the ball rolling up and down the beam, and the other is beam rotating through its central axis. The aim of the system is to control the position of the ball to a desired reference point. This is a complex task because the ball does not stay in one place on the beam but moves all the way with an acceleration that is proportional to the tilt of the beam. Ball balancing beam seems to be an ideal model for complex, non-linear con-rol methods. This system is open

* Corresponding author. Tel.: +91 4312503360.
E-mail address: dhanlak@nitt.edu (K. Dhanalakshmi).

http://dx.doi.org/10.1016/j.asoc.2015.03.057
1568-4946/

loop unstable as the system output (ball position) is unbounded to a bounded input (beam angle). Therefore, a feedback control must be employed to maintain the ball in a desired position on the beam. There are other diffcult issues in this system – the jumping ball phenomenon brings sensor uncertainty and real plant problems such as the sensor noise and actuator saturation and additionally in this case the non linearity of shape memory alloy by itself. These features provide this system two different perspectives, a complete synchronisation between the control system and the smart material and a chance to experiment both the fields.

The control methods that deal with this kind of processes should be sufficiently robust to non linearity, tolerate existing uncertainties like modelling errors, unmodelled process dynamics, and interferences or noise. This paper uses sliding mode control (SMC) which is appropriate for such purpose [14]. Sliding mode control is a technique derived from variable structure control (VSC) which was studied originally by Utkin [15,16]. This kind of control is particularly appealing due to its ability to deal with nonlinear and time-varying systems, as well as uncertainties and disturbances in a direct manner. This paper proposes and uses a modified sliding mode control proposed by Camacho and Smith [25] in which an adaptive sliding surface is designed with the addition of a term determined using fuzzy rules, based on the error and the change of the error of the controlled variable. Then the two input fuzzy logic controller is converted to single input fuzzy logic by using signed distance method. Comparison of the results with that of original sliding mode controller reveals that the designed controller shows effective performance in stabilizing the system. Based on the results, certain design criteria are derived for improving the performance of shape memory alloy wire actuators.

2. Experimental platform – System design

An experimental setup is designed and developed to carry out the experimental study– the schematic is shown in Fig. 1(a) and (b) is its photograph. A horizontal beam is centrally hinged to a rotating shaft on a vertical structure at a required height. SMA wire actuator is configured to actuate (rotate) the shaft for bidirectional angular movement. Two pulleys are fixed diagonally apart on a disc which is attached to one end of the shaft. This arrangement houses two SMA wires to provide antagonistic actuation. Torque developed and angle of rotation of the shaft depends on the dimension of the SMA under test. The beam angle θ is sensed by a laser displacement sensor. Ball position is sensed by a linear potentiometer consisting of two parallel nichrome wires. These wires are stretched along the top of the beam such that the steel ball may roll along the length of the beam, supported by the wires. One of the wires is connected to a voltage source. When the ball rests between the wires it allows a fraction of the source voltage to be measured at the other wire using potentiometer techniques. The output signal is proportional to the ball position x on the beam. The SMA wires are excited by self-designed amplifier circuits. Current transducer measures the current through the SMA. Temperatures of the SMA wires are measured using high precision thermo graphic camera. The system, sensors and actuators are interfaced with a PC installed with Matlab/Simulink with Real Time Toolbox to model and control, via a data acquisition system. The complete design of the system is given in [4]. Table 1 gives the specifications of ball, beam and SMA wires used for experimentation.

Table 1
Specifications of ball, beam and SMA.

Ball, beam and SMA specifications	Value
Length of the beam (cm)	60
Width of the beam (cm)	4
Thickness of the beam (cm)	0.20
Mass of the beam (kg)	0.153
Mass of the ball (kg)	0.023
Radius of the ball (cm)	0.8
Diameter of SMA wire (cm)	0.015
Current at room temperature for safe heating (A)	0.410

3. System model

The ball and beam control system is a multi-loop system which comprises of the ball on a beam and an actuation system. In this case antagonistic SMA wires acts as the driving actuator.

3.1. Dynamics of ball rolling on beam – Mathematical model

The complete description of the ball rolling on the beam is quite complicated. For control system design a simplified derivation is used to give a model that is suitable for controller design [17]. The model shown in Fig. 2 shows the main components involved in the system which includes moments and forces acting on the ball.

Starting with the ball along the beam, it experiences a force due to the rolling constraint along the beam and a downward component due to gravity that depends on the angle of the beam θ.

The nonlinear representation of the system can be simplified by deriving a transfer function of the linearized equations of the system. The transfer function describing the dynamics of the ball and the beam can be derived as follows. The system encounters two forces. One is a translational force (F_b) acting along the x-direction which is due to gravity. Another one is a rotational force (F_r)

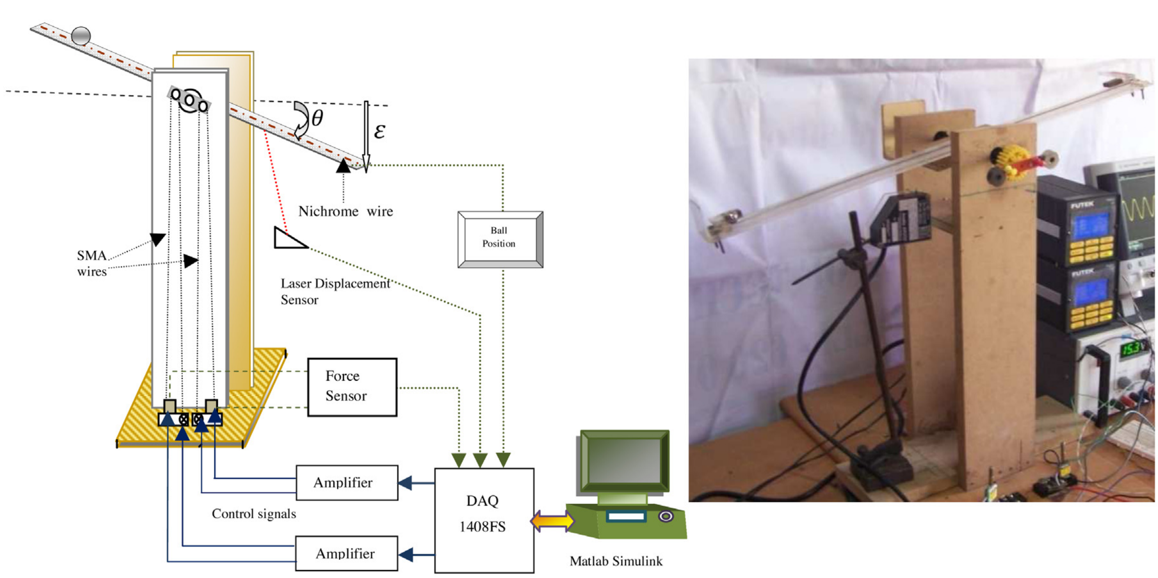

Fig. 1. Experimental setup: (a) schematic diagram (b) photograph.