IOP Publishing — Smart Materials and Structures
Smart Mater. Struct. **18** (2009) 125020 (13pp) doi:10.1088/0964-1726/18/12/125020

Analysis and optimization of the active rigidity joint

Justin Manzo and Ephrahim Garcia

Laboratory for Intelligent Machine Systems, Sibley School of Mechanical and Aerospace Engineering, Cornell University, 138 Upson Hall, Ithaca, NY 14853, USA

Received 21 July 2009, in final form 14 September 2009
Published 29 October 2009
Online at stacks.iop.org/SMS/18/125020

Abstract
The active rigidity joint is a composite mechanism using shape memory alloy and shape memory polymer to create a passively rigid joint with thermally activated deflection. A new model for the active rigidity joint relaxes constraints of earlier methods and allows for more accurate deflection predictions compared to finite element results. Using an iterative process to determine the strain distribution and deflection, the method demonstrates accurate results for both surface bonded and embedded actuators with and without external loading. Deflection capabilities are explored through simulated annealing heuristic optimization using a variety of cost functions to explore actuator performance. A family of responses presents actuator characteristics in terms of load bearing and deflection capabilities given material and thermal constraints. Optimization greatly expands the available workspace of the active rigidity joint from the initial configuration, demonstrating specific work capabilities comparable to those of muscle tissue.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

With the aid of active materials such as shape memory alloy and piezoelectrics, composite beams have been used to control motion with applications in vibration control, robotic manipulation, energy harvesting, and deflection sensing (Bailey and Hubbard 1985, Lee and Moon 1989, Dimitriadis *et al* 1991). These structures exhibit similar deformation trends, either actuating electrically or thermally or instead sensing voltage fluctuations when driven (Smits *et al* 1991). Active beams seldom deform to multiple, passively stable configurations without bulky external mechanical devices (Abdulrahim and Lind 2004, Wiggins *et al* 2004) or constant energy input (Strelec *et al* 2003, Manzo *et al* 2005).

Designed at the Cornell University Laboratory for Intelligent Machine Systems (LIMS), the active rigidity joint is a passively rigid deformable beam capable of large deflections. Precise layering of shape memory alloy (SMA) and shape memory polymer (SMP) as actuator and variable rigidity element, respectively, allows the thermally activated composite joint to be passively locked into different morphologies without constant energy input (Manzo and Garcia 2009). This type of actuation has many potential uses, including applications on morphing aircraft (Kudva *et al* 1999, Lazarus *et al* 1997, Mabe *et al* 2004), where large-scale shape change with low power and weight requirements are all significant design motivators.

Because the joint contains energy dense actuators and yet is rigid enough to carry reasonable loads without being back-driven, the overall system serves two purposes. Above all it is a structural element. Unlike many active hinge joints requiring energy to hold deflection when loaded, the active rigidity joint withstands loading in both active and passive states. In addition, the joint can attain large geometry change with a very small envelope. As such, performance characterization can be viewed from the perspective of conventional actuator design (specific work capacity, energy density, energetic efficiency, etc) as well as passive beam design (stiffness, block force).

The joint is outlined in an earlier paper (Manzo and Garcia 2009), wherein a layering configuration is described capable of overcoming an external load, deflecting to a new curved state, and passively holding rigidity in this new state. Deflections presented using this analytical model are valid for the surface bonded configuration studied but are not optimal—that is, maximum deflection was not achieved in the presence of large external loads with weight or size penalties. Updates to the analytical model improve accuracy given embedded actuators and thermal constraints. Surface bonded actuation is a tempting, simplistic configuration, but

