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DYNAMIC CHARACTERISTICS ANALYSIS AND FEM MODELING OF FLEXIBLE JOINTS OF AN SMA-ACTIVATED FLEXIBLE MULTI-JOINT NEEDLE

Saeed Karimi, Bardia Konh[1]
University of Hawaii at Manoa
Honolulu, HI, United States

ABSTRACT

Minimally invasive percutaneous needle-based procedures such as brachytherapy, ablation, and biopsy are standard clinical procedures in cancer interventions. Active needle steering increases the target placement accuracy, and consequently improves the clinical outcome. In this work, dynamical characteristic analysis and FEM modeling of flexible joints of a 3D steerable active flexible needle, when actuated by three Shape Memory Alloy (SMA) actuators, are studied. The Shape Memory Effect (SME) and Pseudoelasticity (PE) of the SMA actuators, their biocompatibility, and high corrosion resistance have made them appropriate alternatives in biomedical applications. Modelling the dynamics and FEM analyses of the flexible active needle during actuation is essential before predicting the active needle's behavior inside tissue.

Keywords: minimally invasive surgical procedures, 3D steerable active needle, shape memory alloy, flexible joint manipulator, finite element method.

NOMENCLATURE

ACTR	actuator
L	link length
ϑ	bending angle of the flexible joint

INTRODUCTION

In recent years, increasing interests in Minimally Invasive Surgical (MIS) procedures with reduced trauma to the tissue has prompted a continuous demand for dexterous and flexible medical devices and surgical tools for diagnostics and therapeutics. Minimally invasive percutaneous needle-based procedures such as brachytherapy, ablation, and biopsy are among recent standard clinical practices in cancer interventions. Such medical procedures necessitate a precise trajectory tracking and target placement of the surgical needles in soft tissue. This task, however, is challenging since the targeting accuracy is restricted by anatomical obstacles in the needle's path (e.g., critical organs), undesired bending of the needle in the tissue during insertion, and target displacement due to tissue deformation.

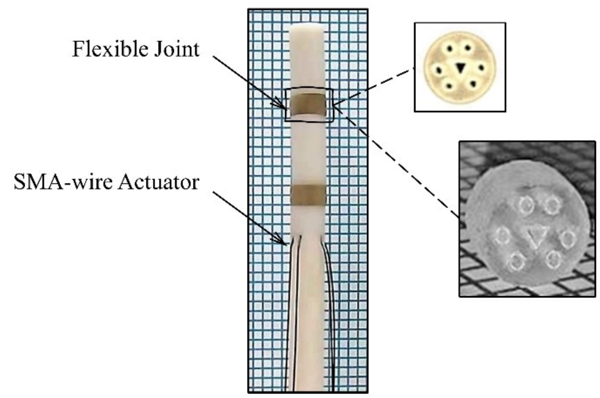

FIGURE 1: SMA-ACTIVATED MULTI-JOINT FLEXIBLE ACTIVE NEEDLE (LEFT), FLEXIBLE JOINTS; 3D PRINTED DIGITAL PHOTOPOLYMER, ©Proto Labs, INC. (RIGHT).

1. SMA-Activated Flexible Needle

In a previous study [1], novel design of a 3D steerable, flexible active surgical needle was introduced. Figure 1 shows the SMA-activated flexible needle. The compliant structure [2] of the active needle was made with three links including a base

[1] Contact author: konh@hawaii.edu.

(Somos® PerFORM, ©Proto Labs Inc.), and two flexible joints (Digital Translucent Photopolymer, Shore A 60 hardness, ©Proto Labs, Inc.). Three Nickle Titanium SMA-wire actuators (FLEXINOL® Wire, ©DYNALLOY, Inc.) were integrated into the needle structure to manipulate the needle. The SMA-wire actuators were actuated via Joule heating, and the kinematics of the active needle under actuation duties for position tracking of the needle tip was studied through characterization of the SMA-wire actuators, [1],[3]. In this work, dynamic analysis and Finite Element (FEM) modeling of the flexible joints of the active needle under actuation are studied. Understanding of the response of the flexible joints will be helpful to control the active needle tip to achieve a precise manipulation at the needle tip.

2. Kinematic Modeling of the Flexible Active Needle

The mechanism of the flexible active needle characterizes a three degree of freedom (3DoF) two-link RR configured manipulator (assuming negligible movement in z direction). Direct motion of the flexible joints (rotation or translation) provides an additional DoF to the manipulator. The design configuration of the needle with two flexible joints increases the steerability of the needle compared to a design with one flexible joint [4]. Three SMA-wire actuators (Fig. 1) are included to actuate the needle and provide 3D steerability at the needle tip [1]. The design configuration of the active needle introduces an effective manipulation at the needle tip. However, the active needle is underactuated since the actuation DoF is less than the kinematic DoF. Figure 2 illustrates the kinematic characteristics of the flexible active needle.

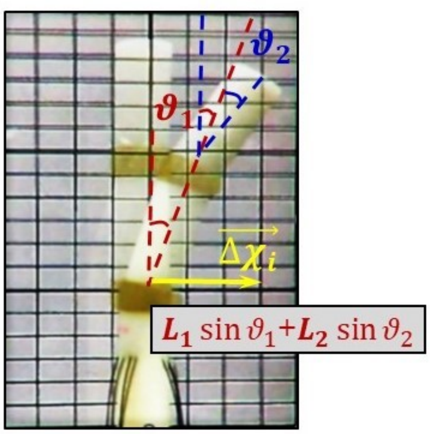

FIGURE 2: KINEMATIC CHARACTERISTICS OF THE FLEXIBLE ACTIVE NEEDLE; 3DOF RR-CONFIGURED MANIPULATOR.

The flexible components in compliant mechanisms undergo large elastic deformations, exhibiting a nonlinear elastic material behavior [5]. The generated stress/strain in SMA-wire actuators forces the flexible joints to deform elastically during the actuation. The deformation, i.e., change of the geometric shape, in the flexible joints causes a rotation in the rigid links, and deflects the needle in the direction of the actuation axis of each corresponding actuator. Therefore, the dynamical characteristics analysis of the flexible joints is important in control, path prediction and position control of the active needle.

The flexible joints are modeled as three independent compression/extension springs; rotating about the actuation axes of the SMA-wire actuators, exhibiting a nonlinear rotational stiffness. The model concept is illustrated in Fig. 3.

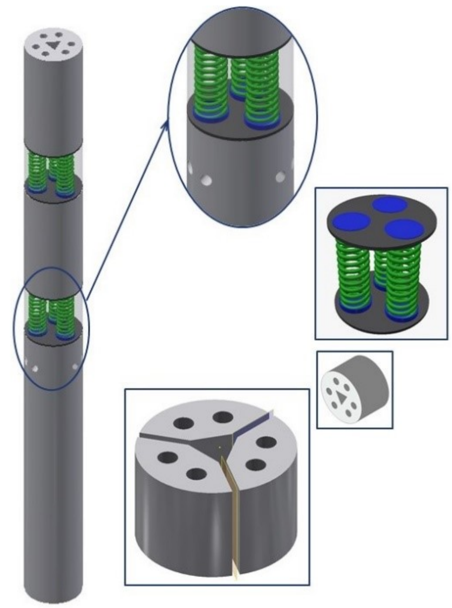

FIGURE 3: ACTIVE NEEDLE FLEXIBLE JOINTS NONLINEAR ELASTICITY MODEL WITH NONLINEAR SPRINGS.

3. Dynamic Characteristics of the Flexible Joints of the Active Needle

The nonlinear elastic material behavior and the deformation characteristics of the flexible joints under actuation of the active needle is also studied to develop a dynamical system model of the active needle under actuation.

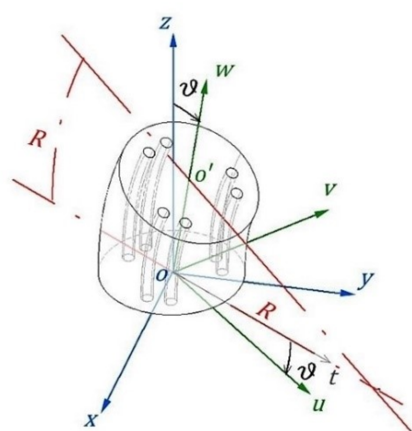

FIGURE 4: DEFORMATION CHARACTERISTICS OF THE FLEXIBLE JOINTS UNDER ACTUATION.

Figure 4 presents a schematic illustration of the deformed flexible joint, and the angle, ϑ_i, under the actuation of single SMA-wire actuator.

A subminiature compression force sensor (VLC856-50LB, ©Stellar Technology) is attached to the bottom of the active needle. The load cell measures the vertical force (***XYZ*** coordinate) applied on the active needle by the SMA-wire actuators during the actuation. The force data vs. time is plotted in Fig. 5.

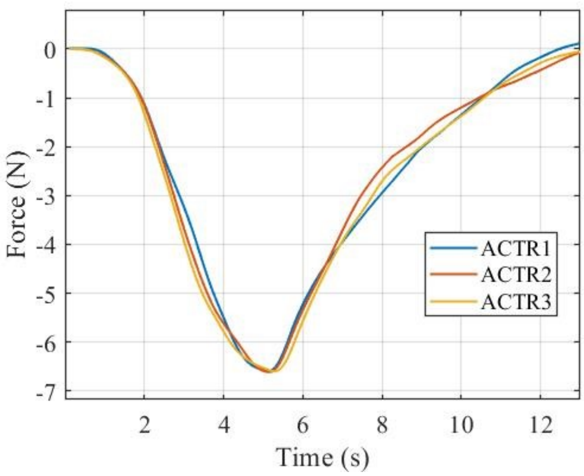

FIGURE 5: VERTICAL FORCE (**XYZ** COORDINATE) OF THE THREE SMA-WIRE ACTUATORS ON THE ACTIVE NEEDLE.

The force sensor data is used to define the loading conditions on the flexible joints during actuation of the active needle and to study the material behavior of the flexible joints with Finite Element Analyses (FEA).

The material characteristics of the flexible joints (digital photopolymer) is modeled in COMSOL Multiphysics®, to study the nonlinear elastic behavior of the flexible joints under compression. The actuation force (generated by the SMA-wire actuator) is applied to the flexible joint, and its response is predicted by the Finite Element Method (FEM). The results of the Venant-Kirchhoff hyperelastic material model are in good agreement with the experimental data. The total displacement (deformation) of the flexible joints under loading conditions is illustrated in Fig. 6.

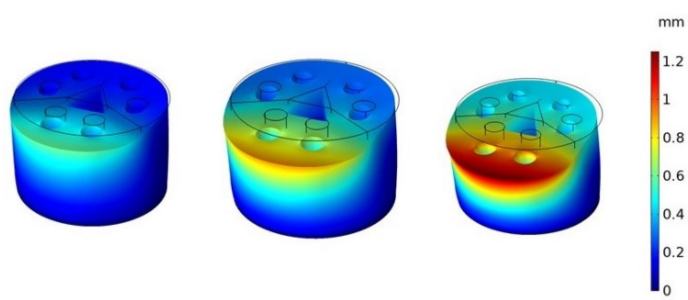

FIGURE 6: NONLINEAR ELASTIC FEA OF FLEXIBLE JOINT UNDER COMPRESSION; TOTAL DISPLACEMENT AT VERTICAL LOADS OF 5.0N, 7.5N, and 10.0N.

The Finite Element (FE) model of the deformation of the flexible joints is validated with experiment results by image processing. The changes in shape and geometry of the flexible joints during the actuation of the active needle are measured using MATLAB Image Processing Toolbox™. Figure 7 illustrates the changes in shape and geometry of the flexible joints.

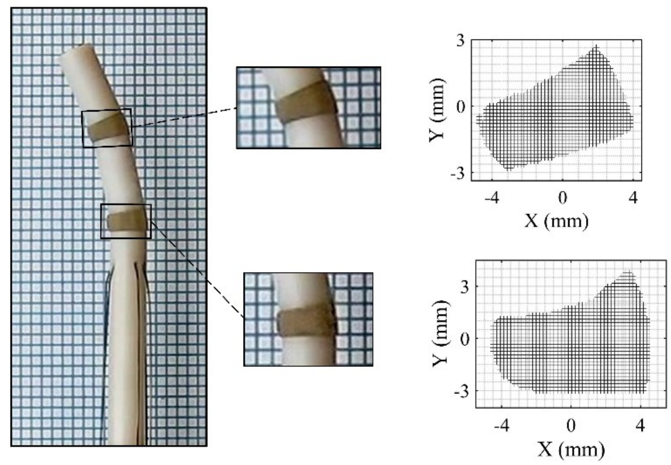

FIGURE 7: MEASURING THE CHANGE IN GEOMETRY OF THE FLEXIBLE JOINTS IN ACTUATION.

CONCLUSIONS

This work showed the dynamic response and FEM analyses of flexible joints of an active needle during actuation. The active needle design includes flexible and rigid joints with bending forces provided by SMA- wire actuators. The flexible joint of the active needle was modeled to predict its shape during needle actuation (i.e., bending). This model is intended to be used in a control algorithm for precise manipulation of the needle in air and tissue.

ACKNOWLEDGEMENTS

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