Closed Loop Control of a Robot Assisted Smart Flexible Needle for Percutaneous Intervention

F. O. Maria Joseph, Member, IEEE, P. Hutapea, A. Dicker, Y. Yu and T. Podder, Member, IEEE

Abstract—This paper presents the experimental evaluation of a coordinated control system for a robot and robot-driven shape memory alloy (SMA) actuated smart flexible needle capable of following a curved path for percutaneous intervention. The robot driving the needle is considered the outer loop and the non-linear SMA actuated flexible needle system comprises the inner loop. The two feedback control loops are coordinated in such a way that the robot drives the needle while monitoring the needle’s actual deflection against a preplanned ideal trajectory, so that the needle tip reaches the target location within an acceptable accuracy. In air and in water experimental results are presented to validate the ability of the proposed coordinated controller to track the overall desired trajectory which includes the combined trajectory of the robot driver and the needle.

I. INTRODUCTION

Several cancer interventional procedures such as, brachytherapy, biopsy, Radio Frequency based thermal ablation, neural stimulation, anesthetic drug delivery and so on require precise needle placement. Today most of these interventions are performed percutaneously. However, precise steering of a needle to a specific target inside tissue is a difficult task. For example in prostate brachytherapy, placement of radioactive seeds into the target locations in the prostate is a challenging task since the seeds expose significant radiation to smaller volume organs and also the urethra and rectum are sensitive to radiation.

Medical imaging and interventional delivery systems have undergone significant growth in the recent years, but the development of needles for percutaneous interventions for clinical integration is undergoing a slow progress [1,2]. Also, most of the clinically used needles are no longer contemporary from a design perspective. Controlling a robot driven needle to reach a target, precisely through a desired trajectory, by the guidance of quantitative sensory feedbacks, could benefit several medical procedures. Accurate and safe navigation of the needle to the desired target is the major challenge in needle based interventional techniques. Needle geometry and lack of proper actuation of the needle contribute to this major challenge. The subsequent steps after the needle reaching the target accurately are simple and they involve permanent implantation of radioactive agents (in brachytherapy) or taking samples (in biopsy) or the insertion of an analytical probe. Considering the location of the urethra at the center of the prostate, Podder et al. [3] have proposed a novel curvilinear approach as compared to the conventional rectilinear approach for radioactive seed implantation showing significant dose reduction in urethra and rectum as well as reduction in needle requirement which poetically can reduce toxicities. For the curvilinear approach one needs an active flexible needle capable of following a curvilinear trajectory. Controlling the active flexible needles to reach the target precisely with a driving robot is a challenging task in percutaneous intervention. Ruiz et al. [4] have performed the closed loop control of a SMA actuated flexible needle in two different medium: in-air and in-water experimental conditions using electromagnetic sensory feedbacks at different sampling intervals. Ayvali et al. [5] have shown the design and development of a multi-degrees of freedom SMA actuated cannula and evaluated the performance by controlling the position through a Pulse Width Modulation strategy. Tip tracking control of a manipulator-needle modeled as a flexible-rigid manipulator by backstepping controller is presented by Irani and Talebi [6]. Using a recurrent neural network, they have estimated the flexible modes of the needle. Mallapragada et al. [7] have proposed a technique for tumor manipulation through robot assistance for breast biopsy for tumor positioning at prescribed location. Based on the visual feedback of the tumor, the implemented PI controller by acting on the positional error drives the actuators placed around the breast to position the tumor in the desired line of insertion of the needle. The independent control of the needle apart from the presented robot control has not been considered by them. Yu et al. [8] have presented a 16 DOF robot assisted prostate brachytherapy system for scientifically accurate needle placements. A 2D semi-automatic robotically assisted needle steering system using duty cycling for needle insertion of adaptive curvature arcs is presented by Bernardes et al. [9]. To compensate for the system uncertainties, the system uses both the manual imagery feedback by an operator and an adaptive path planning strategy. A novel steerable hand held needling device has been developed by Okazawa et al. [10].

In [11, 12], Reed et al. have described a robot-assisted needle steering system that has been tested using three integrated controllers: a motion planner that guides the needle around critical areas to a desired target plane, a planar controller that steers the needle in a desired plane, and a torsion compensator which controls needle shaft axis and

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needle tip orientation to compensate angle and path deviations.
A Robotic coaxial needle insertion assistant has been developed by Lorenzo et al. [13] in order to improve operator force perception. The robotic assistant is admittance controlled, giving the physician a scaled version of force applied from needle tip to tissue. This assistant has been experimentally proven to provide the user with detect the type of membrane the needle was piercing. Fichtinger et al. [14] have presented a robotically assisted ultrasound guided system for prostate brachytherapy and have tested results in training phantoms. Clinical testing and feasibility of a robot guided needle system for prostate brachytherapy have been performed by Song et al. [15]. The controller proposed by Kallem and Cowan [16] utilizes the distance of the needle tip position from the plane of interest as the feedback signal. This feedback signal is generated via two cameras that take video of the needle insertion into phantom tissue. The needle itself is controlled through a kinematic control system which relates movement at the needle base to beveled needle tip motion through a Jacobian matrix.

A method for the steering of flexible bevel-tipped needles in tissue using proportional control of trajectory curvature by means of duty-cycled rotation is proposed and tested in gelatin phantoms as well as in cadaver brain tissue by Minhas et al. [17]. During the experiments, needle insertion was controlled interactively by a physician with the aid of fluoroscopy based image feedback, acquired at intervals of 1-2 cm of insertion depth.

In this paper, we present the experimental evaluation of the proposed coordinated closed loop position control between the outer robot and inner active flexible needle. Target reaching in automated percutaneous intervention can be precisely achieved only with the coordinated controlled movement of the robot as well as the needle. Thus, our motivation is to perform the coordinated control of both the robot driving the needle and the needle itself. The target could not be reached when either of these movements is restricted. Steering of a self-actuating flexible needle for clinical purpose is challenging. The main focus of this work is on the real-time implementation of the robot and needle coordinated position control as the simulation was performed in [18] with the proposed concept. The outline of the paper is as follows: Section II elaborates the method involved in our work. Section III discusses the obtained experimental results. Finally, conclusions are presented in section IV.

II. METHODS

A. Robot-assisted Needling device for percutaneous intervention

The schematic of robotically assisted needle system for percutaneous interventions is shown in Fig. 1. With respect to the world coordinate frame shown in Fig. 1, the guiding robot moves along the x-axis whereas the shape memory actuated needle moves along the y-axis. Since, the needle base is attached to the robot, the later pushes it along the x-axis till it reaches the initial point (entry point) Pi of the anatomical organ. The needle must pierce through the outer skin to reach the tissue. It is assumed that all the needle movement is localized toward the x-axis during this movement.

Being the subset of the overall 3D trajectory involving the whole volume of the anatomical organ, the planar trajectory alone considered in this study. Hence, each point in the curvilinear trajectory joining the initial point Pi and final point Pr can be represented as a 2D vector whose elements are robot’s forward motion position (x) and needle’s deflection (y). In a differential velocity mode, the final target point Pr is reached by the needle tip via the preplanned curved path implemented by the combined motion of the robot in x-axis and the needle in the y-axis. Here, the path from the outer skin to anatomical organ, Rp is accomplished by the robot pushing the needle forward, i.e., due to the robot motion alone; during this time the needle is not being actuated. Inside the anatomical organ, to achieve the curvilinear path for reaching the target point Pr, controlled movements of both the robot and the needle are involved, where ∆x represents the increment in robot movement and ∆y to the needle deflection/bending. Note that the needle bending or deflection is due to the activation of SMA actuator, not by using the needle tip geometry like bevel-tip needle. In real-time experiments, the needle is actuated by the SMA wire generally. By controlling the voltage supplied to the SMA wire, the current (I) passing through the wire generates a heating effect upon it. Due to this heating effect, the SMA wire contracts which in turn is caused by a phase change in the alloy at the molecular level which provides the actuation force on the needle. The heat (H) generated in the SMA wire is given by Joule’s heating law as follows:

\[ H = I^2 R \]  

where, H is the Heat generated, I is the current flow and R is the internal resistance of the SMA wire. The SMA wire is readily used as an actuator due to its capability of restraining its original shape because of its high strain property while heating effect is withdrawn. Such property occurs in SMA because of the phase transformation between the martensite and austenite phases. A multifunctional USB-6259 NI-DAQ Acquisition Card (±10 V) is used to send the control output to the needle via the analog output (AO) port. To amplify the current passing through the needle corresponding to the NI DAQ AO signal, the power amplifier circuit is employed. The current passed through the needle has varied in the range (0 to 0.7 A) in our study thereby heating the SMA from 0 to 70 °C.

B. Coordinated Control of needle and the robot

The control involves a two loop scheme where the outer loop is of the robot movement intended for pushing the needle. The inner loop is of the needle displacement in due...
to the Joule's Heating Effect. The robot is controlled using a PID controller and the needle is controlled using a non-linear PID-P³ whose equations are given as (2) and (3), respectively. The digital PID controller is given by,

\[ u(k) = u(k-1) + K_p[e(k) - e(k-1)] + \frac{K_p h}{T_f} e(k) + K_p T_D [e_f(k) - 2e_f(k-1) + e_f(k-2)] \]  

(2)

where, \( h \) is the time step, \( e(k) = x_d(k) - x(k) \) is the error at \( k \)th instant; \( e_f(k) \) is the low pass filtered error given by \( e_f(k) = \frac{\tau_f}{\tau_f + T_s} e_f(k-1) + \frac{T_s}{\tau_f + T_s} e(k) \); \( u(k) \) is the controller output at \( k \)th instant; \( K_p, K_T, K_p T_D \) are the proportional, integral and derivative gains respectively.

Similarly, the discrete-time PID-P³ controller is given by,

\[ u(k) = u(k-1) + K_p[e(k) - e(k-1)] + \frac{K_p h}{T_f} e(k) + K_p T_D [e_f(k) - 2e_f(k-1) + e_f(k-2)] + K_T[e(k) - e(k-1)] \]  

(3)

Also, the relationship between the robot's position \( X_R \) and the needle's position \( Y_N \) is formulated empirically as

\[ Y_N = \alpha X_R^2 \]  

(4)

The control block diagram used in [18] by the same authors for simulation is used here for the experimental purpose. It varies according to the preplanned desired trajectory.

The two individual control loops are coordinated to achieve the desired target reaching trajectory in the anatomical sensitive organ through a curvilinear fashion thereby avoiding obstacles and minimizing dose exposure to urethra and rectum [3]. The desired input to the outer robot loop is the forward movement to the robot along the x-axis (in reference to the world frame \{W\}). The robot must be controlled to drive the SMA actuated flexible needle by considering the actual position of the needle tip, which is obtained using an electromagnetic (EM) sensor (Aurora sensor, NDI, Waterloo, Canada) installed at the needle tip (Fig. 2). Hence, the error for the controller in the robot (or outer) loop is the difference between the desired x value and the actual x value computed from the actual position of the needle tip. From the actual position of the robot, the reference value for the needle control loop is obtained. The difference between the actual needle displacement and the reference displacement is given as the error input for the PID-P³ controller of the needle. The in-air and in-water experimental results in the trajectory tracking tasks in both curvilinear and rectilinear paths are presented in the next section.

III. RESULTS

In order to better simulate in-vivo conditions, the water is heated to and maintained at body temperature (37.5 °C) in the beginning of our experiment. First, in-air experiment is performed and followed by in-water experiment.

A. In-air experiment

The experimental set up involved in the In-Air medium is shown in Fig. 2. The needle used is a High Dose Rate needle of 17 gauge actuated by a NiTinol SMA. The closed loop control of the robot-driven flexible active needle is performed using the electro-magnetic (EM) sensory feedback at the sampling rate of 100 ms. The PID controller feedback gains \( K_p, K_i \) and \( K_d \) of the outer robot loop are 1.0, 10.0 and 0.001 respectively. Similarly, for the inner needle controller (PID-P³), the corresponding gain values are \( K_p=1.0, K_i=10, K_d=0.001 \) and \( K_t = 0.005 \);

The controller for the robot produces pulse width modulation (PWM) command signals to drive the motor at 50Hz frequency.

Figure 2. Experimental setups. (a). In-air experimental setup. (b). In-water experimental setup.

Fig. 2(a) shows the in-air experimental setup of the robot driving flexible needle system for percutaneous intervention. The coordinated movement of the needle and the driving robot generates the actual trajectory as per the control scheme to track the overall desired trajectory to reach the target \( Pr \) explained in the methods section. For repeatability, a set of five readings is taken for both the curvilinear and the rectilinear cases. One of the readings showing both these trajectory tracking performance is shown in Fig. 3. The root mean square error (RMSE) values are statistically compared.

B. In-water experiment

In order to have more realistic simulation for in-vivo conditions, the water temperature is elevated and maintained at 37.5 °C, same as normal human body temperature for the in-water experiment (Fig. 2(b)). Both the curvilinear and rectilinear trajectories tracking tasks are performed and the trajectory matchings’ are shown in Fig. 4. For repeatability, five readings are taken similar to the in-air case. The RMSE values obtained as a quantitative measure of the trajectory tracking performance of the controller in-air and in-water media are presented in Table I. In-air experimental results show smaller RMSE compared to the in-water experimental results due to perturbations in the water medium.

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TABLE I. RMSE EVALUATION OF TWO LOOP COORDINATED CONTROL EXPERIMENTS

<table>
<thead>
<tr>
<th>Desired Trajectory</th>
<th>RMSE (Mean ± SD in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In-Air Experiment</td>
</tr>
<tr>
<td>Curvilinear</td>
<td>0.11±0.12</td>
</tr>
<tr>
<td>Rectilinear</td>
<td>0.08±0.01</td>
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IV. CONCLUSION

Experimental evaluation of the coordinated control of the robot guiding active flexible needle is presented in this work. The experimental results reveal that both the curvilinear and rectilinear trajectories are tracked accurately within clinically acceptable limits. The repeatability analysis of the experimental results further reinforces this observation. The authors are presently testing the coordinated control concept with ex-vivo tissues thereby validating the proposed control scheme in clinical application with different feedback modalities. An elaborative study addressing the effect of SMA heating to the tissue and needle-tissue interaction is expected to be performed in the future.

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