Development of a coordinated controller for robot-assisted shape memory alloy actuated needle for prostate brachytherapy

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Abstract— **This paper deals with the development of a coordinated control system for a robot and robot-driven shape memory alloy (SMA) actuated needle to follow a curvilinear path for percutaneous intervention. The robot driving the needle is considered as the outer loop and the non-linear SMA actuated flexible needle system forms the inner loop. The two feedback control loops are coordinated in such a way that the robot drives the needle considering the needle's actual deflection so that the needle tip reaches the target location with an acceptable accuracy. Simulation results are presented to verify the efficacy of the controller for tracking the overall desired trajectory which includes the combined trajectory of the robot and the needle.**

I. INTRODUCTION

Prostate cancer is a non-cutaneous, diagnosed malignancy which is treated effectively by several treatment modalities such as brachytherapy, hormonal therapy, radical prostatectomy and external beam radiation therapy. Of these, brachytherapy is one of the most common procedures due to it being less surgically invasive than other options as well as the created convenience of outpatient treatment with minimum treatment sessions. In addition, risks such as urinary incontinence and impotence are lower than the other cancer treatment procedures. Brachytherapy is a methodology in which radioactive seeds are implanted permanently into the prostate gland using hollow needles. The radioactive seeds are delivered from the needle lumen once the target is reached in the prostate. Placement of these radioactive seeds into the target location in the prostate is a challenging task as they provide significant radiation to a smaller volume and also the urethra and rectum are sensitive to radiation.

Due to the location of the urethra at the center of the prostate, Podder et al. [1] 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 flexible needle which is capable of following a curvilinear trajectory. Several research groups, including our group, are developing flexible and passive/active needles [2]-[16]. However, controlling a SMA actuated needle to track the desired path thereby reaching the target is critical, but challenging in the brachytherapy procedure. Okamura et al. [2] and Alterovitz et al. [3] have studied the use of needle bending and tip direction in soft deformable tissues through force modelling and motion planning respectively. However, the advantage of the SMA actuated needle in the curved path includes the certainty of minimal number of needles and radioactive seeds exposed to the urethra and rectum. Ruiz et al. [4] have performed an electromagnetic (EM) sensor feedback control of a SMA actuated needle for prostate brachytherapy. He has tested the performance of his controller while the needle was in different medium, i.e. in air and in water at various temperatures. The position control of SMA actuator using internal resistance with neural network is performed by Ma et al. [5]. They have avoided the use of position sensor with the idea of involving neural network for predicting the actual position of the SMA. Reed et al. [6,7] have proposed an estimator-based controller by considering the friction between the long needle shaft and the tissues, thereby significantly overcoming angle and path deviations. Dickinson and Wen [8] have developed a feedback control of SMA using beam strain information. Ko et al. [9] have performed a closed-loop planar motion control of a probe to address the limited trajectory control in the tissue medium using the bevel geometry. Ayvali et al. [10] have performed multiple joint motion control of a steerable cannula by mounting SMA wires at discrete intervals on the outer surface of the cannula using pulse width modulation controller involving temperature and vision feedbacks. Ahn and Nguyen [14] have proposed an adaptive self tuning PID controller for the real-time control of the SMA actuator displacement. Dutta et al. [15] have presented a tracking control method for a spring-biased SMA wire comprising an inverse compensator and a PD controller with strain feedback. They have designed an effective and simple mathematical model of the spring-biased SMA wire to perform the control. Ryu et al. [16] have presented an MR-compatible active needle that uses internal laser heating of a shape memory alloy (SMA) actuator to produce bending in the distal section of the needle.

In this paper, we present the development of a coordinated position control between the robot driving the SMA actuated needle and the self-actuating, i. e. active flexible needle. The motivation for this work arises from the fact that for a given target position in the prostate, reaching

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the target can only be possible with the coordinated movement of the needle and the driving robot. When either of these movements is restricted then, target cannot be reached. Steering of a self-actuating flexible needle for clinical purpose is challenging. It is difficult, if not impossible, for a clinician to steer a self-actuating needle with desired results. However, incorporation of robot in needle-human loop for a clinical procedure is very daunting. Therefore, we are focusing on the robot and needle coordinated position control. As the needle is driven by the robot, the control of the needle is considered to be in the inner loop and the robot control is performed in the outer loop. The organization of this paper work is as follows: Section II describes the method involved in our work. Section III discusses the simulation results obtained. Finally, conclusions are drawn in section IV.

II. METHOD

A. Robot-assisted Needling device for percutaneous intervention

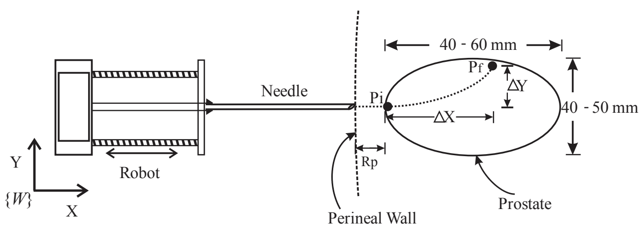

Figure 1. Schematic of robot-assisted needling dvice for prostate intervention.

Figure 1 depicts the robot assisted needling device for prostate intervention. For simplicity, we have considered the robot movement along the x-axis and the shape memory actuated needle movement along the y-axis of the world coordinate frame $\{W\}$. The needle reaches the initial point Pi of the prostate due to the robot pushing the needle along the x-axis. To reach the prostate, the needle has to pierce through the perineal wall. During this movement we assume no needle deflection in the y-direction. We have considered only planar trajectory which is a subset of the overall 3D trajectory covering the prostate volume. Hence, each point in the curvilinear trajectory joining the initial point Pi and final point Pf is a 2D vector whose elements are robot's forward motion position (x) and needle's deflection (y). The target point Pf, is reached by the needle tip through a curvilinear path by the coordinated motion of the robot (x-axis) and the needle (y-axis) in a differential velocity mode. Here, Rp is the path (from perineal wall to prostate capsule) accomplished by the robot pushing the needle forward, i. e., due to the robot motion alone; during this time needle is not active. Inside the prostate, to achieve the curvilinear path for reaching the target point Pf, movements of both the robot and the needle are involved, where Δx corresponds to the robot movement and Δy to the needle deflection/bending. Note that the needle bending or deflection is due the activation of SMA actuator, not by using the needle tip geometry like bevel-tip needle. In general, the width and length of the prostate are in the range of 40-60 mm and 40-50 mm, respectively. In actual experiments [4], the needle is actuated by the SMA wire. By controlling the voltage supplied to the SMA wire, the current (I) passing through the wire generates heating effect on it. Due to this heating effect, the SMA wire contracts due to phase change and provides the actuation force on the needle. The heat (H) generated in the SMA wire is given by Joule's heating law as follows:

$$H = I^2R \tag{1}$$

where, H is the Heat generated, I is the current flow and R is the internal resistance of the SMA wire. The SMA wire has drawn significant attention to be used as an actuator due to its capability of going back to its original shape because of its high strain property while heating effect is withdrawn [5]. Such property occurs in SMA because of the phase transformation between the martensite and austenite phases.

B. Robot-Needle control coordination

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 block diagram of the control system is shown in Figure 2.

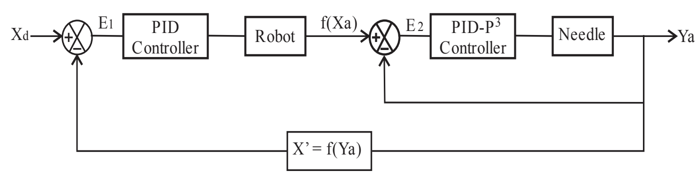

Figure 2. Two loop cotrol strategy for robot assisted needling device to track the given desired trajectory for prostate brachytherapy.

The robot is controlled using a PID controller and the needle is controlled using a non-linear PID-P^3 whose equations are given as (2) and (3), respectively.

$$u(t) = K_P \cdot e(t) + K_I \cdot \int_0^t e(t)dt + K_D \cdot \dot{e}(t) \tag{2}$$

$$u(t) = K_P \cdot e(t) + K_I \cdot \int_0^t e(t)dt + K_D \cdot \dot{e}(t) + K_T \cdot [e(t)]^3 \tag{3}$$

where, $u(t)$ is the controller output to the plant, $e(t)$is the error signal, K_P, K_I, K_D are the proportional, integral, derivative gains, respectively (they are different for the robot and the needle). In the PID-P^3 controller a gain K_T multiplied with the position error is added to minimize error due to the non-linearity effects related to SMA actuator.

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

$$Y_N = \frac{{X_R}^2}{150} \tag{4}$$

Using eqn. (4), f(Xa) and X'=f(Ya) can be obtained. Eqn. (4) is the customized one for this control problem. Xa and Ya are the actual robot and needle positions. It varies according to the desired trajectory given.

The two individual control loops are coordinated to achieve the desired target reaching trajectory in the prostate through a curvilinear fashion thereby avoiding obstacles and minimizing dose exposure to urethra and rectum [1]. 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 needle 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. 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-P^3 controller of the needle. The gains for the PID controller used in the robot loop, are $K_P = 800$, $K_I = 400$ and $K_D = 80$. For the PID-P^3 controller of the needle loop, the gains are $K_P = 800$, $K_I = 90$, $K_D = 10$ and $K_T = 50$. The results in the trajectory tracking are presented in the next section.

III. Result and Discussion

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 P_f explained in the methods section. The curvilinear trajectory tracked by the needle tip with its own displacement in the y-direction and through the robot forward movement in the x-direction is shown in Figure 3. The individual error plots for the robot and needle motion are shown in Figures 4 and 5, respectively. Also, the rectilinear trajectory tracking is also shown in Figure 6. The corresponding error plots for the robot and needle positions are shown in Figures 7 and 8, respectively.

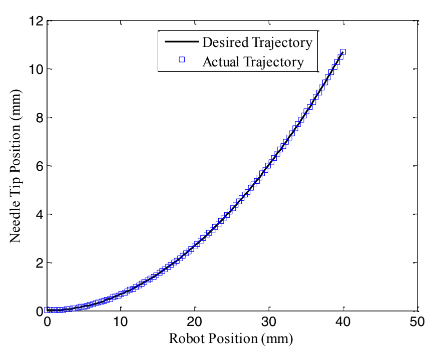

Figure 3. Curvilinear output trajectory of the needle tip due to the coordinated movement of the needle and the driving robot.

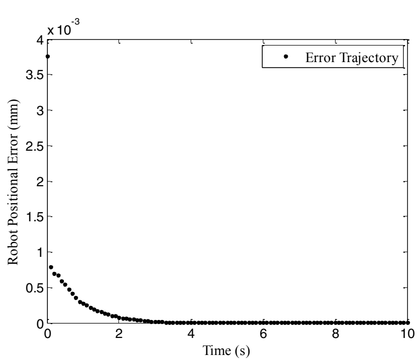

Figure 4. Error plot for the robot positioning in the curvilinear path trajectory

The independent movement of the robot in the x direction with no needle self displacement is shown in Figure 9. Finally, the independent movement of the needle's self displacement alone with no robot pushing is shown in Figure 10. Thus, the results shown reveal the importance of the coordination between the guiding robot and the SMA actuated needle in achieving the overall desired trajectory given to reach the target position where the radioactive seeds be implanted.

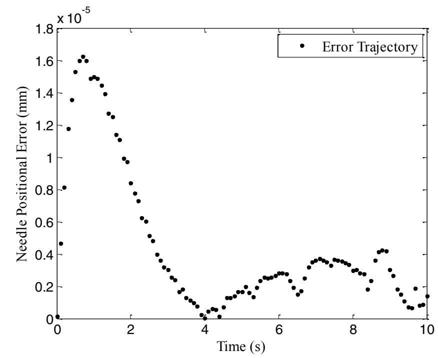

Figure 5. Error plot for the needle tip positioning in the curvilinear path trajectory

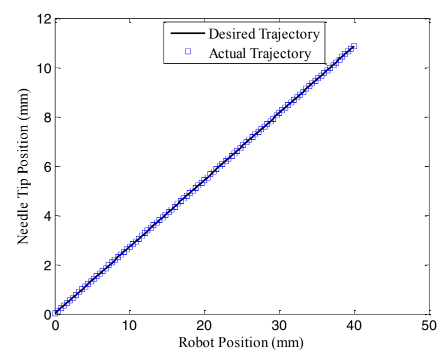

Figure 6. Straight line trajectory of the needle tip to reach the target point in the prostate.

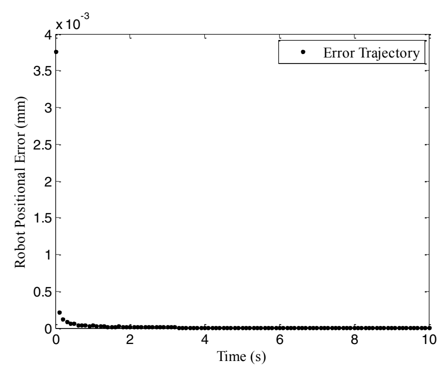

Figure 7. Error plot for the robot positioning in the rectilinear path trajectory

As we mentioned in the introduction section, when either of the robot movement or the needle displacement is not realized, then the target point P_f, cannot be achieved as shown in Figures 9 and 10. The error convergence plots strenghtens the controller performance in both the curvilinear and rectilinear path tracking tasks. These error plots are meant for the overall coordinated trajectory of the robot and the needle while executing the task of reaching the target. Thus, the simulation results in with the intention of guiding the needle tip for delivering the radioactive is achived successfully with the proposed control scheme.

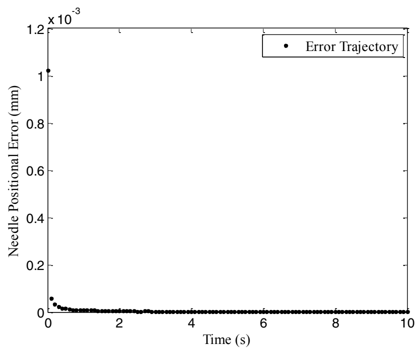

Figure 8. Error plot for the needle positioning in a rectilinear path trajectory

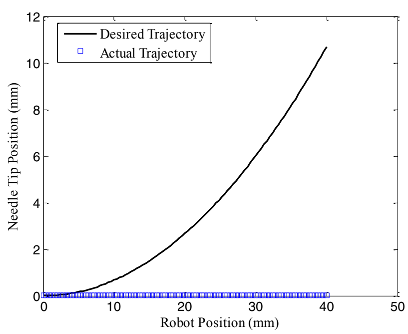

Figure 9. Actual trajectory of the needle tip with no needle self displacement.

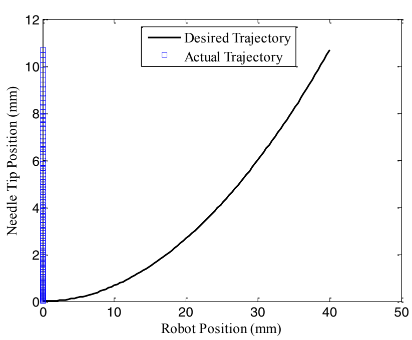

Figure 10. Actual trajectory of the needle tip with no robot pushing

IV. CONCLUSION

The study presents a coordinated position control of a self-actuated flexible needle tip driven by a robot. The non-linear PID-P^3 controller for the SMA actuated flexible needle controller being inner loop while the PID control for the robot control as outer loop becomes coordinated control scheme. The simulation results are shown to achieve the accurate curvilinear path trajectory to reach the target point. More realistic scenarios such as insertion of the flexible needle in soft tissues are being considered for the simulation results validation and error convergence. The real-time experiments are under process involving a 6 DOF robot for driving the SMA actuated needle installing an EM sensor at the tip of the needle to track the actual needle tip position. Obstacle avoidance with interactive rate and 3D trajectory tracking with the closed loop control involving the ultrasound imaging feedback is our ongoing study. Also, the experimental verification the simulated coordinated control for the robot and the flexible active needle is in progress.

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