31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Model Based Stabilization of Soft Tissue Targets in Needle Insertion Procedures

Jerzy Smolen and Alexandru Patriciu
McMaster University
Electrical and Computer Engineering Department
1280 Main Street West, Hamilton, Ontario Canada L8S 4L8
smolenja@univmail.cis.mcmaster.ca
patriciu@mail.ece.mcmaster.ca

Abstract— **This paper presents a soft tissue target stabilization method during needle insertion procedures. The object considered in this study may have fixed boundary sections and limited surface exposed to external manipulation. The target must be stabilized along the needle path during the needle insertion. It is assumed that a paddle with fixed geometry is available for deformable object manipulation. Two approaches were considered for the target stabilization problem. The first approach uses a static paddle placed on the available boundary, at a strategic location, such that the target motion orthogonal to the needle axis is minimized during the needle insertion. The second approach uses a dynamic paddle attached to the available boundary for the active compensation of the target deflection. In this paper we analyze the optimal paddle placement for the two proposed approaches and present initial numerical results for the case of homogeneous and nonhomogeneous deformable objects. The results show that the first approach is sensitive to possible non-homogeneities in the object, therefore it is not robust to modeling errors. The results also show that optimal placement for the second approach is less sensitive to modeling errors, making it more desirable for physical applications.**

I. INTRODUCTION

Current image guided needle insertion procedures are prone to performance errors due to soft tissue deformations that occur as the needle is inserted. Ignoring this matter may result in probing areas of tissue outside a targeted location determined in pre-operative planning images. Depending on the application, this can give misleading biopsy samples or poor implantation of a certain drug or marker. The ability to predict and control these tissue disturbances can be beneficial in terms of patient care and sample location reliability.

To this date, the main two approaches that have been proposed to overcome the target mobility issue during needle insertion, are needle steering in tissue and soft tissue manipulation. DiMaio and Salcudean [2] proposed a needle steering algorithm based on a linear finite element model of the tissue interacting with a nonlinear needle model. While the results presented are very promising it is hard to extend them to arbitrary configurations. Alterovitz et al. performed beveled needle maneuvering within tissue, such as obstacle avoidance, to reach a target position [1] with the assumption that the needle was much more flexible than the tissue. Both approaches are computationally expensive, thus being hard to implement in real time.

In the latter approach, Mallapragada et al. showed the ability to manipulate object boundaries to force targeted points or regions in line with a needle as it was being inserted into the object in real time [4]. This approach was based on the results that Wada et al. achieved on the guidance of multiple control points through indirect object deformations [3].

In this paper, we analyze stabilization of a soft tissue target during needle insertion for the case where the object is subject to predefined fixed boundary conditions. The tool available for target stabilization consists of a paddle with known geometry. This tool can be attached to the deformable object boundary and be used for manipulation. Moreover, it is considered that paddle-tissue contact point is confined to a well defined boundary subset. This models realistically the configuration in which the user has a tool that can be used to stabilize the soft tissue, but is restricted on the possibilities of where to attach the tool to the tissue.

In the present study it is assumed that the needle insertion is performed on a linear path; thus the goal is to restrict the target motion orthogonal to the needle axis. Two target stabilization approaches are considered. In the first approach the paddle is used as a static fixture during needle insertion. In the second approach the paddle is used for the dynamic adjustment of the target position during the needle insertion. This paper analyzes the optimal paddle placement for the two approaches. The analysis is based on mesh-less nonlinear deformable models with tissue like characteristics.

II. DESCRIPTION OF DEFORMABLE OBJECT MODEL

The object model used in this paper is a continuum deformable body with an attached coordinate system. The initial body configuration is represented by uppercase X with a domain of Ω_X and boundary Γ_X. The deformed configuration is represented by lower case x, and occupies the region Ω_x with boundary Γ_x. The deformation of the body is a one to one function ϕ, where $x = \phi(X,t)$ and

This work was partially supported by *NSERC Discovery Grant RGPIN*356081 − 08 "Automatic manipulation of soft tissue under image guidance" and *CFI − LOF/MRI − RI Grant* "Robotic test bed for soft tissue image guided medical interventions research".

the displacement is represented by $u = \phi(X,t) - X$. It is assumed that movement of the body is achieved solely through essential boundary Γ_x^g displacements g, resulting from the body interacting with its external environment. The task left is to calculate the displacement at coordinate $u(X,t)$ based on the characteristics of the defined object.

The soft tissue can be modeled as a hyperelastic material described by a strain energy function W. Then, the constitutive 2nd Piola-Kirchhoff stress relations, connecting the derivative of the current strain energy with respect to the strain measure, is computed

$$S_{ij} = \frac{\partial W}{\partial E_{ij}} \tag{1}$$

where $F = \frac{\partial x_i}{\partial X_j}$ is the deformation gradient and $E = \frac{1}{2}\left(F^T F - I\right)$ is the Green Lagrangian strain. The partial derivative equations describing the static deformation of the object

$$\tau_{ij,j} + b_i = 0 \tag{2}$$

subject to displacements on the essential boundaries

$$u = g \qquad on \qquad \Gamma_x^g \tag{3}$$

where τ_{ij} is the Cauchy Stress derived from the 2nd Piola-Kirchhoff stress, b_i the body forces.

Further, the nonlinear partial differential equations describing the deformable object are linearized according to [5], resulting in a set of incremental equations. These are discretized using the RKPM method [6]. In RKPM formulation the displacement at coordinate X is expressed as a linear combination of particle attached shape functions ψ

$$u_i(X,t) = \sum_{I=1}^{NP} \psi_I(X) d_{iI}(t) \tag{4}$$

where NP the total number of particles and d_I the coefficient attached to particle I. Using the previous expression plugged into the incremental equation, results in a linear system of equations in increments of coefficients d_I. One drawback of the RKPM method is that the essential boundary conditions require special treatment because kernel functions do not have dirac delta property. In this implementation the RKPM shape functions were modified to accommodate the essential boundary using the approach described in [6]. Finally, employing nodal integration in the linearized equation yields the incremental matrix equation

$$K\delta d = \delta f \tag{5}$$

where K is a stiffness matrix, δf is global force increment vector and δd represents the nodal displacements related by the RKPM shape function. It should be noted that methods other than RKPM can be used to get the same equation as 5. However, the mesh-less methods proved to be more stable than the finite element methods for large deformations [6].

III. SIMULATION RESULTS

In this study, all simulations were performed using a planar object stabilized against an immobile boundary as shown in Figure 1. This object configuration was chosen to provide limited access to boundary points that could interact with the external environment. The targeted region of the object was stabilized through object boundary manipulations during a needle insertion procedure. It was assumed that there was no boundary slippage against the inserted needle shaft, and the needle insertion was modeled as a uniform compression of the three indicated nodal points in a straight line trajectory throughout the simulation. Further, Fung's Strain Energy function

$$W = 1/2 E_{ij} A_{ijkl} E_{kl} + c/2 e^{E_{ij} C_{ijkl} E_{kl}} \tag{6}$$

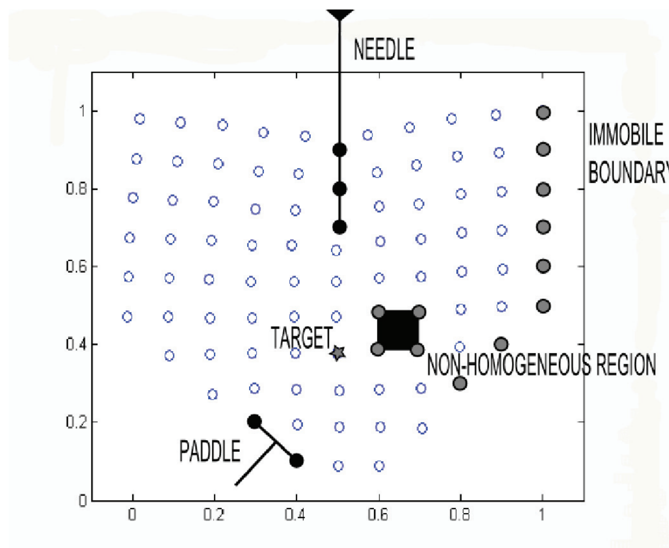

Fig. 1. Deformed object model indicating immobile boundary, needle insertion, stabilizing paddle, a non-homogeneous region, and a target point.

was employed to help define the object characteristics, where c is a positive constant, E is the strain tensor represented as a vector and A and C are symmetric second-rank tensors. The values employed for A and C are listed in table I, and were determined through tissue measurement in [7].

A_{ijkl}	*Value*	C_{ijkl}	*Value*
$A(0,0,0,0)$	1020	$C(0,0,0,0)$	3.5
$A(1,1,1,1)$	1020	$C(1,1,1,1)$	3.5
$A(0,1,0,1)$	254	$C(0,1,0,1)$	0.5
$A(1,0,1,0)$	254	$C(1,0,1,0)$	0.5
$A(0,0,1,1)$	383	$C(0,0,1,1)$	1.5
$A(1,1,0,0)$	383	$C(1,1,0,0)$	1.5
$A(0,1,1,0)$	383	$C(0,1,1,0)$	1.5
$A(1,0,0,1)$	383	$C(1,0,0,1)$	1.5

TABLE I

VALUES FOR A AND C TENSORS. ALL VALUES NOT INDICATED ARE ZERO.

Target Stabilization was performed in position control, making the reactive forces of the tissue boundary negligible compared to the imposed paddle forces. These paddles were oriented parallel to the tissue boundary and strictly acted on the boundary perpendicular to this axis. Further, their geometry was restricted to connect two adjacent boundary points on the essential boundary for the positions listed in Table II. These constraints were imposed from a practical perspective, since one standardized tool is typically used for a given procedure even though various tools may be available. Also, a paddle covering two adjacent points is the smallest width that could be used in this model case, considering that the paddle must interact with specific nodes on the essential boundary. As a result, a maximum number of paddle positions in the accessible area are given.

Paddle Index	$Coordinates(x,y)$
1	$(0.4,0.1),(0.3,0.2)$
2	$(0.3,0.2),(0.2,0.3)$
3	$(0.2,0.3),(0.1,0.4)$
4	$(0.1,0.4),(0.0,0.5)$
5	$(0.0,0.5),(0.0,0.6)$

TABLE II
INDEX RELATING TO PADDLE POSITIONS.

A. Target Point Stabilization with Static Paddle

Using a homogeneous object model, a needle initially in line with the desired position was inserted into the object and continued to follow a straight trajectory. During the insertion, the paddle was fixed. The displacement of the target was computed and recorded using the deformable model. The fixture positions were incrementally changed to cover successive boundary nodal points on the object, beginning at the position shown in Figure 1. It must be noted that there was a limited boundary perimeter to which the fixtures could be applied to. The measure of paddle placement quality was the maximum displacement of the target in a direction orthogonal to the needle axis. For the model presented in Figure 1, Figure 2 depicts the displacement of the target point on the x axis as a function of paddle position along the object boundary. The results show that the optimal placement corresponds to position 4.

Next, a non-homogeneous square region was implemented into the object as shown in Figure 1, with a stiffness coefficient 100x that of the surrounding object, at indices (0.6, 0.4), (0.7, 0.4), (0.7 0.3), (0.6, 0.3) . Emulating the previous procedure, the results are shown below in Figure 3. The results show that the optimal paddle placement correspond to position 2. This indicates that the static paddle placement is a function of tissue structure justifying the use of a dynamic paddle to manipulate the target.

B. Stabilization of Targeted Point with Dynamic Paddle

In this section we compute the placement of a dynamic paddle that provides the best controllability over the target point. A simple control law based on a Jacobian estimate of the transformation between a boundary displacement and control point displacement can be used for the control of the target [8]. Then the controllability measure for a certain paddle position is defined as the norm of the required paddle displacement in order to achieve a given displacement of the target in the direction orthogonal to the needle axis. In particular for the chosen configuration this is $||J^{-1}[10]^T||$. The Jacobian is estimated by displacing the paddle with a small amount in the principle directions and recording the induced displacement in the target. For the assumed configuration the optimal paddle position is the one that minimizes the controllability measure $CM = ||J^{-1}[10]^T||$, consequently providing the best controllability in the x dimension. Table III shows the controllability value as a function of paddle position for homogeneous and nonhomogeneous deformable object. It is clear that paddle position 3 provided the greatest effect on the target point.

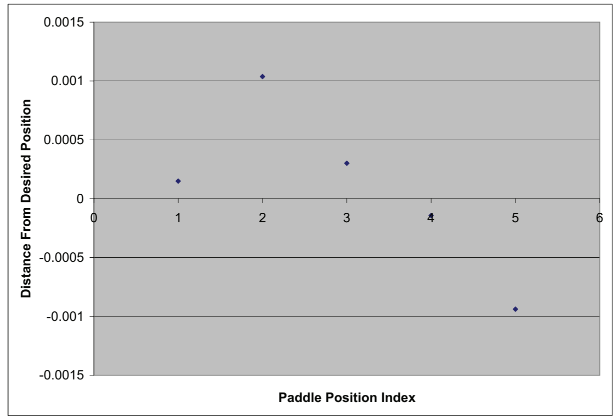

Fig. 2. Target point error in the axis orthogonal to the needle axis of a homogeneous object as a function of paddle position.

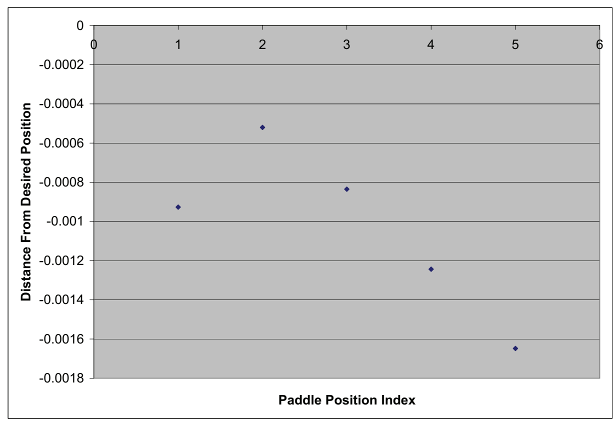

Fig. 3. Target point error in the axis orthogonal to the needle axis of a non-homogeneous object as a function of paddle position.

Paddle Index	Homogeneous Object	Non-Homogeneous Object
1	4.7822	6.3556
2	4.1544	5.3583
3	3.2715	4.8749
4	3.3748	5.4552
5	3.3999	5.9523

TABLE III
CM AS A RESULT OF CALCULATED JACOBIAN MATRICES.

IV. DISCUSSION

In previous soft object manipulation model approaches to straight needle insertions, it is important to note that an assumption was made allowing for external interaction with any point on the object boundary. Relying on this assumption is rather unrealistic due to anatomical constraints that could make such procedures unfeasible. The deformable object model developed in this study is prescribed by anatomy, such that only a portion of the object is accessible. Also, the user is limited to a specific sized paddle geometry.

In the static paddle case, paddle position 4 gives the best target point stabilizing effect for the homogeneous object, as this represents the smallest target point displacement in the axis orthogonal to the needle axis. Paddle position 2 becomes the optimal position when a non-homogeneous region is added to the object. It is clear from the results that a shift in the target point displacement occurs as an impurity is added to the object. In this particular case, as shown in Figure 3, the shift is in the negative x direction.

From these results it is shown that a stabilizing paddle position can be computed for a given targeted region, although it is quite limited when the object becomes non-homogeneous. If more non-homogeneous areas are added, the control point deviation becomes even more difficult to predict. Due to this limitation, utilizing dynamic paddle manipulations of the object is justified.

In the case of a dynamic paddle we seek for the placement that provides the best controllability over the target. The results show that such measure is not constant over the possible placements. For the considered geometry the computations show that position number 3 is optimal for both the homogeneous and non-homogeneous object. This suggests that dynamic paddle stabilization is a better choice than using a static fixture. These results also show that for deformable objects subject to certain fixed boundaries the target stabilization with respect to needle direction can be achieved using only one actuator. Moreover, the proposed approach provides also the direction in which the paddle has to be moved in order to achieve maximum displacement in the direction orthogonal to the needle axis. For the assumed model this is $J^{-1}[10]^T$.

To address the issue of extending the model dimensional properties, the model can be extended to three dimensions. However, this makes the target stabilization problem more complex since an additional paddle needs to be utilized to control the newly imposed degree of freedom. The planar model was used to obtain preliminary results since it could be quickly prototyped.

V. CONCLUSION

In this study, a mesh-less (RKPM) deformable object model was used to study the stabilizability of a soft tissue target during needle insertion. The deformable object was considered as having an immobile surface section and a limited accessible boundary for external paddle interaction. Two specific cases were analyzed; the placement of a static paddle and the placement of a dynamic paddle.

Two different optimality criteria were defined for the characterization of the best paddle placement for the static and the dynamic cases. The results showed that the optimal placement of a static paddle varies greatly with the object properties, whereas the optimal placement for the dynamic case was less sensitive to changes in object structure. Although the results were obtained for a particular geometry they indicate that a dynamic paddle is more suitable for the target stabilization during needle insertions.

Future developments will include the implementation of a target stabilization algorithm using a physical model of various shape complexities and model constituents. As well as improving computational efficiency for the model solver.

REFERENCES

[1] R. Alterovitz, A. Lim, K. Goldberg, G.S. Chirikjian and A.M. Okamura, Steering Flexible Needles Under Markov Motion Uncertainty, *IEEE/RSJ International Conference on Intelligent Robots and Systems*, August 2005, pp 120-125.

[2] S.P. DiMaio, S.E. Salcudean, Needle Steering and Motion Planning in Soft Tissues, *IEEE Transactions on Biomedical Engineering*, vol. 52, June 2005, pp. 965-974.

[3] T. Wada, S. Hirai, S. Kawamura, N. Kamiji, Robust manipulation of deformable objects by a simple PID feedback, *IEEE Internation Conference on Robotics and Automation*, May 2001, pp. 21-26.

[4] V.G. Mallapragada, N. Sarkar, T.K. Podder, Robot assisted real-time tumor manipulation for breast biopsy, *ICRA 2008. IEEE International Conference*, May 2008, pp. 2515-2520.

[5] J.S. Chen, S. Yoon, C.T. Wu, Non-linear version of stabilized conforming nodal integration for Galerkin mesh-free methods, *International Journal For Numerical Methods in Engineering*, vol. 53, 2002, pp. 2587-2615.

[6] J.S. Chen, C. Pan, C.T. Wu, W.K. Liu, Reproducing Kernel Particle Methods for large deformation analysis of non-linear stuctures, *Computer methods in applied mechanics and engineering*, vol. 139, January 1996, pp. 195-227.

[7] Stephen C. Cowin, Stephen B. Doty, *Tissue Mechanics*, Springer, New York, NY; 2007.

[8] J. Smolen, A. Patriciu, Deformation Planning for Robotic Soft Tissue Manipulation, *Advances in Computer-Human Interactions, 2009. ACHI '09. Second International Conferences on* 1-7 Feb. 2009, pp. 199 - 204.