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Spatial Rigid/Flexible Dynamic Model of Biopsy and Brachytherapy Needles Under a General Force Field

Athanasios Martsopoulos[1,2], Rajendra Persad[3], Stefanos Bolomytis[3], Thomas L. Hill[1] and Antonia Tzemanaki[1,2]

***Abstract*— Computer-aided simulation of percutaneous needle insertion, as a training tool for junior surgeons, is expected to significantly increase targeting accuracy during minimally invasive operations. This work presents a novel mathematical model, based on the theory of flexible multibody dynamics, that captures the spatial dynamics of needles used for brachytherapy and local anaesthetic transperineal prostate (LATP) biopsy, under a general three-dimensional force field. Due to its accuracy and its computational efficiency, the proposed model is expected to constitute a valuable tool for both real-time visual/haptic simulation and control of percutaneous needle insertion.**

Index Terms— Medical Robotics, Needle Steering, Flexible Multibody Dynamics, Finite Element Method, Rayleigh-Ritz Method

I. INTRODUCTION

Minimally invasive surgery (MIS) and localized therapy have become integral parts of modern medical practices as they are characterized by decreased recovery time, reduced patient discomfort and lower risk of infection when compared to open surgery procedures [1]. Percutaneous needle insertion constitutes one of the main practices for performing MIS operations, including a plethora of diagnostic and therapeutic applications, such as tissue biopsy, brachytherapy, neurosurgery, and deep brain stimulation [2].

The success rate of these operations heavily relies on the accuracy of needle placement, while imprecise targeting can often lead to severe complications, such as false negatives in biopsy or ablation of healthy tissue [3]. At the same time, accurate percutaneous needle placement is a highly challenging task. The limited visual feedback during the operation, combined with factors, such as tissue anisotropy, heterogeneity and variability in anatomical structures among different patients, significantly complicates navigation through the tissue and thus decrease the operation's overall accuracy [4].

In recent years, the biomechanics and robotics research communities have come up with different solutions that have the potential to significantly increase the accuracy of needle placement procedures. These mainly focus on the development of robotic systems that will allow autonomous navigation and accurate needle placement to targeted locations inside soft tissue. Another approach, is the development of high-fidelity visual/haptic medical simulators for the training of junior doctors in a variety of surgical scenarios or for the planning of complex procedures by experienced doctors [2].

This work focuses on the formulation of a mathematical model that captures the spatial dynamics of brachytherapy and local anaesthetic transperineal prostate (LATP) biopsy needles under a general 3D force field. The proposed model considers: a) the needle's base as a rigid body that follows any arbitrary spatial trajectory, which corresponds to the doctor's hand movements during percutaneous needle insertion, and b) the needle's shaft as a flexible body that deforms elastically under a general state/time dependent field of forces, which corresponds to the interactions between the needle and the surrounding tissue (distributed load $\underline{p}(x,t,\underline{q},\dot{\underline{q}})$ and point load $\underline{F}_B(t,\underline{q},\dot{\underline{q}})$). By employing this multibody rigid/flexible modelling approach, this work captures both the dynamics of the needle's deflection and the reaction forces that act on the surgeon's hand, while accounting for the inertial forces caused by the overall motion of the system.

The accuracy and the computational efficiency of the proposed model, allow its application to both real-time visual/haptic simulation and control of percutaneous needle insertion. It should be noted that, while this research is mainly focused on the operations of prostate brachytherapy and LATP biopsy, the generalised modelling of the needle-tissue interaction forces allow its application to other types of needle placement procedures.

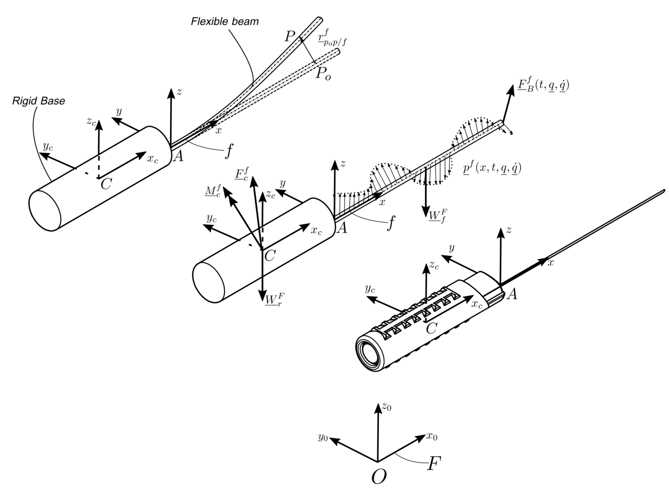


Fig. 1. Model of rigid/flexible brachytherapy/LATP needle

[1] A. Martsopoulos, T. L. Hill and A. Tzemanaki are with the School of Civil, Aerospace and Mechanical Engineering, University of Bristol, Bristol, UK {athanasios.martsopoulos, antonia.tzemanaki, tom.hill}@bristol.ac.uk

[2] A. Martsopoulos and A. Tzemanaki are also with the Bristol Robotics Laboratory, University of the West of England, Bristol, UK

[3] R. Persad and S. Bolomytis are with the Bristol Urological Institute, Southmead Hospital, Bristol, UK

II. METHODS

The development of the spatial dynamic model of the needle is based on the theory of flexible multibody systems. For the analysis of such systems, different approaches have been proposed in the literature, such as the component mode synthesis [5], the rigid finite element (RFE) method, the absolute nodal coordinate (ANC) formulation and the floating frame of reference (FFR) formulation [6]. This work is based on the FFR formulation as it allows the description of arbitrarily large rigid-body displacements and rotations and a straightforward addition of complex force functions and constraint equations [6].

The mathematical description of the needle's deformation is based on the assumed modes method. For this, two approaches are examinined; namely the Rayleigh-Ritz and the finite element method. The first approach estimates the deformation field as a linear combination of a finite series of shape functions that satisfy both the boundary conditions of the cantilever beam and smoothness requirements (admissible functions). In the proposed model, the admissible shape functions are the orthonormal mode shapes of the cantilever beam, as this ensures that both requirements are satisfied. In the second approach, the beam is discretized by a finite number of beam elements, each of which is deformed based on local admissible shape functions, and characterized by local mass, damping and stiffness properties.

In both of the aforementioned approaches, the position of an arbitrary point P on the flexible needle, with respect to the FFR f (Fig. 1), is approximated as

$$\underline{r}^f_{AP/f} = \underline{r}^f_{AP_0/f} + \mathbf{\Phi}(\underline{x})\ \underline{q}_f \tag{1}$$

where, $\underline{r}^f_{AP_0/f}$ is the position of the point before deformation, $\mathbf{\Phi}(\underline{x})$ is the matrix of shape functions and $\underline{q}_f$ is the vector of generalized elastic coordinates. Note that both $\mathbf{\Phi}(\underline{x})$ and $\underline{q}_f$ differ between the two approaches.

Having defined the position of an arbitrary point on the flexible body and by applying the *principle of virtual work* for the flexible needle of Fig. 1, subject to generalized contraint forces from the rigid body, we obtain the set of differential equations

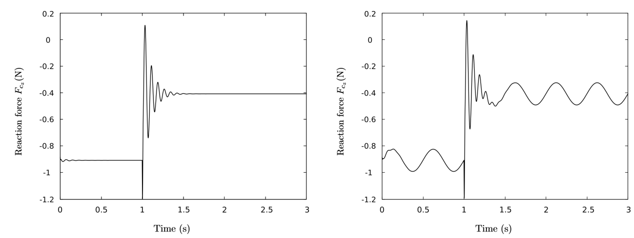
$$\mathbf{M}_f\ \ddot{\underline{q}}_e + \mathbf{C}_f\ \dot{\underline{q}}_e + \mathbf{K}_f\ \underline{q}_e = \underline{f}_{v_f} + \underline{Q}_f + \underline{Q}_c \tag{2}$$

where, $\underline{q}_e = \left[(\underline{r}^F_{OA/F})^T \quad \underline{\theta}^T_f \quad \underline{q}^T_f\right]^T$ is the state vector that describes both the rigid-body motion of the needle and its elastic deformation. The highly nonlinear mass matrix $\mathbf{M}_f$ is both depedent on the system's state and the selection of the shape functions, the stiffness matrix $\mathbf{K}_f$ is constant, while the daming matrix $\mathbf{C}_f$ is defined based on the classical Rayleigh damping as $\mathbf{C}_f = \mu\mathbf{M}_f + \kappa\mathbf{K}_f$. The vectors $\underline{f}_{v_f}$, $\underline{Q}_f$ and $\underline{Q}_c$ represent the coriolis/centrifugal forces, the generalized external forces and the generalized constraint forces, respectively.

Given that the position and the orientation of the rigid body are known functions, with continuous second derivatives, equation (2) can be integrated numerically to obtain the time evolution of the elastic coordinates $\underline{q}_f$, and thus, the vibrational behaviour of the needle. Furthermore, formulating the equations of motion of the rigid-body, we can easily evaluate the reactions forces and moments $\underline{F}^F_c$ and $\underline{M}^F_c$ acting on the needle's handle (haptic feedback).

III. RESULTS

To illustrate the performance of the proposed model, a simple test case of step force loading is considered. Let $\underline{F}^f_B = \begin{bmatrix}0 & 0 & F_B\ \mathcal{H}(t-1)\end{bmatrix}^T$, an external force vector applied on the needle's tip as shown in Fig. 1, where F_B is the applied force magnitude with an arbitrary value of $0.5\ N$ and $\mathcal{H}(t)$ is the Heaviside function. Next, the response of the system is considered for two distinct cases. In the first case the surgeon's hand remains fixed with respect to the inertial frame F, while in the second case its trajectory (position and orientation) is described as $\underline{r}^F_{OC/F} = \begin{bmatrix}0 & 0 & a_z \sin(2\pi f_{dz} t)\end{bmatrix}^T$ and $\underline{\theta}_r = \underline{0}$, where a_z the displacement magnitude with an arbitrary value of 0.2 m and f_{dz} the displacement frequency chosen as 2.0 Hz.



(a) Reaction force in z direction with fixed base.

(b) Reaction force in z direction with moving base.

Fig. 2. System response under step force loading.

As seen in Fig. 2(a) and 2(b), the proposed model can capture the dynamics of the needle's vibration while also accounting for the inertial forces caused by the overall rigid body motion. It should be noted that, even though this example examines only a simple 2D case, the proposed model can be used for any arbitrary spatial trajectory of the needle's base and under any 3D loading conditions.

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