Position-based simulation of deformations for autonomous robotic ultrasound scanning

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***Abstract*—Realistic and fast simulation of anatomical deformations due to ultrasound probe pressure is of outstanding importance for testing and validation of autonomous robotic ultrasound systems. We propose a deformation model which relies on the position-based dynamics (PBD) approach to simulate the probe-tissue interaction and predict the displacement of internal targets during US acquisition. Performances of the patient-specific PBD anatomical model are evaluated in comparison to two different simulations relying on the traditional finite element (FE) method, in the context of breast ultrasound scanning. Localization error obtained when applying the PBD model remains below 11 mm for all the tumors even for input displacements in the order of 30 mm. The proposed method is able to achieve a better trade-off among accuracy, computation time and generalization capabilities with respect to the two FE models. Position-based dynamics approach has proved to be successful in modeling breast tissue deformations during US acquisition. It represents a valid alternative to classical FE methods for simulating the interaction between US probe and tissues.**

***Index Terms*—Autonomous robotic ultrasound scanning, position-based dynamics, robot simulation**

I. INTRODUCTION

Although ultrasound (US) imaging is extensively employed in the diagnostic field, the quality of US examinations is highly dependent on the sonographer's expertise. Robotic ultrasound systems (RUS) can help to overcome this limitation, due to the intrinsic high precision, dexterity and repeatability of robotic manipulators [1]. In recent years, autonomous robotic ultrasound systems (ARUS) have been also proposed, in order to further increase repeatability of the acquisition and to simplify the entire workflow, reducing both times and costs of the current clinical systems [2]. The introduction of ARUS in the medical field poses some challenges especially when it comes to the validation of new control schemes. In general, the first step to test new algorithms in robotics is represented by simulation, since it allows to foresee unsafe or unexpected configurations. Simulation is of critical importance when dealing with medical applications, where guaranteeing patients' safety is the primary concern.

The most demanding task when simulating an ARUS is to realistically model the deformations induced to the tissues due to the pressure applied with the US probe during the scanning. The preferred approach when high physical accuracy is required relies on the finite element (FE) method, where soft tissues mechanical behavior is described through the laws of continuum mechanics. However, this method usually comes at the expenses of high computational complexity, especially when tool-tissue interactions have to be explicitly modelled [3]. An alternative to FE models is represented by geometry-based approaches, like the position-based dynamics (PBD). Although PBD formulation does not depend on tissues mechanical parameters, different types of elastic materials can be realistically simulated by fine-tuning modelling parameters and constraint functions of the system [4].

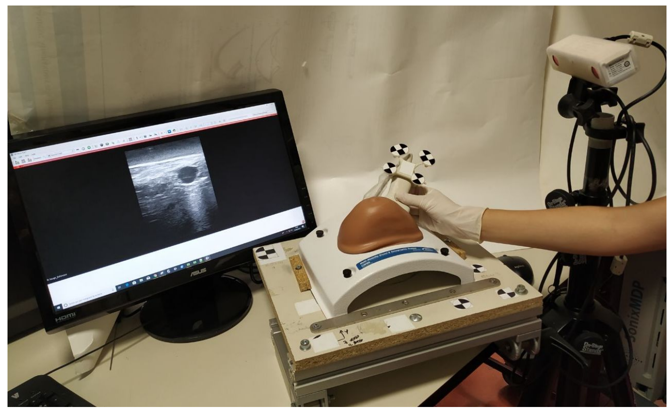

Fig. 1. Experimental setup. From left to right: US image, CIRS breast phantom, FUS, optical tracking system.

In this work, we evaluate the capability of a patient-specific PBD model to simulate anatomical deformations during ultrasound scanning. In particular, we focus on an ARUS for the breast, a very active and promising field which would significantly benefit from accurate anatomical simulations, due to the highly deformable nature of breast anatomy [5]. The proposed PBD model demonstrates to be able to realistically mimic the complex interaction between the breast and the US probe under different levels of probe induced deformations, achieving a trade-off between accuracy, computation time and generalization capability, which is comparable to those obtained by state-of-the-art FE implementations, but without requiring the generation of a 3D mesh and thus simplifying its employment in general simulation software.

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II. Materials and Methods

In this work, we evaluate the performances of three different simulation approaches for modelling the interaction between the US probe and the breast anatomy.

1) Position-based dynamics model (PBD): an anatomical model of the breast is created exploiting the PBD implementation provided by NVIDIA FleX, which relies on the region-based shape matching constraint. Patient-specific simulation parameters are selected according to [4]. Probe-tissue interaction is described as a collision problem, handled by the default implementation provided by the Unity engine.

2) Finite element model with explicit modelling of contacts (FE-contacts): the Neo-Hookean formulation of nonlinear elasticity provided by the SOFA framework [6] is exploited for breast modelling, using the mechanical properties estimated in [7]. Interaction between the US probe and the breast is formulated as a linear complementarity contact problem.

3) Finite element model with prescribed displacements (FE-displ): the same physics model described in previous point is used, but probe-tissue interaction is obtained by prescribing the displacement of the mesh nodes on the breast surface below the US probe to follow probe motion. Differently from the previous two scenarios, this last approach assumes that the breast-probe contact area is a-priori known and does not change throughout the simulation (i.e., no sliding occurs). Despite limiting its generalization capabilities, this model relies on an equation system which is simpler to solve, since it does not introduce the kinematic nonlinearities due to contact modelling.

In order to evaluate model performances, we rely on experimental data acquired from a Freehand Ultrasound System (FUS) based on a MicrUs US device (Telemed, Vilnius, Lithuania) equipped with a linear probe (model L12-5N40) without loss of generality (the same experiments can indeed be repeated with the probe held by a robotic manipulator). An optical tracking system MicronTracker Hx40 (Claron-Nav, Toronto, Canada) is used to track the probe pose with respect to a realistic breast phantom (Model 073; CIRS, Norfolk, VA, USA) with several stiff internal masses of diameter 5-10mm. (Fig. 1). Model performances are assessed by evaluating the capability of the models to provide correct estimates of 10 segmented internal lesions at increasing levels of probe-induced deformations.

III. Results

Localization errors are computed as difference between the model-predicted and real lesion position (extracted from US images), at five different deformation levels. The red, purple and green lines in Fig. 2 show the trend of the localization error at increasing deformation. In general, accuracy obtained with the PBD model is comparable to FE models. It is interesting to notice that the error made by both PBD and FE-contacts is always higher than the one obtained with FE-displ, suggesting that the explicit modelling of contacts introduces further inaccuracies into the simulations. The average simulation time needed to predict anatomical deformations

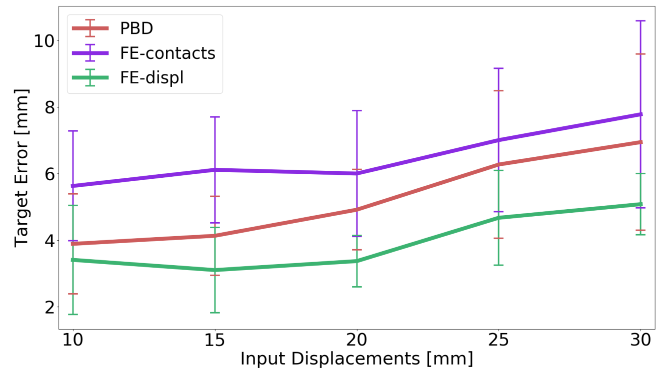

Fig. 2. Average localization error at the increasing deformation for the different models [mm].

after the entire input displacement is applied is $6.99\,s \pm 0.34$, $7.81\,s \pm 2.22$ and $4.83\,s \pm 0.32$ for PBD, FE-contacts and FE-displ respectively. Also in this case, PBD model achieves performances which are in between those obtained by the two FE approaches. Although FE-displ achieves the best performances both in terms of accuracy and computation time, such method cannot handle generic input probe motions since it relies on prior knowledge of probe motion, thus lacking generalization capabilities.

IV. Conclusion

Accurate and fast simulation of probe-tissue interaction is of paramount importance for the validation of new control schemes in autonomous robotic ultrasound systems. A simulation strategy which relies on the PBD approach has demonstrated to be able to realistically describe such interaction in the context of breast US scanning, achieving a better trade-off among accuracy, computation time and generalization capabilities with respect to conventional FE methods. As future work, we will perform more extensive ARUS acquisitions including not only pushing but also sliding.

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