A Concept for Fail Safe Robotic Needle Insertion in Soft Tissue

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Abstract

This paper presents a concept of automatic needle placement for brachytherapy. For the success of this minimally invasive treatment, a precise and safe placement of needles inside soft tissue is fundamental. The presented concept incorporates information about the needle as well as the tissue to find a suitable needle trajectory. A patient-specific tissue model is derived from different imaging modalities and updated during the insertion. Essential for this concept is that during the robotic placement of the needle, it is continuously verified if proceeding is safe.

1 Introduction

Brachytherapy represents one alternative for minimal-invasive cancer treatment in soft tissues. We consider high-dose rate (HDR) brachytherapy, where a hollow needle or tube is placed into the tumor, and radioactive sources moving inside the needle deliver the therapeutical dose. As the dose is delivered from inside the tumor, the side effects to surrounding, healthy tissue are reduced. However, as the sources can only be moved along the needle it is important to precisely place the needles inside the tissue. This can be challenging, particularly as the needles and the tissue deform during insertion. The impact of the needle type and insertion speed on the displacement is illustrated in Figure 1 and has been studied recently [MSM^{+}12]. An additional problem is that typical tissue is not completely homogeneous and the deformation of tissue and needle are depending on the mechanical properties of different tissue layers. Figure 2 illustrates how one gelatine layer in a simple gelatin phantom is deformed before it is penetrated by the needle. Interestingly, the rupturing of the tissue typically results in a quick relaxation along the needle. This can cause two types of artifacts. First, before the tissue ruptures it is displaced by the needle, i.e., while the needle has traveled the planned distance with respect to

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the outer patient anatomy, it has not reached the desired depth inside the tumor. Second, when the needle is advanced until the tissue layer ruptures, the resulting relaxation may leave the needle to deep inside the tissue. This may lead to unwanted side effects, e.g., puncturing of the bladder during prostate brachytherapy.

2 Needle Insertion as an MCPS

Conventionally, the needles are inserted manually by trained physicians. Often, a rigid template is used and the needle is primarily advanced be the physician using some sort of image guidance, e.g., ultrasound or, less typical, magnetic resonance imaging (MRI). Either image modality is not free of artifacts and often it is necessary to move the needle back and force multiple times before a final position is reached. Nevertheless, due to the deformations and needle deflection this may not resemble the initially desired placement. Hence, it is common practice to first insert the needles and subsequently identify the position of all needles in images of the target region, and then to optimize the dose delivery. Over the past decade, the idea of robotic brachytherapy has been studied by a number of groups [PBC+14][LHB+12][PNY07]. The promise is a fully optimized and fully automatic treatment, where the needle positions are determined by an optimization algorithm and placed in exactly the same arrangement with respect to the anatomy using an autonomous robotic needle driver. Potential advantages include a further reduction of side effects and the use of few needles to focally treat tumors in an early stage. However, one of the key challenges is the safe insertion of the needles, i.e., in the desired depth within the target while avoiding damage to surrounding structures. The proposed setup resembles an MCPS as illustrated in Figure 5, with the control loop including the robot and its actuators, sensors and imaging, and the tissue inside the patient. Clearly, the robotic insertion is subject to similar difficulties as the manual procedure, i.e., tissue deformation and needle deflection. However, unlike in manual placement the robotic motion of the needle can be more precisely adapted to the sensor readings. For example, we include optical fibers in the needle to obtain high resolution images of the tissue structure in front of the needle tip using optical coherence tomography (OCT). Doppler OCT also allows estimating tissue motion and deformation [OHS12]. We are working on integrating this information into a tissue model, which in turn will be used to estimate and predict the tissue behavior for different needle motion, e.g., to distinguish loading deformation, rupture and cutting through tissue. Hence, the needle driving will be optimized with respect to the tissue properties. Initially, deviations between planned and measured needle trajectory are compared and large errors will lead to stopping and an operator decision whether to proceed or retract. Estimates of the accuracy of the model and impact of failures should ultimately be checked during the procedure. The concept is summarized in Figure 4, Figure 3 shows our experimental setup.

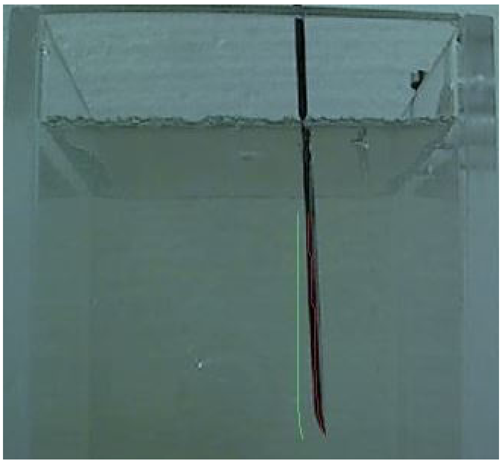

Figure 1: Needle offset between planed trajectory (green line) and actual path (black needle) [Koc13]. This offset has be accounted for during insertion.

Figure 2: Overlay of a colored gelatin layer before penetration with a needle. The darker image shows the layer before needle contact. The lighter image shows the deformed layer.

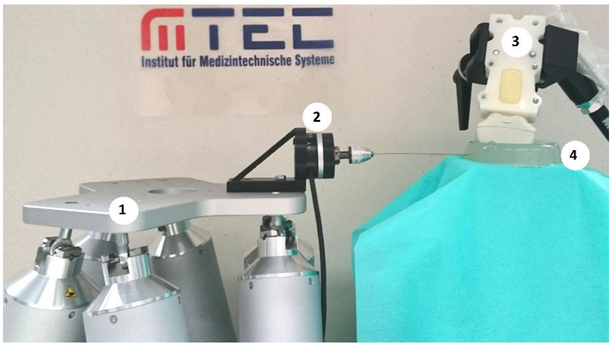

Figure 3: Test Setup with hexapod(1), needle with force torque sensor (2), ultrasound transducer (3) and gelatin phantom(4).

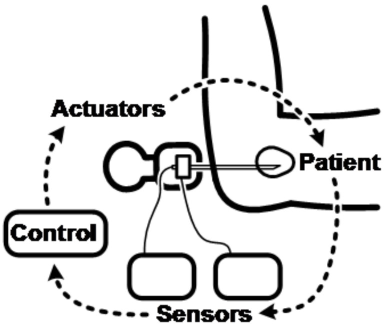

Figure 4: Concept for fail safe robotic needle insertion in soft tissue with the patient in the loop. The sensors include OCT and force-torque measurements.

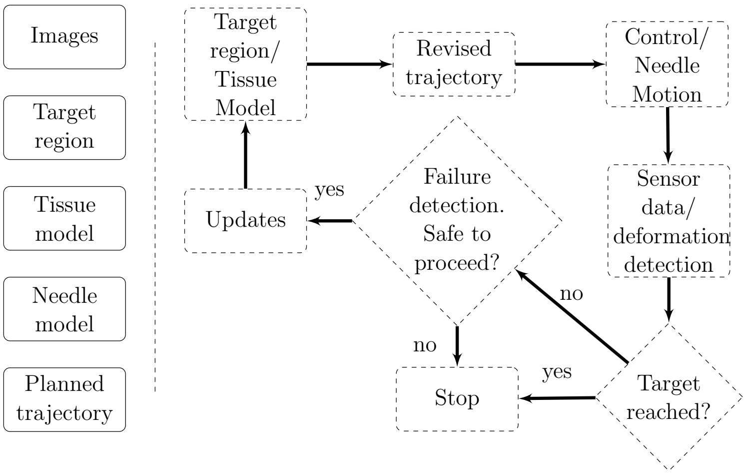

Figure 5: Flowchart of the fail safe procedure. Left: data and models acquired before the needle insertion. These are necessary input for the algorithm. Right: Fail safe algorithm for needle insertion. From the needle model, the current target region and the current tissue model an optimal needle trajectory is computed.The needle is moved further into the tissue, meanwhile the deformation is monitored. For offsets to the planed trajectory it is checked if proceeding is safe. Criteria for failure are for instance an uncorrectable path or a pending rupture close to avoidable areas. If it is safe, the target region as well as the tissue model are updated and the next loop starts. If it is not safe or the target area is reached, the insertion is stopped.

2.1 Conclusion

We have summarized a concept for automatic needle placement incorporating sensor information, tissue modelling and actuator control to maintain fail safety. Extensions, e.g., online model checking can be implemented, as all sensor data processing, motion planning, and control is realized in software.

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