Flexible needle steering for computed tomography-guided interventions

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Conclusions and Future Work

Percutaneous needle insertion procedures are commonly used for diagnosis e.g., biopsy and therapy e.g., brachytherapy. Success of the procedures highly depends on accurate placement of the needle. Clinicians use various imaging modalities, such as CT, MRI and ultrasound in order to reach the target accurately. Current imaging technology can provide accurate localization of lesions. However, precise targeting of the lesions by manual insertion of rigid needles is both difficult and time-consuming. Furthermore, physiological motions induces movement to the tissues specially near the diaphragm, such as liver or lungs. This can results in an increase in the number of pleural punctures which increases the chance of complications such as pneumothorax and pulmonary hemorrhage.

In the United States and Europe lung cancer screening with low dose computed tomography is recommended for people at high risk or within clinical trial settings. The introduction of lung cancer screening results in an increase of detected nodules. However, targeting the nodules remains challenging. This thesis presents a novel CT-compatible needle insertion setup, which is designed to address the challenges of needle interventions. The robot is composed of the NID and the remote-center-of-motion arm. The design and evaluation of the NID and the arm are presented in Chapter 2 and 4, respectively. In Chapter 2, first the CT-compatibility of the robot is evaluated, and then several needle steering experiments are performed. The experimental results suggest that a real-time feedback of needle tip position is critical in order to achieve high accuracy. Therefore, a data fusion scheme using unscented Kalman filter is discussed in Chapter 3. Ultrasound images are fused with FBG sensor data, in order to track the needle tip accurately and close the control loop using the real-time data. An actuated-tip needle is also investigated in the experiments. Chapter 4 presents the design of the RCM arm and a modified version of the unscented Kalman filter discussed in Chapter 3. For the experiments, real-time EM tracking data are fused with intermittent CT images in order to increase the targeting accuracy. The next chapter discusses physiological motion compensation, which is achieved using a force sensor and ultrasound images. The tissue motion is estimated using the force sensor data, and the target is tracked in the ultrasound images. In order to apply the estimates motion to the needle, a robotic arm (UR3) is used. In order to conclude this work in a realistic experimental scenario, Chapter 6 presents a clinical situation to perform needle steering experiments. A new steering method is described and tested in a human cadaver.

7.1 Conclusions

In chapter 2, needle steering experiments in biological tissue embedded in a gelatine phantom are performed. In order to close the control loop, real-time EM tracking data are used in one case, and intermittent CT images are used in another case. The results show a targeting accuracy of 1.11±0.14mm and 1.94±0.63mm for EM tracking and CT images, respectively. These results suggest that the real-time feedback of needle tip pose has a considerable influence on the targeting accuracy. Therefore, in chapter 3, a data fusion scheme based on unscented Kalman filter is developed. In this chapter, FBG sensor data are fused with ultrasound images. A tendon-driven actuated-tip needle is used in the experiments. Needle steering experiments are performed both in gelatine phantom and biological tissue, and real targets are used in both cases. The targeting error is 1.29±0.41mm and 1.42±0.72mm for gelatin and biological tissue, respectively. The targeting error is higher in biological tissue, due to tissue heterogeneity. The results show that the data fusion scheme is feasible for needle steering application. Consequently, in the next chapter, other than introducing the RCM robotic arm, the data fusion method is modified and it is used for fusing EM tracking data and CT images. The designed robotic system is demonstrated to be CT-compatible through experiments. Furthermore, needle steering experiments towards real targets embedded in an anthropomorphic phantom of the thorax show an accuracy of 1.78±0.7mm. The results suggest that the data fusion of two tracking modalities, one real-time and one intermittent can be beneficial for such procedures.

Chapter 5 discusses physiological motion compensation of the body and the target during the procedure, which is a challenging topic in the needle steering domain. A motion profile is applied to a phantom which mimics the liver motion during breathing. The motion is tracked using a force sensor and it is compensated for in the controller. Needle steering is performed, while the motion is compensated and targeting error is 1.2±0.8mm and 2.5±0.7mm in gelatin phantom and biological tissue, respectively. Finally, in the last chapter, a realistic experimental scenario is employed. A fresh frozen human cadaver is used to perform needle steering. The work-flow of the experiments is as similar as possible to the clinical practice. Experiments in the lungs of the cadaver using EM tracking shows a targeting error of 1.39±0.49mm and 2.89±0.22mm using CT images.

7.2 Discussion and future work

This thesis covers several key challenges of needle insertion procedures, specifically for lung and liver interventions. The main contributions of this work are as follows. First, design and evaluation of a CT-compatible remote-center-of-motion needle insertion device is presented. The systems is designed specifically for lung and liver procedures. Therefore, the form factors and the choice of materials are based on commercially available CT scanners. In order to obtain high targeting accuracy real-time tracking of the needle is required. As a result, an unscented Kalman filter is designed to fuse intermittent CT images with real-time EM tracking data. The issue of physiological motion is studied and compensated by developing a new control scheme. The controller uses force sensor and EM tracker data in order to compensate the motion of the phantom. Finally, a new needle steering algorithm using a mechanics-based model to steer the needle using intermittent CT images is developed. This algorithm is used along with a pre-operative path planner in order to define the most suitable insertion point. This is evaluated through needle steering experiments in gelatin, biological tissue and human cadaver using clinical fine-needle-aspiration needles.

The presented system design and experimental results demonstrate the improvements in targeting accuracy and show the flexibility of current system to be used in different experimental scenarios.

The needle insertion setup presented in this thesis is designed in order to proof the concept, feasibility and applicability of flexible needle steering. In order to use such a robotic setup in clinic, the design should be improved and become more user friendly and to get more acceptable by the clinical community. Possible design changes to make the system even more compact should be investigated. In the current design, it is not easy to detach and sterile the needle holder. This is essential for clinical use and should be considered in the next version of the system. On the other hand, the needle holder does not have a mechanism to release the needle in emergency situations. Possible solutions should be investigated in order to increase the safety of the patient when possible complications occur. Furthermore, EM tracker and FBG sensors are used in the experiments. EM trackers are commercially available which makes them easy to use. However, it is challenging to use it in CT scanner, because of surrounding metallic parts. FBG sensors are very promising for medical applications, but it is not yet commercially available. Integration of FBG sensors in clinical diagnostic and therapeutic needles should be investigated.

Along with robust tracking methods, registration of tracking data from different tracking devices could be challenging. For instance, body movements could result in large measurement errors. Therefore, it is necessary to develop registration methods which consider possible movement of the body and the tracking device. Sensor fusion algorithms, such as unscented Kalman filter which is discussed in this thesis, could then be used to combine the body tracking data with needle tracking data. Furthermore, the experiments discussed in chapter 6 in the human cadaver are very similar to the clinical situation. However, in-vivo experiments are needed in order to test the system, more specifically the motion compensation method.

Finally, considering the experimental results discussed in this thesis, flexible needle steering seems very promising for interventions in lung and liver. The results suggest that using flexible needle steering we can reach an acceptable accuracy with high repeatability. Furthermore, the accuracy of such a system is user-independent, and clinicians with different levels of experience can reach a high accuracy in the surgeries. Hopefully, this technology will soon be ready for clinical use, and patients and clinicians will benefit from it.