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Issues in closed-loop needle steering☆

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ABSTRACT

Percutaneous needle insertion is amongst the most prevalent clinical procedures. The effectiveness of needle-base interventions heavily relies on needle targeting accuracy. However, the needle interacts with the surrounding tissue during insertion and deflects away from its intended trajectory. To overcome this problem, a significant research effort has been made towards developing robotic systems to automatically steer bevel-tipped needles percutaneously, which is a comprehensive and challenging control problem. A flexible needle inserted in soft tissue is an under-actuated system with nonholonomic constraints. Closed-loop feedback control of needle in tissue is challenging due to measurement errors, unmodelled dynamics created by tissue heterogeneity, and motion of targets within the tissue. In this paper, we review recent progress made in each of the complementary components that constitute a closed-loop needle steering system, including modelling needle-tissue interaction, sensing needle deflection, controlling needle trajectory, and hardware implementation.

1. Introduction

Surgical robotics has significantly grown over the past decade to enable the use of robotic systems in various complex medical procedures that are arguably impossible to perform with conventional means. Robotic systems are used to augment and extend the capabilities of surgeons, offering great levels of dexterity and precision in diagnosis and treatment. The goal of surgical robotics is not to replace the surgeon, but rather to extend his/her capabilities. Thus, one often refers to surgical robots as assistants that work in tandem with surgeons (Taylor et al., 2008).

A special subclass of these systems is devoted to minimally invasive surgery and therapy (MIST), where the surgeon inserts the surgical tools into the patient's body through small incisions or natural orifices. To date, MIST has been deployed in numerous clinical scenarios including treatments for cancers (Advincula and Song, 2007; Giulianotti et al., 2010; Kang et al.,2009; Kim et al., 2010; Luketich et al., 2003), radio-frequency and microwave ablation of liver and lung (Boctor et al., 2004), treatments for astroesophageal reflux disease (Chapman et al.,2001), gastric bypass and banding (Nguyen et al.,2001), uterine fibroids and prolapse (Falcone and Bedaiwy, 2002), benign cervical disorders (Tinelli et al., 2011), mitral valve prolapse and repair (Nifong et al., 2003), atrial septal defect (Morgan et al.,2004), atrial fibrillation (Di Biase et al., 2009), kidney disorders (Horgan et al., 2002), and bariatric (Gill et al.,2011) and prostate surgeries (Lanfranco et al., 2004). When compared to open surgery, MIST has been shown to reduce pain and blood loss, lower risk of infections, shorten hospital stay, and quicken recovery time.

Irrespective of the application, precise system performance and patient safety are shared requirements in these systems. Examples of the former include accurate steering of flexible needles during percutaneous soft-tissue insertions subject to tissue inhomogeneity and limited control over the needle trajectory, surgical instrument control under physiological organ motion in surgery on a beating heart (Bowthorpe & Tavakoli, 2016), image-guided control and motion tracking of medical instruments (Glozman & Shoham, 2007; West & Maurer, 2004), and optimal trajectory planning for deformable catheters (Gayle et al., 2005). Regarding patient safety, surgical robots can show a large variety of extent of automation. Some are held and operated directly by the surgeon and supplement the ability of the surgeon to perform operations inside the patient's body with superhuman dexterity and precision. Others rather work in tandem with the surgeon and perform functions such as orienting and stabilizing an ultrasound probe or keeping a surgical tool still.

One may surmise that the higher the autonomy granted to the surgical robot, the higher the risk of injuring the patient if the system performance is mediocre or if it becomes unstable (Fei et al.et al., 2001). A medical tool operating under feedback control is vulnerable to various sources of disturbances. Amongst other factors, a surgical instrument that interacts with deformable tissue is subject to uncer-

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tainties arising from the contact with the tissue (Abolhassani et al. 2007), measurement noise and delay (Bowthorpe et al., 2014) including image registration errors (Grimson et al., 1996), and poor visualization of the task being performed (Keereweer et al., 2011). Treating these systems from a closed-loop feedback control perspective will allow us to highlight the trade-off that exists between system performance, patient safety, and clinical translation of robotic technologies.

To illustrate the above problem, in this paper we will focus on control issues in percutaneous needle steering; a particularly challenging subclass of MIST. Percutaneous needle insertion has become part of routine clinical practice for tissue sampling, pinpoint drug delivery, permanent brachytherapy, radiofrequency and microwave ablation of liver, lung, and kidney, and regional anaesthesia. The success of these procedures heavily relies on accurate needle placement within an inner body target location. Bevel-tipped needle steering is particularly challenging. Firstly, a flexible needle inserted in soft tissue is an under-actuated system whose equilibrium condition is never reached as it travels in tissue. Secondly, the needle and tissue form a high-dimensional coupled system subject to uncertainties and disturbances arising from tissue heterogeneity and deformation, anisotropy, anatomic organ motion, and target displacement. These observations make the needle steering in soft tissue a challenging control problem.

This paper is not intended to be a traditional survey on surgical robotics. Rather, we will narrow our focus to the different subsystems that are needed for closed-loop feedback control of flexible needles in percutaneous therapy. This survey is based on the author's extensive work on modelling (Carriere et al., 2015; Fallahi et al., 2015a, 2015b, 2016a, 2016b; Rossa & Tavakoli, 2016; Rossa et al., 2016; Rossa et al., 2016b; Waine et al., 2016), sensing (Carriere et al. 2016; Fallahi et al. 2016; Lehmann et al., 2015, 2016; Waine et al., 2016; Waine, 2016), control (Fallahi et al., 2016; Khadem et al., 2016a, 2016b; Lehmann et al., 2016; Rossa et al., 2016; Waine et al., 2016), and design (Khadem et al., 2016a; Rossa et al., 2016b; Rossa, Usmani, Sloboda, & Tavakoli, 2017) of robotics-assisted needle steering. As a starting point for our discussion, let us consider the fully automated needle steering system depicted in Fig. 1. The issues addressed in this paper arise from each of the subsystems that compose the fully automated closed-loop system i.e., (1) Modelling needle-tissue interaction for trajectory prediction, (2) Sensing needle tip deflection; (3) Model-based and non-model-based controller design; and (4) Collaborative vs. fully automated steering.

The rest of the paper is organized around each of the above points, which will be discussed in details from Sections 2–5, respectively. A discussion on open challenges regarding each of these points will then conclude the paper.

2. Needle-tissue interaction modelling

Here we will consider steerable needles with an asymmetric beveled tip inserted in soft tissue. The needle's mechanical behaviour during insertion depends on the coupled deformations of both the needle shaft and the surrounding tissue. The interaction can be classified into four distinct phases as illustrated in Fig. 2, i.e., tissue puncturing, tissue cutting, needle-tissue friction, and tissue deformation (Misra et al. et al., 2008; Okamura et al., 2004).

Tissue puncturing: Puncturing happens at the initial contact between the needle tip and the tissue. It starts by deforming the tissue and continues until the contact force reaches its maximum and a crack is formed in the tissue surface. Puncturing results in a relatively large force at the needle tip that drops when the needle tip enters the tissue (Khadem et al., 2016; Misra et el., 2008; Okamura et al., 2004).

Tissue cutting: As the needle tip further advances into tissue, it displaces the immediate surrounding tissue and the crack grows, creating the effect of tissue cutting (Khadem et al., 2016b). Considering the tissue as an elastic medium, tissue compression at the needle tip leads to a distributed load being applied on both sides of the needle tip that, due to the asymmetric bevel tip, results a net force normal to the needle shaft (Q in Fig. 2) (Misra et al., 2010).

Friction: Friction is applied tangentially to the needle shaft against the motion of the needle (see Fig. 2). Three regimes of interest exist: (1) The static friction while the needle is in steady state, (2) the transition from the steady state to the sliding state, and (3) the velocity-dependent forces as the needle moves (Asadian et al., 2011; Khadem et al., 2016). Friction contributes to tissue displacement along the needle shaft but does not have a significant effect on needle deflection (Misra et al., 2010).

Tissue deformation: The force Q applied at the needle tip makes the needle bend and follow a curved trajectory as it moves. Consequently, the deformed needle shaft compresses the surrounding tissue, which in turn applies forces to the needle shaft and influences the tip trajectory (Khadem et al., 2016a). Tissue reaction forces are applied perpendicularly to the contact surface between the needle shaft and the tissue. Therefore, needle deflection and tissue deformation are coupled effects that influence each other (Rossa et al. 2016a; Wan et al., 2005).

From a control perspective, the bevelled tip has antagonistic effects: As it facilitates cutting and penetrating the tissue, it also increases the deflection as the needle advances. Thus, twisting the needle base axially

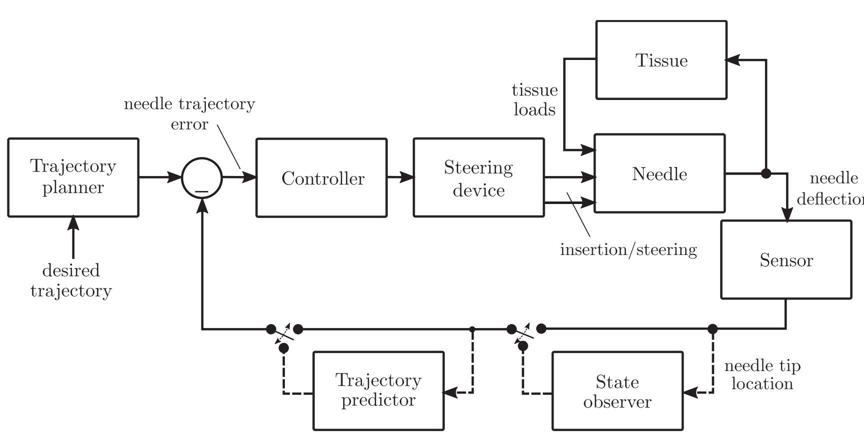

Fig. 1. Block diagram of feedback control for fully-automated needle steering illustrates the concept of using a measurement of needle tip position to control the system by comparing its output to a desired trajectory.