早稲田大学大学院 先進理工学研究科

博　士　論　文　概　要

論　文　題　目

Soft Tissue Puncture Model for Situation Awareness Percutaneous Robot

自動状況認識穿刺ロボットのための軟組織モデルの構築

申　請　者

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It is not a surprise that minimally invasive (MI) treatments have generated a great interest in surgeons and patients. MI treatments have proven to reduce the physical burden of surgery in patients, what translates into less post-surgical complications, early recoveries, reduced stay in hospital and minor cosmetic effects.

Percutaneous treatments are a class of minimally invasive surgery commonly used for cancer treatments or biopsy. In this type of surgery, a physician introduces a needle into a cancerous area, and then applies radio frequency ablation (RFA), chryoablation or chemotherapy to destroy the cancer, or takes a sample of the suspected area for a biopsy. Because of their minimally invasiveness and low cosmetic effects, a needle mark on the skin, and because they affect only the cancerous region where it is applied, it is a desired choice among patients, even if their success is still low due to the complexity of an accurate needle placement into the cancerous area.

Breast cancer has one of the biggest incidences among women in the advanced world. Furthermore, its incidence it is also growing in the developing world. Early detection and treatment improves significantly survival chances, but the treatment can be highly invasive, what causes great concern to women due to the cosmetic damage that the breast might suffer. This proves to be a significant psychological burden to patients, who must not only face surgery and a fight against cancer, but also have to face the possibility of breast deformation.

RFA for liver cancer is becoming one of the most common treatments, with over 1500 centers providing it in Japan. As well as with breast cancer, percutaneous treatment for liver cancer produces better cosmetic results and limited effect on the body, but it is also a big challenge for physicians, who have to guide the needle into a target with limited visibility, only US image can be used in real-time but it is noisy and have low resolution, needle deflection, low tool maneuverability because of limited motion of needle inside tissue, involuntary patient's movement, and human tissue deforms easily when a needle is inserted and the target moves. In addition, mechanical properties of human tissue change between patients, thus, surgeons must rely on tactile feedback and experience.

In order to solve the problem of accurate needle placement, many researchers developed robotic systems to accurately place a needle into a targeted area. These approaches range from needle tissue interaction, finite elements simulation to real-time needle steering. For example Di Maio *et al.* modeled the puncture event based on fracture mechanics theory. Okamura *et al.* identified the forces acting on a needle during insertion to create a model for robot control. On the other hand, Kobayashi *et al.* and Salcudean *et al.* developed a robotic system for liver RFA and prostate brachytherapy respectively using mechanical simulation to calculate the needle trajectory. The latest approach is flexible needles that can change their direction by controlling their tip's orientation.

Despite their good results with known conditions, none of these proposals achieve all the goals required for a successful percutaneous robot: be cheap, simple to use and with short workflow, able to adapt to different patients, and able to collaborate, supervise or react to different situations found during needle insertion.

It has been recognized that to achieve these goals, robotics systems have to become more "intelligent". This achieved through two techniques: statistical modeling to compensate for variability, and situation awareness to adapt to the on-going situation.

The goal of this research is to develop a simple algorithm that doesn't require detailed knowledge of a patient in a pre-operative phase, but still can adapt to changing conditions while being able to be use for robot control operatively.

When a needle is inserted into tissue, the cutting process follows a distinctive pattern that can be divided into two phases: First, the needle pushes the tissue increasing the insertion force steadily. During this phase the tissue deforms until the stress limit is reached. Next, the needle punctures the tissue and advances into it followed by tissue relaxation. Physicians can feel these tissue breaks, and from experience to know the type of tissue they are puncturing, and what is the phase they are going: initial puncture, advancing inside the tissue, reaching the goal, detect big or small deformations, etc., and react to it. We aim to imitate this ability with the use of the analysis of needle insertion force signal.

To understand what is the current phase of the process, one must know the events that have happened to reach that particular state, and the future event that will change the state. In order to detect these events, we propose to use the distinctive pattern in needle insertion force as well as the different stress limits of each particular tissue to: classify the type of tissue being punctured, the state of friction between tissue and needle, and estimate the local value of biomechanical parameters.

First, it will be proven that different types of tissue generate different profiles in needle insertion force, both in puncture force peak value and in shape, and that using statistical modeling, those differences can be used to classify the type of tissue being punctured even if the biomechanical properties of the tissue change.

Next, an iterative algorithm to estimate the local value of the biomechanical properties of a particular tissue, and the state of friction between needle and tissue will be presented.

The statistical models presented in this thesis correspond to swine liver. First, a model of swine liver is derived to prove the feasibility of this proposal. The reason to use liver is on one hand, that it has been commonly used as a target organ for needle insertion robots and allows us to compare with previous research, and on the other hand, because liver has a simple tissue composition, consisting basically in a membrane that covers it, hepatocytes (referred here as hepatic tissue), and a network of veins and arteries. Therefore, we need to model only two types of tissue: hepatic and vein. Since the membrane is a thin layer only present on the initial puncture, we can neglect it.

After proving the feasibility of this method with swine liver, we prove that swine breast also presents the same patterns, but with a more complex structure. In this case, the main tissue consists of mammary gland, with layers of ligaments embedded in it and a network of milk ducts.

Once the statistical tissue puncture models are presented, we will show the application for tissue classification using an algorithm based on fault detection algorithm.

Finally, an online friction and biomechanical parameters estimation algorithm is presented. This algorithm uses iterative least squares fitting. With this algorithm we aim to estimate both the local value of the elastic modulus as a non-linear function, and the overall tend of friction between tissue and needle during needle insertion.

This thesis is structured as follows: In chapter one we will present the background and motivation of this research. We will explain in a detail previous and related research in the field as well as the current state of the art. We will also establish the goal and define the objectives of this research. Chapter two will introduce the design of the percutaneous robot and the concept of *situation awareness* for which the algorithms are developed.

In chapter three we will present the methodology used to model needle insertion puncture into soft tissue, and the statistical models that later will be used for tissue classification and biomechanical parameters estimation.

Chapter four is dedicated to the real-time tissue classification algorithm. First we will introduce briefly the methods of machine learning that can be used for classification and justify our choice for a particular method. Next, the puncture detection algorithm will be presented. Finally, the data of *ex-vivo* experiments will be presented to prove the efficacy of our classification algorithm.

Chapter five presents the algorithm to estimate the value of local elastic module and friction, and its validation with *ex-vivo* tissue. Finally, chapter six collects the results and conclusions from this research, as well as proposed future work.

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査読論文	[1] Q. Liu, Y. Kobayashi, B. Zhang, J. Ye, **I. Elgezua**, Y. Cao, Y. Sekiguchi, Q. Cao, M. Hashizume, M. G.Fujie “Design of an Insertable Surgical Robot with Multi-Level Endoscopic Control for Single Port Access Surgery”, The 10th International Conference on Robotics and Biomimetics (ROBIO), December, 2013.
○	[2] **Inko Elgezua**, Sangha Song, Yo Kobayashi, Masakatsu G. Fujie, “Event Classification in Percutaneous Treatments based on Needle Insertion Force Pattern Analysis”, The International Conference on Control, Automation and Systems, ICCAS. Gwangju, Korea, October 20-22 2013.
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