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Force estimation and failure detection based on disturbance observer for an ear surgical device

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ABSTRACT

The disturbance observer is one of the useful tools for estimating the contact force between the subject body and the environment in robotic and mechatronic systems. This paper introduced a novel automatic office-based ear surgical device for the treatment of Otitis Media with Effusion (OME) under the guidance of force sensing information. Since the force sensing information must be reliable so as to ensure the safety of the device, a contact force estimation method based on the disturbance observer is proposed. The system model is built and a control strategy is proposed and developed. In the control strategy, a composite motion controller for an ultrasonic motor (USM) stage is presented, and then the design and the stability analysis of an advanced disturbance observer is given. Furthermore, a contact estimator and a failure detector, aiming to enhance the safety and reliability enhancement, are designed. Finally, the proposed control strategy is studied with both simulation and experiment. The experimental results show that the advanced disturbance observer can estimate the actual contact force correctly and precisely, and the disturbance observer based force estimation and failure detection method is feasible which can be used in force sensing, contact detection and fault diagnosis.

1. Introduction

Mechatronic and robotic systems are increasingly used in medical applications. One application is the semi-automatic/automatic surgical device, which aims to assist the surgeon to carry out the surgery more efficiently. However, in case a fault occurs (even though it is a small fault) in the device, it will potentially cause an injury to the patient. Hence, safety is the most important requirement to such kind of device.

In this paper, its concern is with the safety issue on an automatic office-based ear surgical device for the treatment of Otitis Media with Effusion (OME). Different from the existing office-based surgical devices for OME, the sensing and control system have been developed and involved in the proposed device, which makes the proposed device to be of a higher precision and intelligence. Significantly, a force sensing system (using a force sensor) has been designed to measure the contact force between the tool set on the proposed device and the Tympanic Membrane (TM). The contact force information will be provided to the surgeon and the device during the surgery. Moreover, this information is used to assist the supervision of the whole surgical procedure by the device. Therefore, the dependency on surgeon's skills can be minimized and the cost to access this treatment can also be reduced. Nevertheless, the safety and reliability is one of the key issues needed to be addressed in the proposed device. In other words, if there is a fault occurring in the force sensing system during the surgery, the proposed device may become malfunctional, possibly leading to an injury to the patient. Therefore, it is very important to make sure that the force sensing information is reliable or the force sensing system fault is detectable.

In this case, a redundant force sensing system can be considered to improve the safety and reliability of the proposed device, i.e., another fore sensing system can be integrated into the device. However, an additional force sensing system will increase the weight and the size to the overall system which may affect its compact form and portability. To detect the force while using the same hardware setup, a Disturbance Observer (DOB) can be considered.

In recent years, plenty of research works on utilizing the state observer and the DOB in robotic and mechatronic systems can be found in [1–12]. In [1–3], different observers have been designed for disturbance rejection in the control system. Furthermore, some research works on observer based fault diagnosis and force sensing have been proposed in [4–12]. In [4], a sliding mode observer

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was designed for current sensor fault diagnosis. In [5], the fault diagnosis for a motor system based on a disturbance observer was investigated. In [6], a fault detection system was designed for a process experimental system by using a combined observer using an unknown parameter identification mechanism combined with a disturbance observer. In [7], a robust adaptive fault diagnosis approach was proposed on the basis of disturbance observer. In [8], the fault detection and isolation technique in sensors applied to a concentric-pipe heat exchanger was designed based on high gain observers. In [9], a force estimation method based on disturbance observer was proposed for force control of a robot manipulator without force sensor. In [10], researchers implemented another force sensing approach using a disturbance observer instead of the force sensor for force control. In [11], two Neural-Network based contact force observers for robotic manipulators and haptic devices were developed. In [12], a Kalman-filter based disturbance observer using multi-sensor signals was designed for fore sensing. As can be seen, the disturbance observer is not only useful in fault diagnosis but also efficient in force sensing. In the proposed device, the contact force can be considered as a kind of disturbance present in the motion control system and a well designed DOB is capable of observing this disturbance. The force information can be obtained by the DOB without the force sensor, which can be served as the redundant force information to the device. Thus, the safety and reliability can be increased and the fault of the force sensing system can be detected. Hence, a DOB based force estimation method is proposed and developed in this paper.

The main contribution of this paper is to develop a method using the disturbance observer to carry out the force and contact estimation without force sensor and the sensor failure detection for a novel ear surgical device, so that a redundant force sensing system can be built and the safety and reliability of the device can be enhanced while keeping the same hardware setup.

The rest of this paper is organized as follows. First, the proposed device and its working process are provided in Section 2. In Section 3, the control strategy consisting of system modeling, motion controller design, disturbance observer design, contact estimator and failure detector is presented. Next, a simulation study is carried out. In Section 5, experimental validation on the actual application is given and discussed. Finally, conclusions are drawn in Section 6.

2. Background

In this section, the proposed ear surgical device is presented at first and followed by the description of the working process.

2.1. Ear surgical device

Once an accumulation of fluid occurs within the middle ear space (behind the TM), a common ear disease affecting people of all ages called “Otitis Media with Effusion” will arise [13]. After the medication as the first treatment fails, a small surgery called “Tympanostomy Tube Insertion (TTI)” is needed to be carried out on the patient. In this surgery, the patient will be put under general anesthesia (GA), then an incision is made on the TM by the surgical knife (this procedure is known as “myringotomy”) followed by an insertion of a tympanostomy tube (grommet) on the TM. Therefore, the fluid inside the middle ear can be drained out from the tube. This conventional surgery can be done by an experienced surgeon in about 15 minutes, however it has a number of disadvantages: (i) health impacts of GA (concern on delay in brain development of children [14]); (ii) high dependency on surgeon's skills; (iii) high economic burden to patient (approximately US$2000 per surgery [15]); (iv) inaccessible to underserved population; (v) delay in treatment (long scheduling time to reserve operating room as well as long waiting time before and after surgery due to GA).

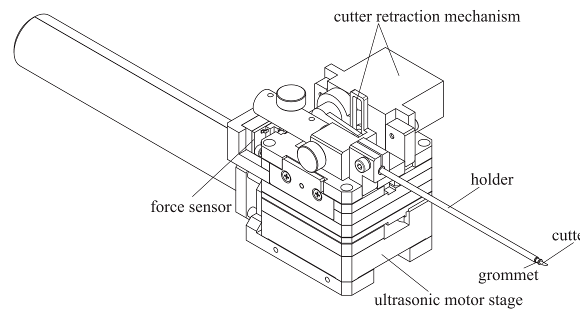

Fig. 1. Ear surgical device.

To overcome these disadvantages of the conventional surgical treatment, the office-based surgical device will be a good solution. Some office-based approaches can be found in [16–20]. Thus, an office-based and easy-to-use surgical device has been developed to offer the surgical treatment in a patient with OME under local anesthesia (LA) automatically, precisely and quickly [21].

The ear surgical device is shown in Fig. 1. It is controlled by a computer embedded with an control card, and it mainly consists of the following systems:

(i) Mechanical system (i.e. the main body).
(ii) Motion control system designed to yield the necessary precise and customised motion sequences for the device. The heart of the motion control system is a linear ultrasonic motor (USM) stage. It is used to drive the tool set (and the grommet tube) along *Z*-axis for completing all the required surgical procedures. The minimum incremental displacement of the USM stage is 0.3 μm and the velocity is up to 400 mm/s. A built-in linear encoder with resolution of 0.1 μm is used for position measurement [22].
(iii) Force sensing system designed to provide the contact force information between the tool set and the membrane during the surgery. In the force sensing system, a highly sensitive low cost force sensor with a sensitivity of 0.12 mV/g is chosen to be integrated into the device. It provides precise force sensing performance in a compact commercial grade package [23].

2.2. Working process

Before the proposed device start to carry out the surgery, the desirable insertion spot is determined by the surgeon with the help of the microscope, and then the cutter tip is pointed at the spot and the tool set is moved slowly close to the TM (without contact) manually by the surgeon. After that, there are mainly four steps to complete the surgery by using the proposed device, which working process is shown in Fig. 2.

(i) *Touch detection*: after the proposed device is in position as mentioned above, the surgeon is allowed to press the start-up foot pedal. Upon activation of the foot pedal, the tool set (includes cutter and holder) carrying the tube is driven by the USM stage towards the membrane until the tube touches the membrane at a certain contact force.
(ii) *Myringotomy*: the surgeon triggers the foot pedal again to initiate the procedures of myringotomy.
(iii) *Tube insertion*: immediately following the myringotomy, the cutter is retracted slightly inside the holder to avoid hurting the inner ear or ear bones during the tube insertion, and then