Sensors and Actuators A 249 (2016) 163–171

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

An electrorheological spherical joint actuator for a haptic master with application to robot-assisted cutting surgery

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ARTICLE INFO

Article history:
Received 6 April 2016
Received in revised form 30 August 2016
Accepted 30 August 2016
Available online 31 August 2016

Keywords:
Electro-rheological (ER) fluid
ER spherical joint actuator
Haptic master
Slave robot
Cutting surgery
Force feedback

ABSTRACT

This paper presents a spherical joint actuator using an electrorheological (ER) fluid to make a new haptic master which can be applicable to a robot-assisted cutting surgery. The proposed haptic master consists of two actuators for different motions; ER spherical joint device for 3-DOF rotational motion and ER linear device for 1-DOF translational motion. An appropriate size of the haptic master is designed based on the governing equations of the dynamic model and manufactured. The haptic master is then connected to a slave robot for the cutting surgery of a tissue. In the surgical process, the forces required to cut the tissue (a pork in this work) are obtained using a force sensor via experimets and used as the desired forces to be tracked by a slave robot controlled by a proportional-integrative-derivative (PID) controller. The desired repulsive forces are then embodied through the haptic master so that the operator can feel the forces occurred in cutting process (actual forces). In order to validate the effectiveness of the proposed haptic master, the tracking control performances between the desired force and actual force are evaluated in time domain.

1. Introduction

Recently, a human-machine interface has become more and more important to achieve communication between humans and machine systems via human senses such as sight, hearing and touch. The interfaces with the third human sense, the sense of touch, are being actively researched in various application fields [1–3]. These systems which provide stimulus information such as kinesthetic force to a user are called haptic systems or simply haptics. Recently, a robot-assisted minimally invasive surgery has been introduced by incorporating with a haptic master device whose function is not only to generate the motion for a slave robot, but also to reflect some physical constraints to the haptic operator such as viscosity and stiffness of the touched tissues of bones and organs. A. Frisoli et al. [4] designed a force-based impedance control of a haptic master for a haptic interface system. A gripper with force feedback in minimally invasive surgery was also developed by M. MacFarlane et al. [5]. In addition, the haptic master for mobile manipulator has been proposed a lot [6,7]. In general, the haptic device requires an actuating component for the tactile feedback. Currently, a motor driven by an electronic circuit is a typical actuator for the haptic devices, and many physical haptic feedbacks are carried in the form of vibration based on eccentric motors. The commercial eccentric motors generate vibration using an unbalanced mass. It has some disadvantages such as complex mechanism, difficulty in continuous and smooth force control and safety problems [8]. Therefore, the haptic feedback using the vibration motor limits the ability to discriminate the tactile force. To overcome this limitation, a voice coil motor (VCM)-type actuator has been introduced for the haptic devices; a linear resonance actuator using resonance frequency to generate vibrations [9]. However, this device has a limited application area in haptic feedback because the human sense of touch is far more sensitive than the senses of sight or hearing. A continuous and complex force feedback is still required in various robotic applications. Therefore, many researchers are working on a new actuating mechanism based on smart materials such as piezoelectric actuator, shape memory alloys, electro-active polymers, and so on [10].

Subsequently, several researches have been recently made by adopting smart fluids such as electro-rheological (ER) fluids and magneto-rheological (MR) fluids to overcome those obstacles. The yield stress of the smart fluids is easily changed by controlling the intensity of electric or magnetic field. Due to this phenomenological behavior, smart fluids have several benefits such as resistance to external forces or pressures, high stability owing to the viscous property and reliable control performance [11]. Li et al. [12] developed an MR fluid based haptic system featuring MR brake and gimbal structure. Senkal et al. [13] developed an MR spher-

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http://dx.doi.org/10.1016/j.sna.2016.08.033

ical brake and performed virtual test. Blake et al. [14] developed a force-feedback haptic glove which can allow the user to pick up and feel virtual objects. Kikuchi et al. [15] proposed a novel limb rehabilitation system using ER brake. Mavroidis et al. [16] proposed an ER haptic device called MEMICA (MEchanical MIrroring using Controlled stiffness and Actuators). Böse et al. [17] researched an ER fluid-based force-feedback joystick consisting of a ball and socket joint. The haptic feedback using smart fluids can give continuous, good stability and reliable force feedback. But, these previous studies on the haptic feedbacks using smart fluids are limited in their degree-of-freedom for dynamic motions. Subsequently, the haptic device capable of multi-degree-of-freedom and multi-motion force feedback is still required for effective applications such as surgical robots and rehabilitation devices. On the other hand, several researches on the application of ER or MR haptic master to surgical system have been undertaken. Ahmadkhanlou et al. developed haptic systems for teleoperational surgery using MR fluids for semi-active force feedback [18]. An & Kwon modeled MR actuators by considering magnetic hysteresis to determine the nonlinear torque-current relationship [19]. A haptic joystick based on MR brake mechanism has been also utilized by Bachman & Milecki [20], and Blake & Gurocak proposed a haptic glove that can obstruct finger movement [21]. A.M Okamura implemented several different types of tele-manipulation control laws, which can provide different capabilities for position, force, and environment impedance [22]. Reiley et al. achieved a successful visual force feedback resulted in reduced suture breakage, lower forces, and decreased force inconsistencies among novice robotic surgeons [23]. Scilingo et al. reported the possibility of using MR fluids to mimic compressional characteristics of biological tissues [24]. More recently, Kim et al. developed force modeling of various tissues and applied the model to robot-assisted cutting surgery using MR haptic master activated by bi-directional clutches. It is here noted that the bi-directional clutch based on the haptic master has a complex mechanism [25]. Therefore, a simpler actuator for the haptic master mechanism needs to be developed along with application to the robot-assisted surgery.

Consequently, the main contribution of this work is to propose a simple actuator for the haptic device using an ER fluid and apply it to the robot-assisted surgery. In order to achieve this goal, 4-DOF haptic master consisting of a simple spherical joint actuator and a linear actuator utilizing ER fluid is devised and manufactured. For the design of the haptic master, the generated torque and force are mathematically analyzed based on the device geometry and Bingham characteristics of ER Fluid. The manufactured haptic master is then tested by investigating the generated force and torque as a function of an electric filed applied to ER actuators. Subsequently, the haptic master is connected to the slave robot to undertake a simple cutting surgery. The effectiveness of the haptic feedback system on the cutting surgery is verified by adopting a pork as a cutting tissue in which a part of tumor is intentionally indexed. The tumor is excised from normal tissue with and without the haptic force feedback action and the results are compared in time domain.

2. Design of ER actuators

The most typical smart fluids are MR and ER fluids, which belong to a family of rheological materials that undergo rheological phase-change under the application of fields. These smart fluids, in general, have been considered as the Bingham fluid whose constitutive equation is given by [26,27]:

$$\tau = \eta\dot{\gamma} + \tau_y(\cdot) \tag{1}$$

Where τ is the shear stress, η is the dynamic viscosity, and $\dot{\gamma}$is the shear rate. $\tau_y(\cdot)$ is the dynamic yield stress of the smart fluid, which is a function of field strength. The dynamic yield stress can be described by a simple exponential form or more complex form such as polynomials. In this work, a silica based ER fluid is used for 4-DOF haptic master system and its measured yield stress is determined in exponential form as follows [26]:

$$\tau_y(E) = 484.463E^{1.374} \tag{2}$$

where E denotes the electric field with units of kV/mm. This equation will be used to calculate the generated force (or torque) from the haptic master (refer to equations (5) and (7))

Fig. 1(a) shows the configurations of a 4-DOF haptic force feedback device utilizing ER actuators. It is seen that two distinct actuating mechanisms are introduced to achieve both rotational and translational motions. One is the spherical joint which features a simple mechanism, but can generate 3 rotational motions and corresponding force reflections. The other is the linear actuating device which can generate translation force reflection. From the schematic configuration of the proposed ER spherical joint, it is seen that there exist the spherical ball and spherical housing as the inner and outer electrode, respectively. The ER fluid is fully filled between the inner and outer electrodes. The proposed piston type linear device is divided into the upper and lower chambers by the piston head. These chambers are fully filled with the ER fluid. When the piston moves, the ER fluid can be transferred from one chamber to the other. The inner and outer cylinders are playing as the positive and negative electrodes. Two columns are fixed between top and bottom plates. If the operator rotates the forceps in yawing direction, this motion is transmitted to bottom plate via fixed columns. The bottom plate is connected with operation link of ER spherical joint to transfer yawing motion of forceps to ER spherical joint. The most fascinating feature of the proposed actuating mechanism is that the force-feedback can be achieved along operator's moving direction in a semi-active manner.

The generated torque by the ER spherical joint actuator consists of controllable torque, T_{ER}, and viscous friction torque, T_η which can be expressed by surface integral as follows:

$$\begin{aligned} T_{ER} &= \iint_S \tau_y r_m dA \\ T_\eta &= \iint_S \eta\dot{\gamma} r_m dA \end{aligned} \tag{3}$$

where S is the surface area of the spherical joint. r_m is the distance of moment arm from the one point on the spherical surface to rotational axis. Fig. 2 shows a spherical coordinate system considering three rotational motions: pitching, rolling and yawing. An arbitrary point on the surface of electrode is described by the angles u and$v$. The moment arm for X, Y and Z axis are determined by

$$\begin{aligned} x_{r_m} &= r_e\sqrt{(\sin v)^2 + (\cos v \sin u)^2} \\ y_{r_m} &= r_e\sqrt{(\sin v)^2 + (\cos v \sin u)^2} \\ z_{r_m} &= r_e \cos v \end{aligned} \tag{4}$$

where r_e is the radius of the spherical joint. The generated controllable torque, viscous friction torque in three rotational motions are derived by surface integral as follows:

$$\begin{aligned} {}^X T_{ER} &= \tau(E) r_e{}^3\pi^2 - \int_0^{\frac{\pi}{2}-v_0}\int_0^{2\pi} \tau_y(E) r_e{}^3\sqrt{(\sin v)^2 + (\cos v \sin u)^2}\cos v du dv \\ {}^Y T_{ER} &= \tau(E) r_e{}^3\pi^2 - \int_0^{\frac{\pi}{2}-v_0}\int_0^{2\pi} \tau_y(E) r_e{}^3\sqrt{(\sin v)^2 + (\cos v \sin u)^2}\cos v du dv \\ {}^Z T_{ER} &= \int_{\frac{\pi}{2}}^{v_0}\int_0^{2\pi} \tau_y(E) r_e{}^3\cos^2 v du dv \end{aligned} \tag{5}$$