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A cable-pulley transmission mechanism for surgical robot with backdrivable capability

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ABSTRACT

Compact actuators, low friction and back-drivable transmissions are essential components in haptic and impedance type surgical robotic systems, since their performances affect overall volume, force feedback capability and power consumption. An innovative miniaturized, low friction, back-drivable reducing mechanism for haptic or surgical robot applications has been designed, developed and evaluated. A new differential mechanism having a cable comprises a sheave wheel supported by a yolk is also implemented. Low friction and back-drivable, compared to conventional non-back-drivable mechanisms based on gear coupling, is achieved by means of differential cable driven method. The system has been integrated with a permanent-magnet DC motor and a drum on which a tendon is wound, and then finally connected to the remote end joint. Several experiments to validate the feasibility of the reducing device were carried out.

1. Introduction

Currently, teleoperated robotic surgery is performed unilaterally, that is, the surgeon receives no haptic feedback from the operating site other than the visual information from the endoscopic camera. The visual clues provided by the excellent 3D vision of current robotic systems act as a substitute for haptic feedback to the surgeon [1–3]. However, visual feedbacks are incapable of justifying the force magnitudes of dynamic motions. When handling delicate patient tissue, surgeon should ensure the gripped tissue is not damaging by the excessive force applied through the gripper and should maintain static grip force sufficient to firmly hold the patient's tissue as a lock [4–9]. To overcome this problem, many research groups have studied force sensing techniques for minimally invasive surgical robot system [10–14].

The lack of force feedback is largely due to the challenges associated with measuring the interaction forces between the surgical robot and the patient's tissue. Recently, a number of studies have been carried out to integrate force sensors into the surgical instruments for sensing the contact force at the instrument tip. King et al. [15] fabricated a multi-element tactile force sensor system to translate contact force distribution on the end effectors of a surgical robot. Although the proposed system can measure contact forces, it solely evaluates the system tactile perception. Hong and Jo [16] developed a compliant forceps to sense the grasp and pulling forces of the surgical instrument by using strain gauges at the rear of the forceps. However, the prototype proposed in this study can only sense single axis pulling force during tissue manipulation. Kim et al. [17] designed a forceps integrated with a four degree-of-freedom force sensor for minimally invasive robotic surgery. Experimental results show that the proposed force sensor can directly sense the normal and shear forces at the surgical instrument tip. However, this forceps can only measure the inner applied force at the front portion of the forceps. When needing the forces at other regions of the instrument tip, this force sensing forceps cannot meet this requirement.

Nevertheless, force sensors occupy space and cannot be placed sometimes where the force needed to be measured [18,19]. The first challenge for sensing the contact force is the size of the force sensor. The best interaction force sensing is obtained by integrating sensing elements with the tip part of surgical instrument inside the patient's body. However, such sensing elements location imposes critical size limitations. The normal diameter of the surgical instrument is 5 mm or 8 mm. Today, there is no off-the-shelf force sensor with such comparable size. Although, it is difficult to add force sensors directly to existing robotic

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instruments that were not designed with force sensing in mind [20]. The cost of the equipment raises the second challenge problem for the measurement of the contact forces. Integrating force sensing elements will make the surgical instruments more expensive.

Different from the industrial robots, it is sought to have a reversible driving system with low friction and small play in the field of surgical robots and haptic devices [21,22]. A transmission mechanism is defined as back-drivable when it transmits motion both from the input to the output axis and vice-versa. This back-drivability concept of the mechanical transmission is a paramount requirement that impedance type surgical robot must fulfill. In contrast to direct-drive motors, the back-drivability of geared drives is poor due to friction in the gearbox.

In literature, system back-drivability is divided into two types: accelerate dependent and velocity dependent. A driving mechanism which has good acceleration dependent back-drivability generates small inertia induced forces when accelerated. Similarly, a driving mechanism which has good velocity dependent back-drivability generates small friction induced forces in response to imposed end tip velocity. It is commonly known that a transmission mechanism which use motor-gear combinations and has dry friction will not be back-drivable at all. Good back-drivability causes the surgical manipulator to behave desirably without dependence on closed loop control. If the open loop force control is utilized and the manipulator is back-drivable over a practical bandwidth, then the forces which are applied to the tip of surgical instrument can be “sensed” at the actuator without the need for force sensors installed at the tip.

To serve as a force display, it is desirable that the surgical robot or haptic device have substantially no backlash, very low friction, and very low inertia. Backlash, friction and inertia detract from the operator’s natural feeling to the device. It has been confirmed that no matter how sophisticated a control algorithm is implemented, if the haptic device or surgical robot suffers from significant amounts of backlash, friction or inertia, then its usage as a force display is compromised.

In order to achieve the goal of back-drivability and no backlash in transmission mechanism for surgical robot, this paper proposes a novel reducing mechanism capable of having a high reduction ratio and of simple embodiment. The introduced reducing device comprises two differential systems having a cable in opposition connected by a secondary cable driving a driven pulley. Each differential system having a cable comprises a sheave wheel supported by a yolk moved mainly in translation. By varying the free length of the cable, the cable is wound on two synchronized drums. It is then possible to impose different winding and unwinding lengths so that the total length of the free portion of the cable varies. Advantageously, since the cables have a low inertia, this reducing mechanism is possible to reduce the masses in movement. In addition, friction is low and the efficiency of the system is high.

This paper is organized as follows. In Section II, the limitations of the commonly used reduction devices are discussed. We present the design of the reducing mechanism in Section III. In Section IV, implementation of the proposed mechanism to actual joint control system is introduced. Experimental results are presented in order to verify the proposed novel reducing device in Section V. Finally, this paper is summarized and concluded in Section VI.

2. Limitation of present approach

Even without measuring joint torque or contact force directly, we may refer the contact force by interaction force estimation method [23]. If the actuator of the surgical instrument is a DC motor which is the most common actuator used for surgical robot, the current can be driven through the motor windings, and with the knowledge of the torque constant and transmission ratio, estimate the joint torque without reference to direct mechanical strain measurements. Properties comparison of the following methods is shown in Table 1.

Table 1
Properties comparison for commonly used reduction mechanism.

	Motor-gear box	Direct-drive	Capstan drive
Reduction ratio	High	Unity	Limited
Backlash	Large	None	Low
Friction	Large	None	Low
Inertia	High	None	Low
Efficiency	High	High	High
Convenience	Easy	Limited	Limited
Size	Compact	None	Large

2.1. Motor-gearbox method

Usually, reducing devices, such as gear reducing devices, ball screw reducing devices, harmonic drive reducing device, worm gear, etc., are provided between the actuating devices and the actuated elements to amplify the force. In such a way, a large rotation of the driving motor is transformed into a small displacement of the robot tip. This in turn means that when a large force is applied to the tip of the robot, it corresponds to a small torque on the driving motor.

Such mechanical transmissions and reducing devices pose the problem of high friction, loss of energy and high inertia [24]. In practice, the output axis of the motor cannot actively rotate because any torque applied on it is locked by the transmission mechanism. This type transmission mechanism can passively rotate only when driven by the input axis through the transmission.

In general, the simplest way to achieve some degree of non-back-drivability is by means of transmissions having a large reduction ratio. Accordingly, the fidelity of such systems are limited since there are dynamic forces present in most surgical robots that are difficult to account for and often mask the relatively minute forces of interacting with the patient. As a result, the forces applied to the patient would not be estimated without using force sensors.

2.2. Direct-drive approach

There are two ways to solve the above mentioned problem when using the gearbox transmission to estimate the external contact force. The first approach of a manipulator designed for good external force estimation without using force sensor is called Direct-drive method [25]. Direct-drive actuators have force display advantages over indirect drive actuators. This method was built to improve the force control performance by placing driving motors directly at the robot links and eliminating the actuator-to-joint mechanical reducing transmission.

Consequently, the compliance, friction, backlash, inertia, and mechanism complexity normally associated with the reducing devices are eliminated [26,27]. Therefore, the motion of the robot is very clear and is precisely described by joint motion equation. However, the use of Direct-drive method imposes two restrictions. First, as there is no speed reducing device between the driving motor and the robot joint, the output joint torques are limited by the output torque of the motor. Second, the mass and bulk of direct-drive motor s must be placed at the joints they drive. Consequently, the heavy outermost joint motor must be supported and accelerated by a stronger and heavier supporting link.

2.3. Capstan drive mechanism

Most cable-driven based robots use capstan drive mechanism for power transmission from the actuators to robot links. Meanwhile, the capstan drive mechanism is another generally preferred reducing device for robotic device with haptic feedback [28]. One of the cable-driven implementations that use a capstan drive is the Phantom haptic device manufactured by SensABLE Technologies Corp. Haptic device requires light weight, low inertia, high stiffness, back-drivable transmission with zero backlash. Capstan drive mechanism is composed of a driving wheel,