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Research paper

A cable-pulley system modeling based position compensation control for a laparoscope surgical robot

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ABSTRACT

Due to nonlinear friction and backlash characteristics of cable-driven mechanism (CDM) in laparoscope surgical robot end-effector, it is difficult to predict force and control position precisely during the surgical procedure. Current studies of transmission characteristics of CDM mainly focus on the tendon-sheath system (TSS) with the classical Capstan equation which neglects the effect of bending rigidity of the cable. However, analysis for transmission characteristics of a cable-pulley system (CPS) is rare. This paper presents a tension and displacement transmission model of a CPS in the end-effector of laparoscope surgical robot. The model considers the bending rigidity of the cable and spatial location of the pulleys. Experiments validate the proposed model. Based on the model, a position compensation algorithm of feedforward control is presented to reduce the tracking position errors. The experimental validations show substantial improvements on performance of position tracking errors for the use of the proposed algorithm.

1. Introduction

Laparoscope surgical robots have draw great attention during the past few years, especially due to the introduction of the da Vinci surgical system. Compared with conventional minimally invasive surgery, the robotic technology provides more dexterous and precise control to the end-effector, and it can intuitively transmit some complicated surgical operations from surgeon to the end-effector. This greatly improves surgical success ratio and alleviates surgeon's fatigue. As the end-effector of laparoscope surgical robot is operated inside patient body, transmitting surgical operations precisely is very important in actual surgery. If there are some errors of position and force, then it is extremely dangerous because the end-effector may damage the patient's tissues and organs and even threaten to patient's life. Thus the precise position and force control of the surgical robot has been a research focus and puzzle. To realize precise position and force control, modeling an accurate transmission characteristic of the surgical robot system is very urgent and necessary. Laparoscope surgical robot mainly uses the cable-driven mechanism as it could work in narrow space, reduce size and weight, and transmit high load. However, there are some drawbacks in the cable driven mode which are caused by nonlinear problems such as hysteresis, backlash, and dead zone [1,2]. These nonlinear behaviors lead to tension loss and poor system performance.

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Nomenclature

α_i	deviation angle between two pulleys
ΔL_e, ΔL_a	elongation of cable
$\dot{\xi}$	moving direction of the grasper
μ_p^p	friction coefficient between adjacent pulleys
μ_s^p	friction coefficient between pulley and shaft
μ, μ_c^p	friction efficient between cable and pulley
$\overline{M}$	the number of coaxial pulleys
ϕ	angle corresponding to the infinitesimal cable
ρ	radius ratio of cable and pulley
τ_{in}, τ_{out}	input and output torque
θ	wrap angle of cable
θ_{in}, θ_{out}	input and output displacement
A	cross sectional area of cable
d_i	length of the cable between adjacent pulleys
E	elastic modulus of cable
f	friction between the infinitesimal cable and pulley
f_g	friction between two graspers
$f_{ap,i}^N$	friction between adjacent pulleys
$f_{cable,i}^N$	friction between cable and pulley
$f_{loss,\ i}$	tension loss of the cable
$f_{ps,i}^N$	friction between pulley shaft
$f_{pulley,i}^N$	friction caused by the pulley
$K(\theta_i)$	tension ratio of cable
M	shear force of infinitesimal cable
N	normal force of infinitesimal cable
P_i^N	the i^{th} pulley passed by the cable N
Q	shear force of infinitesimal cable
r	radius of cable
R_j	radius of pulley
T	tension of infinitesimal cable
T_p^a, T_p^e	initial pretension of the cable
$T_{i-1,i}$, $T_{i,i+1}$	incoming and outgoing tension of cable
$T_{\text{in}}^{A,E}$, $T_{\text{out}}^{A,E}$	input and output tension of cable A,E

Based on mechanical structure and transmission mode, the cable-driven mechanism in laparoscope surgical robot is mainly divided into two institutions. One is cable-pulley system in which pulleys are used to change the direction of the cable, and the other is tendon-sheath system with high flexibility in which the transmission route is configured arbitrarily. Both of them are used in various surgical robotic systems, such as da Vinci surgical system [3–5], endoscopic device [6,7], Medrobotics Flex system [8–10], MASTER system [11,12], and Viacath system [13]. Due to the nonlinear problems of the cable driven system, it is difficult to control force and position of the end-effector effectively and precisely. One solution to solve this problem is integrating sensors in the tip of end-effector to obtain the grasping force [14–17]. However, since the structure of end-effector is complicated and small which is different from large mechanism [18], it is difficult to mount some suitable sensors directly in the end-effector. An important problem is that the sensors cannot tolerate the harsh chemical environment of the sterilization processes. In addition, it is not economical to use the comparatively expensive force sensors for instruments which can only be used for a few times.

An alternative solution is used to estimate the force online according to the mathematical model of the force and position transmission. Kaneko et al. [1,2,19] built the tendon-sheath model and formulated the transmission characteristics for the first time. They expressed the input-output relationship in linear form with the equivalent backlash and tendon-stiffness, and proposed a lumped mass numerical model for tension transmission. Palli et al. simulated the static and dynamic friction models [20], characterized hysteresis phenomenon with a viscoelastic model in the transmission system [21], and proposed a control strategy to compensate nonlinear effects. Do et al. [7,22–26] proposed a dynamic friction model of tendon-sheath system, investigated the characterization of hysteresis phenomenon caused by friction, and proposed control schemes for the purpose of compensation. Tian et al. [27] and Low et al. [28] characterized the tendon-sheath transmission by using lumped mass model elements. Kim et al. [29] and Phee et al. [28,30] used governing equations and elongation of cables to estimate the haptic force. Agrawal et al. [31] developed a mathematically distributed model for the transmission characteristics in cable-conduit mechanisms, which described nonlinear behaviors of the dual tendon-sheath like backlash. Wu