Chapter 26
Modular Cable-Driven Robotic Arms for Intrinsically Safe Manipulation

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ABSTRACT

A Cable-Driven Robotic Arm (CDRA) possesses a number of advantages over the conventional articulated robotic arms, such as lightweight mechanical structure, high payload, fault tolerance, and most importantly, safe manipulation in the human environment. As such, a mobile manipulator that consists of a mobile base and a CDRA can be a promising assistive robot for the aging or disabled people to perform necessary tasks in their daily life. For such applications, a CDRA is a dexterous manipulator that consists of a number of cable-driven joint modules. In this chapter, a modular design concept is employed in order to simplify design, analysis, and control of CDRA to a manageable level. In particular, a 2-DOF cable-driven joint module is proposed as the basic building block of a CDRA. The critical design analysis issues pertaining to the kinematics analysis, tension analysis, and workspace-based design optimization of the 2-DOF cable-driven joint module are discussed. As a modular CDRA can be constructed into various configurations, a configuration-independent kinematic modeling approach based on the Product-of-Exponentials (POE) formula is proposed. The effectiveness of the proposed design analysis algorithms are demonstrated through simulation examples.

INTRODUCTION

The advancement in medical and healthcare has allowed people to live longer. As a result, the proportion of aging population is projected to rise from 8% in year 2000 to 21% by year 2050 (United Nations, 2002). Hence, significant research efforts have been carried out in assistive robotics for the aging population (Garcia, Jimenez, Santos, & Armada, 2007). Countries like Japan, Korea, and the European Union have already embarked on national campaigns in service robotics (Inter-

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national Advanced Robotics Programme, 2004), with a focus on using assistive robots to enable people to continue leading active and productive lives in their old age, without being a burden to others. In addition to the aging population, research efforts on assistive robotics have also been focused on disabled people who require supervision and assistance in many of their daily life activities. The advances in assistive robotics will open up new possibilities to enhance their quality of life.

Among various existing assistive robotic devices, assistive robotic arms have received significant interest and attention because robotic arms have the potential to provide aging and disabled people with a means to carry out tasks in their daily living. Human-robot interaction is inevitable as the robotic arms and their users share a common working space. Therefore, it is necessary for the robotic arms to possess safety features in their design and control. In this research, a Cable-Driven Robotic Arm (CDRA) is proposed as an assistive manipulator. The CDRA possesses a number of advantages over the conventional articulated robotic arms. The flexible nature of cable allows the arm to have a natural compliance thus making it intrinsically safe in the human environment. In addition, with lightweight driving cables and mounting the cable actuation units at the base, the CDRA has an extremely lightweight mechanical structure and low moment of inertia. As such, a CDRA with a low speed mobile base can be a promising and intrinsically-safe assistive robot for the aging or disabled to perform necessary tasks in their daily life.

The CDRAs have been investigated by various researchers. Yokoi (Yokoi, Tanie, Inamura, Kawai, & Agou, 1991) utilized 1-DOF cable-driven pulleys to design a 7-DOF manipulator. Yang (Yang, Mustafa, Yeo, Lin, & Lim, 2011) and Wang (Wang, Chen, Lei, & Yu, 2007) designed 7-DOF cable-driven robotic arms assembled from 1-DOF and 3-DOF cable-driven joint modules in which the cable-driven joint modules were serially arranged to mimic the motion of the human arm. In general, the 1-DOF cable-driven joint module has simple mechanical structure but lack compactness as more modules are required to build a robotic arm. The 3-DOF cable-driven joint module can provide three axes rotational motion but it has very limited torsional motion. In this work, a 2-DOF cable-driven joint module is proposed as the basic building block of a CDRA as the 2-DOF cable-driven joint module can provide two axes dexterous motion with a compact design. With an inventory of such 2-DOF cable-driven modules, various CDRAs can be rapidly constructed to cater for different service tasks. The critical design analysis issues pertaining to the kinematics analysis, tension analysis, and workspace-based design optimization of the 2-DOF cable-driven joint module are discussed. A configuration-independent modeling approach based on the Product-of-Exponentials (POE) formula is proposed for kinematics analysis of the modular CDRAs. The modular design concept not only simplifies the design, analysis, and control of CDRA but also brings in the advantages of flexibility, rapid change-over and ease-of-maintenance.

CABLE-DRIVEN UNIVERSAL JOINT (CDUJ) MODULE

In this article, a 2-DOF *Cable-Driven Universal Joint* (CDUJ) module is proposed as the basic building block of the CDRA. The CDUJ module is a cable-driven mechanism in which the moving platform is connected to the base via a passive universal joint as shown in Figure 1.

Four driving cables are employed to control the motion of the moving platform. With identical cable-driven joint modules, various modular and reconfigurable CDRAs can be rapidly constructed. A modular CDRA configuration is illustrated in Figure 2.

In robotics literature, Dessen (1986) investigated the velocity and force control of a CDUJ module used for redundant manipulators. Hamid

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