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Inverse kinematics and workspace analysis of a cable-driven parallel robot with a spring spine

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ABSTRACT

We present a cable-driven flexible parallel robot with low motion noise to mimic a human neck in this paper. The fixed base and moving platform of the robot are connected by three cables and a compression spring. The spring serves as the cervical spine to support and facilitate the motion of moving platform corresponding to human head. The cables serve as the muscles around the human neck to drive the robot. Due to the flexible compression spring, we cannot solve the inverse kinematics directly. As shown in this paper, it should be combined with the statics for possible solutions. Based on the inverse kinematics and statics analysis, we optimize the cable placements to minimize the actuation force. Moreover, the workspace of the robot is analyzed with the constraint of positive cable tension. Simulations were performed and demonstrated the correctness and feasibility of the inverse kinematics and workspace analysis of the parallel robot. The approach presented in this paper can be extended to other parallel robots with a flexible compression spring.

1. Introduction

In harmful environments where there exist nuclear radiations or chemical substances, people need to wear personal protective equipments such as donning respirators or chemical-resistant jackets. But these personal protective equipments will generate noises when users move around. The noises generated by moving the head are extremely harmful because they may influence people's hearing of useful information and make them perform wrong actions. Therefore, we should analyze the effect of such noises on a human's hearing. To conduct such an acoustic investigation, we can use a low motion noise robotic neck for experiments instead of relying on humans to perform head movements which may cost higher and not achieve the ideal results [1].

To successfully use a robotic neck for such acoustic experiments, it should resemble a human neck in two key ways. On one hand, it should have the same degree of freedom and motion range as a human. This way, we can conduct the experiment for various types of motion and motion ranges. On the other hand, the robotic neck should not make noises itself during the movements without wearing equipments such as respirators or jackets. To examine the noise effect of wearing equipment, all the other noises should be eliminated as much as possible.

The principles of human head movements have been studied extensively in the biomechanics field. Clinical studies show that the head motion relies on the cervical portion of the human spine consisting of seven cervical vertebrae [2]. Although each vertebra has 6 DOF (degree of freedom), researchers usually take the overall neck as 3DOF (pitch, roll, and yaw). Many humanoid neck mechanisms in the context of humanoid robots have been designed and developed in the past decade. We divide all of them into two categories: serial and parallel. The serial neck has advantages of simple structures and easy control because each DOF of

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the neck is actuated independently. The Honda ASIMO [3] and HRP-2 [4] have serial necks with two DOF—pitch and roll. The Dav [5], the Albert HUBO [6], and the final design of iCub [7] have serial necks with three DOF—pitch, roll, and yaw. The robots presented in [8,9] have serial necks with four DOF in which an additional nodding DOF is considered. The parallel neck is based on a parallel manipulator, which consists of a moving platform, a fixed base, several identical actuated chains, and a passive spine if necessary [10]. This approach normally realizes the two DOF of the neck motion, i.e. pitch and roll, and the yaw motion is accomplished by an additional mechanism. The head mechanism of SAYA is based on a spring spine and several pneumatic artificial muscles [11]. The iCub robot has two parallel necks in addition to the serial one. The first one uses a spring spine and three actuated cables; the second one uses a three DOF parallel manipulator with a central passive spherical strut [12]. The James [13] humanoid robot also has a head similar to the first parallel neck of iCub. Another parallel neck mechanism based on two cable-driven elastic limbs and a passive limb without a spine is proposed in [14].

Although all the robotic necks in the previous papers can realize the head motion, they fail to achieve the low-motion noise as the actuators are installed inside the robot. An exception is the acoustical telepresence robot presented in [15], which can reconstruct the sound environment for a listener at a remote location and follow the listener's head motion at the same time. The robot is driven by motors via cable and pulley systems. Since no gears are used in the robot, the noise from the robot motion can be low. Nevertheless, the motors can still generate considerable noise since they are installed right beneath the head. The same group also investigated the feasibility of using the ultrasonic servomotor to replace the traditional motor [16].

To eliminate the movement noise, we propose a mechanism shown in Fig. 1. Its key mechanism is a cable-driven parallel manipulator with a spring spine, which has a similar function of the cervical vertebrae in human necks. It supports the robotic head and can bend around the neutral axis to generate two DOF pitch and roll movements. A cable–pulley structure mounted on the moving platform is used to realize the yaw motion. Three driving cables, with similar functions of human neck muscles, are equally spaced at 120° on both the moving platform and the base. The pitch and roll motion of the moving platform is driven by these three cables, which are remotely pulled by the actuators sealed in a sound insulation box. Between the robotic head and the sound insulation box, the driving cables are guided and protected by cable housings. As no sound generation parts are embedded into the robotic neck, little noise is generated by the robotic neck during its motions.

The mechanism shown in Fig. 1 belongs to the general cable-driven parallel mechanisms, which has recently attracted many research interests. Compared to traditional mechanisms, cable-driven parallel mechanisms have the advantages of large workspace, low inertia, high payload to weight ratio, transportability, reconfigurability, and full remote actuation [17]. As a result, cable-driven mechanisms are well-suited for applications such as surveillance of large-scale places, interaction with disaster sites, and manipulation of heavy payloads. Since cables can only generate unilateral pulling force, the full control of cable-driven parallel mechanisms with n DOF needs at least $n + 1$ cables. For mechanisms with cable numbers no more than the number of DOF, extra loads or wrenches are required to determine the pose of the moving platform together with the driving cables. Some researches call these cable-driven parallel mechanisms as underconstrained cable-driven parallel mechanisms [18–20]. The mechanism considered in this paper, as shown in Fig. 1, is a typical underconstrained cable-driven parallel mechanism because only three cables are used to control three DOF of the moving platform, i.e., its height, pitch angle, and roll angle, which leads to the challenge of dealing with the coupling between the kinematics and the statics.

A large number of cable-driven mechanisms have been developed, such as the RoboCrane for moving heavy loads over a large workspace [21], the WARP manipulator for high-speed assembly of lightweight objects [22], the large-scale FAST system for a large radio telescope receiver [23], the NIMS3D cabled robot for actuated sensing applications [24], and the flexible link mechanism for keeping stiffness against load [25]. There are also many studies on kinematics, workspace, and optimal cable

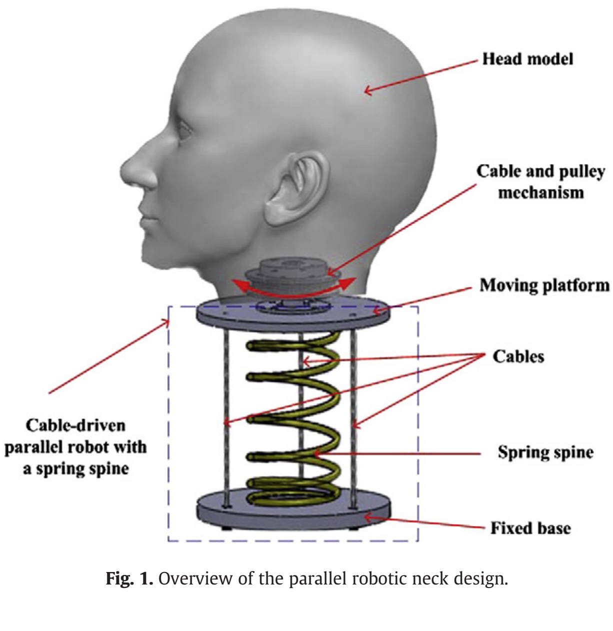

Fig. 1. Overview of the parallel robotic neck design.