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Development and hybrid force/position control of a compliant rescue manipulator☆

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ABSTRACT

Performing search and rescue tasks in the ruins after disasters demand rescue robots with slender and compliant structure to accommodate the complicated configurations under debris. This paper presents the structural design and system composition of a novel tendon-sheath actuated compliant rescue manipulator with slender and flexible body. The proposed robot can drill into the narrow space where rescuers and traditional rigid robots cannot get in because of size limitation or toxic environment. The self-sensing calibration, dynamic modeling, and hybrid force/position control trajectory of the compliant gripper with integrated position and force monitoring capabilities are analyzed and discussed. With the aim of regulating the gripper displacement and clamping force during operation, a hybrid force/position control strategy is proposed based on a cascaded proportional-integral-derivative (PID) controller and a fuzzy sliding mode controller (FSMC). Experimental setups mainly consisting of servo motor, tendon sheath transmission components, compliant gripper, and real-time control system are established to calibrate the strain gauge sensors and identify the dynamic model parameters. Further experimental investigations involving force tracking experiments, position tracking experiments, and object grasping experiments are carried out. The experimental results demonstrate the effectiveness of the developed self-sensing approach and control strategies during rescue operation.

1. Introduction

In the last decade, large numbers of people have suffered from different kinds of natural or man-made disasters causing large scale of damages, such as earthquake, landslide, mining accidents, floods, and so on. After these disasters, it is of great significant to search the survivors in the ruins and provide necessary medical assistance and treatment as soon as possible. Existing researches indicate that the difficulty and risk of disaster rescue will increase rapidly after the so-called golden seventy-two h [1]. The surface survivors can be easily found and rescued in time. However, for the interior victims trapped inside the confined spaces under rubble piles, it is difficult and dangerous for the responders and canine teams to execute the rescue and relief works due to the harsh conditions. Therefore, more and more researchers have focused their efforts on developing rescue robots to explore deep under debris [2,3].

Most of the existing rescue robots were designed with smart size, multiple joints, and strong crawling capacity to drill into small crevices and access victims. Arai et al. [4,5] developed a series of snake-like crawler vehicles called Souryu for in-rubble searching operation. These robots were equipped with motors, cameras, sensors, battery and control unit inside the body and remote-operated via wireless joystick. The large cross section area definitely limited its mobility within narrow space. Kitagawa et al. [6] investigated a small-size rescue robot, named Active Hose, for searching the survivors within collapses. The Active Hose, made up of eccentric wire mechanism, was driven by several wound tube actuators and capable of curving to arbitrary direction. The major drawback of this rescue system is the large friction between robot body and external environment. A rescue manipulator with duplex parallel mechanism was designed by Hirayama and Kazuyukilto [7] in Hosei University to search narrow space for victims. This robot needs to be operated manually by rescuer with the consideration that electrical power supply might not be obtained in practical disaster situation. Chen and Wang [8] have designed a researching robot, composed of modular rigid steering head and flexible body, to work within small voids of rubble and confined space. Preliminary experimental results showed that the rigidity

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property of steering head reduced the effectiveness in searching the interior through a rubble channel.

Because of space limitations, traditional rescue robots with rigid body have difficulty in adapting to the complicated configurations under debris and executing rescue actions. Besides, in certain cases the end-effector of rescue robot needs to provide necessary assistance to the weaken victims. The compliance control technology, such as impedance control [9], admittance control [10] and hybrid force/position control [11], can be applied to ensure human-robot-environment interactive safety during rescue operation [12]. Generally, the stiff joints of rigid manipulator need to be equipped with additional nonintegrated force/torque sensors and position sensors, such as capacitance sensors, inductance sensors, laser sensors, and optical reflective sensors, to acquire required feedback information and achieve desired compliance [13,14]. It leads to larger robot dimension and heavier weight and, thus, is not suitable to the miniature robot applications. Integrating the resistive strain gauge sensors with robotic system is an effective measuring method to achieve self-sensing capacity without additional commercial sensors, and it has been applied in many electromechanical systems [15]. Yang et al. [15,16] developed a piezo-driven gripper based on parallelogram mechanism and double-rocker mechanism. Two groups of strain gauges are attached to the flexure hinges and beams to measure the position and the gripping force. Xu [17] designed a compact compliant stage with a large rotational range by utilizing multistage compound radial flexures. The driving torque acting on the stage and the resulting rotational angle were detected via a strain-gauge sensor attached to the leaf flexure. Kam et al. [18] proposed a new strain gauge-based sensing scheme to measure the displacement of ionic polymer-metal composite actuators for water applications.

Taking the above into account, in this paper a brand-new slender robot with a flexible body and a compliant manipulator is developed for disaster research and rescue. Firstly, the mechanical structure of the compliant manipulator is described, which consists of a rotary joint, two bending joints and a compliant gripper. The position and clamping force of the gripper can be detected by several strain gauges sensors attached at the beams with large strain. And then, a hybrid force/position control scheme is developed to regulate both gripper tip position and clamping force and, furthermore, achieve smooth interaction. The force control is realized via a cascaded proportional-integral-derivative (PID) controller, whereas the position control is realized via a fuzzy sliding mode controller (FSMC). Finally, the effectiveness of the presented mechanical structural design, sensing strategy and control algorithm are demonstrated by trajectories tracking experiments and closing-clamping-opening operation of gripper.

2. Overview of the rescue robot system

The overall architecture of the developed rescue robot system is depicted in Fig. 1. The rescue robot system is mainly composed of a driving system located at the proximal end, a slender flexible tube with a diameter of 40 mm and a length of 3 m, an automatic insertion system consisting of a crawling mechanism and a pushing/pulling mechanism, and a compliant manipulator mounted at the distal end of the slender tube. A micro-camera integrated with audio intercom system (ASK-40, Mensa Inc.) is installed on the front of the manipulator for the purpose of collecting the environment information and guiding the rescue operation. The rescuer is able to get the view of micro-camera from the monitor and communicate with the survivors through intercom to acquire their real-time conditions and requirements. There are three degrees of freedom (DOFs) adjusting the orientation and posture of compliant manipulator and an extra DOF

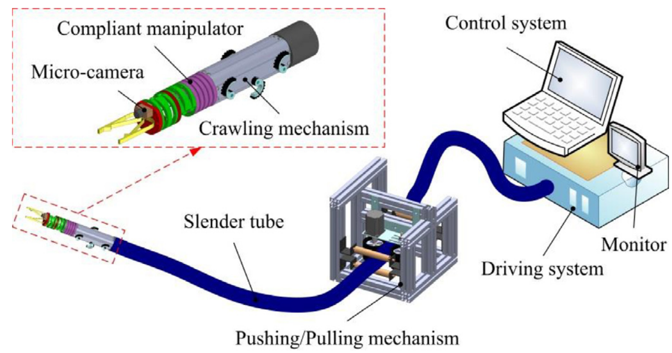

Fig. 1. Schematic diagram of the tendon-sheath actuated rescue robot system.

performing grasping operation. The food, water, fresh air, and emergency medicine can be transferred to survivors through the slender flexible tube. In some situations, the manipulator needs to feed the survivors, or even provide simple treatment to the injured victims. The CAD model and geometrical dimensions of the compliant manipulator is presented in Fig. 2. As can be observed, the tendon-sheath driven manipulator can be basically divided into three parts: the gripper, the rotary component and the bending component. The gripper will clamp and grasp the object if the tendon attached to the internal beam of gripper is pulled. On the contrary, because of the recoverable property of elastic deformation, the gripper will automatically open if the tendon is relaxed. The rotary joint plays a significant role during rescue operation. When the tendon fixed on the groove of driving pulley is pulled, the rotary component is able to perform the rolling movement in the range of $\pm 90°$. The bending component consists of two C-shape compliant bending units, which are mutually orthogonal and can perform the yawing movement and the pitching movement in the range of $\pm 45°$ respectively. Fig. 3 illustrates the photographs of the compliant manipulator performing different actions [19].

The tendon sheath transmission mechanisms packaged inside the slender flexible tube are capable of providing remote power transmission through the narrow tortuous space. The tendons utilized in the robot system are stainless steel wires with a diameter of 0.8 mm. The sheaths are tightly wound springs made from alloy steel wire and having an inner diameter of 1.2 mm. With the tendon sheath transmission mechanisms, all of the active joints and the gripper of manipulator are actuated by the servo motors placed in the base box of driving system. Therefore, the actuation system can be separated from the end-effector. It is beneficial to simplify the mechanical structure design and achieve low body weight and small dimension. A worm driven crawling mechanism is connected between the compliant manipulator and the slender tube to insert the rescue system into the crevices of ruins. In addition, the pushing/pulling mechanism located on the tail of the tube is actuated via a stepper motor and capable of providing pulling force and pushing force to the tube via the action of friction. If the rescue system is trapped in the ruins, it can be pulled back easily with the cooperation of crawling mechanism and pushing/pulling mechanism. The detailed descriptions of the automatic insertion system have been introduced in our previous researches [20,21]. Each servo motor is equipped with a pulley to its shaft to convert driving toque into pulling force. The driving system is controlled via a microcontroller (C8051F040, Silicon Labs Inc.) which can process data and perform computation internally. All the sub-control systems are connected together to communicate with the host laptop computer (ThinkPad-E450, Lenovo Inc.) via a CAN bus network.