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Collaborative dual-arm continuum robot for operating in underwater environments

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***Abstract*—**In many industries worldwide, decommissioning is a significant and growing engineering challenge requiring specialist tools and robots. This is particularly the case in underwater or submerged nuclear sites, such as the stricken Fukushima Daiichi reactors. However, most currently available decommissioning tools are bulky structures lacking dexterity. In this paper, a novel dual-arm robot, composed of two 6-DoF continuum arms designed to work together, is developed with the intent to collect material samples from underwater environments.

Index Terms: continuum robot, robot collaboration, dual-arm robot, material retrieval

I. Introduction

Nuclear decommissioning activities requires the removal of radioactive materials to the point that it no longer requires radiation protection before the progressive demolition of the structures [1, 2]. This is a hazardous, expensive, and time-intensive process that is exacerbated when the environment is underwater.

Several underwater manipulators are available, but most of them are bulky to ensure sufficient environmental protection or have limited degrees of freedom (DoF) [3-5]. To improve the payload capacity and kinematic accuracy, conventional linkage structures have been frequently adopted [6, 7], which are normally actuated by heavy linear motor units [8], hydraulic cylinders [9] and smart actuators [10, 11]. For example, a unified 6-DoF lightweight robotic arm was developed for use in confined spaces [12]. However, the built-in actuators at the joints caused the center of mass (COM) to be far away from the base, causing the instability of the system. Furthermore, a 7-DoF lightweight robotic arm, which is comprised of serially connected linkages, was constructed for the subsea servicing industry [13]. However, it is too bulky to be combined with small commercial UUV for operating in confined spaces. Additionally, recently a remotely operated vehicle, which included two 6-DoF arm robots, was developed for the subsea intervention [14]. However, this system was designed for the heavy-duty conditions, which is unsuitable for the environments featured with confined spaces.

II. Task-oriented Design

Based on the aforementioned challenges, a new dual-arm robotic system, which is comprised of two 6-DoF continuum robots and corresponding end-effectors has been developed for coping with complex engineering tasks in unconstrained environments. The advantages of the system can be summarised as the following:

1) two 6-DoF cable-driven continuum manipulators have been integrated capable of performing cooperatively, reducing weight and improving dexterity;

2) given the manipulators are cable-driven, the electrical hardware can all be placed within a single sealed unit simplifying waterproofing and environmental protection;

3) the dual-arm robotic system can be attached to a commercial ROV system for underwater applications, with the added advantage that the COM of the manipulators is close to constant and near the centre of the UUV, increasing stability and simplifying control.

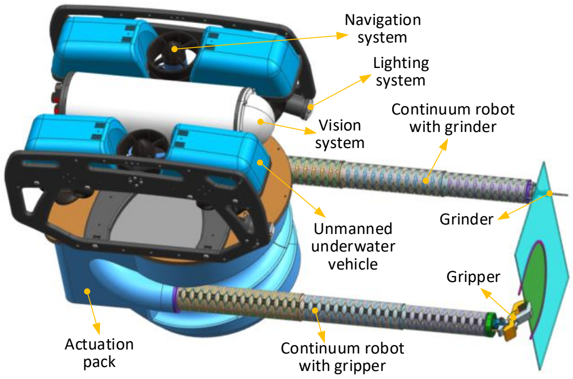

Figure 1. Task-oriented design of the dual-arm robotic system for the underwater sample retrieval

Based on these requirements, a dual-arm robotic system combined with an existing commercial UUV has been developed, seen in Figure 1. One arm with a grinder at the end has been designed to cut the material from structures, while the other arm has a gripper to collect the removed fragment. Besides the collecting function, the gripper can also aid the stability of the overall system during the material removal process, as the reaction force from the grinder will cause the position of the system to otherwise drift.

III. Implementation of the Dual-arm Continuum Robot

The physical dual-arm continuum robot is shown in Figure 2, which is comprised of two 6-DoF continuum arms, two end-effectors (i.e., gripper and grinder respectively), actuation system (i.e., 18 motors for the continuum arms and two motors for the gripper and grinder respectively), hardware for the control system, and GUI controller. For controlling the shape of the continuum robots and closure of the gripper, displacement-based closed-loop controllers were developed. For the grinder, a speed-based closed-loop controller was developed. In order to improve the response speed of the system, a National Instruments sbRIO-9627 FPGA-based embedded controller has been used.

As each arm is comprised of three serially connected 2-DoF sections, by controlling the shape of the three sections,

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the high dexterity motion of the 6-DoF arm can be achieved. To control the shape of the 2-DoF section, the cable-driven strategy is adopted (i.e., one end of the cable is attached to the motor shaft, while the other end is attached to the tip of the 2-DoF section).

A GUI was developed using LabView software for regulating the real-time shape of the continuum robots, rotating speed of the grinder and closure of the gripper. By planning the collaborative motion path of the two 6-DoF continuum arms, grinding speed and gripping motion, the desired fragment can be hold and removed from the environmental structure.

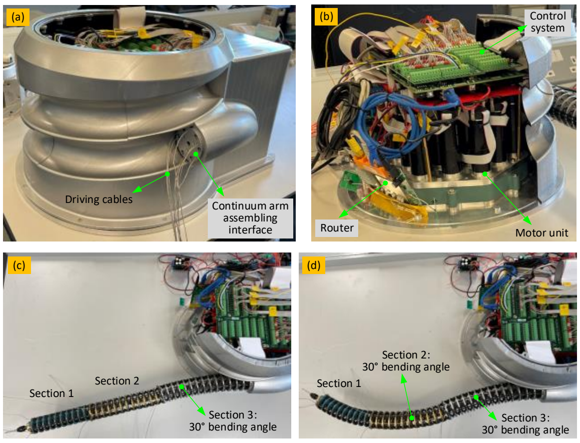

Figure 2. Experimental setup and detailed structure of the continuum robot system: (a) is the actuation system; (b) is the real-time closed-loop control system; (c) and (d) is a continuum arm with different sections bending

The cable-based actuation system is driven by a compact array of DC motor units (Maxon, motor type: RE 25, gearbox: GP26 A with a reduction ratio of 236, encoder: ENC16 with 1024 pulses). A network of flexible steel cables surrounded by flexible spring tubes with a higher stiffness in compression are used throughout the system. The central supports along the axis of the robots include flexible hinges with a special shape to achieve the desired performance (i.e., high rotational stiffness and low bending stiffness). These were produced using Digital Light Processing (DLP) (machine type: Photocentric LC Magna, resolution: 137 µm, material: durable resin).

This design is biomimetic in nature and each robot arm is made in three sections, with the dimensions of the continuum arm structure (e.g., diameter and width of the flexure hinge) in section-1 being larger than those of section-2 and section-3 to improve the kinematic performance. The detailed parameters of the continuum arm can be seen in Table 1.

Table 1. Structure parameters of the continuum robot (unit: mm)

Parameters	Length	Diameter	Width	Thickness
Section-1	210	46	6	1
Section-2	180	43	5	1
Section-3	150	40	4	1

A pair of special end-effectors were developed for removing and collecting material from the environment, see Figure 3. The grinder unit shown in Figure 3 (a) is designed to cut the fragment off from the environment and is actuated by a DC motor located within the actuation pack via a flexible shaft. By applying different tools to the chuck, a range of hard materials (e.g., concrete and metal) can be operated on. Then, by planning the motion trajectory of the 6-DoF continuum arm (i.e., bending and phase angles of the three 2-DoF segments), the desired shape of the fragment can be removed. For collecting the removed material, a gripper has been designed and assembled at the end of the other 6-DoF continuum arm. The control of the gripper is achieved using cable-based actuation, assisted in opening by a torsional spring assembled in the shaft.

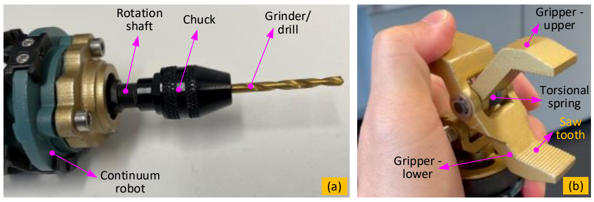

Figure 3. Prototypes of the end-effectors: a) and b) are the grinder and gripper, respectively

IV. Conclusions

In this paper, a novel dual-arm continuum robot composed of two 6-DoF continuum arms has been developed to perform cooperative engineering tasks; the case study in this paper being sample retrieval in-situ in confined underwater environments. Furthermore, by integrating the developed dual-arm continuum robot with a commercial ROV manipulator, the wider application (e.g., remote underwater engineering) can be demonstrated.

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