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Continuum robots collaborate for safe manipulation of high-temperature flame to enable repairs in challenging environments

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Abstract— this letter presents two long continuum robots, inserted through small holes, work collaboratively in a crammed space to manipulate an extreme-temperature (> 2000°C) flame for coating repair on aeroengines without the need of their disassembly. One robot (Adder) carries a thermal spray nozzle while the other (Observer) carries cameras and a flame ignitor, supporting the locomotion and operation of the Adder, which was demonstrated on a real aeroengine offering advantages in both operational time and repair costs.

***Index Terms*— Continuum robot, collaboration, challenging environment**

I. INTRODUCTION

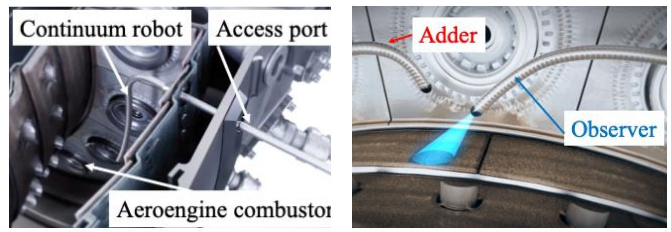
Continuum robots, with their unique slenderness and ability to conform to complex terrains, offer a great capability in navigation and operation in narrow environments, e.g. minimal invasive surgery [1].

Recently, investigations to develop continuum robots to enable "industrial surgery" for performing in-situ repair and maintenance, i.e., without the need to disassemble the object, have been reported [2]. Unlike healthcare applications [3, 4], these "industrial surgeries" commonly require the robot to be designed with a high slenderness (length/diameter ratio of 50 or more) to replace at least the capability of a human arm in accessing large crammed spaces [5]. Further, to ensure safe navigation and operation conducted in the industrial task, control strategies have been proposed for the path planning of systems with scanned or a priori (i.e., CAD) information of the environments as well as additional sensors/signals, such as fiber brag sensor [6], to improve the positioning accuracy of the robot end-effector under constant/variable payloads.

While these are notable advancements, up to now, for "industrial surgery" applications, single continuum robot is generally used, which carries all the end-effectors (e.g., camera and tools) for conducting both inspection and repair tasks. However, in some of industrial applications, the harsh working conditions (e.g., high temperature) generated by the tools make it impossible for the mechatronic devices (e.g., camera) to survive during the operation. Hence, it requires more than one continuum robot to collaborate to complete the tasks, enabling the fragile mechatronic systems to be carried separately with the tools. However, this introduces new challenges in navigation and operation of the continuum robots within confined industrial environments, which is presented in the following section.

II. CONCEPT OF CONTINUUM ROBOTS COLLABORATION

This research reports two continuum robots (> 0.7 m length; 12.5 mm diameter that have been developed in our previous works [5, 7]). They can be inserted through small holes and work collaboratively in a crammed space to manipulate an extreme-temperature (> 2000°C) flame for coating repair on aeroengines without the need of disassembly (Fig. 1). In this application, one continuum robot is used to manipulate a miniature thermal spray nozzle for thermo-barrier coating repair in tight spaces. However, any on-board supervision (e.g., camera) system is not feasible for working in the high-temperature zone (>400°C) generated by the repair operation; this makes the robot that deposits the coating, the Adder, "blind" to the environment. Hence, the Adder is fully dependent on another similar continuum robot, the Observer, to guide the Adder through a long narrow space, reference it against the target workspace, assist with its end-effector by igniting the flame, and track the Adder's position to enable control of the 3D movement of the TCP (thermal spraying nozzle).



(a) (b)

Fig. 1. Generic representation of the tasks conducted by two continuous robots: (a) Insertion into the engine via access ports; (b) Adder deposits the coating by thermal spraying (>2000°C) while Observer supervises the process.

To support this set of tasks in Fig. 1, the navigation and operation approaches of a "blind" continuum robot under the supervision of a "guide" robot were developed and tested in a rig of an aeroengine combustor:

C1. Collaboration for navigation to the work zone: firstly, the Observer is inserted into the installation (i.e., engine) through a small assess port ($\emptyset < 13mm$) and navigated by the visual feedback from its own cameras (Fig. 2a). In the navigation, the middle line of the combustor was used as a 2D pre-defined navigation path [5]. As all the parameters of the path are pre-known, the section configurations for each increment movement of the arm (1mm) during the navigation was pre-calculated in a 2D joint space to enable the arm following the pre-defined path [8]. However, the arm could deviate from the path, due to the uncertainties, e.g., cable elongation. Hence, an avoidance condition was introduced, which can be described by the following equation:

$$c_i = d_0 - d_i \geq 0 \; for \; i = [1, 13], \tag{1}$$

where d_0 is the minimum distance to be maintained (set by user, 35mm), d_i is the minimum distance between the i^{th} section tip of the robot and the estimated closest obstacle to that section (measured by the Observer, Fig. 2b) [9], c_i is the collision avoidance constraint of the i^{th} section, and i is the index of sections of the Adder in the Observer's field of view (usually section 11, 12 and 13 with the end effector, can be seen).

Once the condition is not fulfilled, the navigation is paused, and the configurations of the sections in the Observer's field of

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view is adjusted by kinematics control (2D up or down motion [5]) until the condition is met, then the pre-planned path navigation restarts (Fig. 2g). This strategy repeats until the end effector reach desired work zone. Fig. 2a-c presents a set of successive steps of collaboration between the two robots, for guiding the Adder to the target work zone. Here, two scenarios are presented where the Adder navigates into the work zone without (see red line – Fig. 2h) and with (see black line – Fig. 2h) the feedback from the Observer. It can be found that there is a significant improvement in the Adder's performance in navigating to the work zone (the following-the-path error decreased by up to 62%).

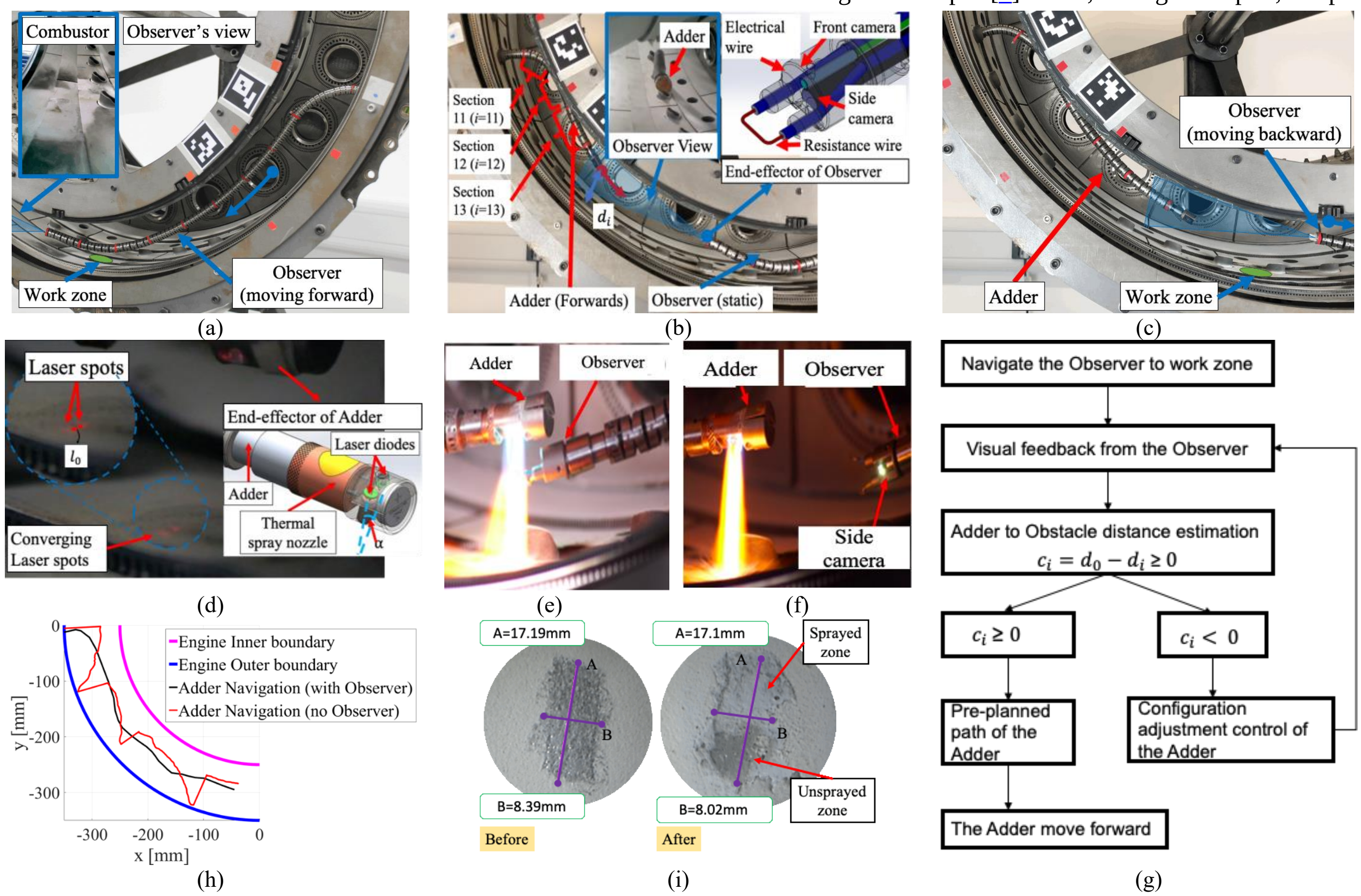

Fig. 2. Collaboration between the two continuum robots in a rig of an aeroengine combustor: (a) Insertion of the Observer into the engine; (b) Navigation of the Adder to the work zone with the Observer's feedback and the end-effector design of the Observer (front camera - ScoutCam Ltd - micro ScoutCam Q² (±2mm, 20Hz); side camera- General Electric-Mentor Visual IQ (±0.5mm, 50Hz)); (c) The Observer moves backward to enlarge its field of view for the Adder to advance; (d) Observed distance between the laser spots during the position adjustment and the end-effector design of the Adder; (e) The Observer ignites the flame by moving beneath the Adder; (f) The Adder performs the deposition while the Observer provides visual feedback; (g) The schematic of the navigation approach used in the collaboration between two robots; (h) Acquired path of the Adder's tip while navigating to the work zone with and without the Observer (captured by an external Logitech webcam and analyzed offline by Image Acquisition Toolbox (MATALB)) (i) An artificial damage before and after several rounds of deposition;

C2. Collaboration for setting up: after the Observer detects and measures the zone for coating repair, the Adder is positioned at a given standoff distance from it, assisted by the Observer. The Adder has an onboard distancing system with two laser diodes positioned with a pre-defined inclined angle α (Fig. 2d) to ensure that the laser spots converge when the desired stand-off distance is achieved. The two converging spotlights can be detected by the cameras of the Observer; in this way, the Adder is set at a particular distance relative to the target zone, when the two laser spots converge into one ($l_0 < l_d$, l_d is the max difference between the two laser spots, set by the user). Further, the thermal spray of the Adder is ignited by positioning an on-board electric igniter on the distal end of the Observer (Fig. 2e). Thus, the collaboration is based on the control of the relative distance between the Adder's TCP and a target surface, and on the control of the relative motion of the robots' TCPs for the flame ignition task.

C3. Collaboration for operation: after the ignition, as temperatures more than 2000°C develop in the flame operation cone and in near vicinity (due to reflections from the target surface), the Observer carrying the fragile devices, such as cameras, retracts to a stand-by position (Fig. 2f). Before the repair, the Observer is firstly used for quantitatively controlling and testing the repair path of the Adder by tracking the position of the converged laser spot [7]. Then, during the repair, the pre-tested repair path is executed, and the accuracy of the operation relies on the high repeatability of the robot and low reaction force of the flame (<5g). The Observer monitors qualitatively the plume of the flame since it must retract away from the thermal spray. Once the repair is complete, the Observer evaluates the coverage and, if needed, the procedure is repeated (eventually from the setting-up stage). In the trail, it took two hours to coat the sprayed zone by the robots (Fig. 2i), and another hour for navigating them in and out the engine. Compared with the current repair approaches in industry, the continuum robots can remarkably reduce the time and cost on logistics, disassembly, and assembly of aeroengines (generally two-three months),

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offering great advantages to the end users.

III. EXPERIMENTAL RESULTS

With the collaboration validated on the rig of the aeroengine combustor, a demonstration was performed on a real gas turbine engine (A Rolls-Royce aeroengine–Fig. 3a), including navigation and operation. In the full engine trial, the working conditions, such as accesses, illumination, and the state of the engine, fully represent the reality of in-situ aeroengine repair in industry. In this trial, three ports in the aeroengine combustor are available for the continuum robots to access to the target for repair. Hence, the Observer and Adder have been positioned/aligned against two of the access ports situated at an angle of 136° relative to each other and navigated through these holes to access the combustion chamber and perform the operational stages presented before. Further, for documenting the demonstration of the system, a third access port, at the bottom dead centre, was utilized by an industrial endoscope (Olympus IPLEX NX) for providing extra monitoring and illumination of the operation so that the process can be documented.

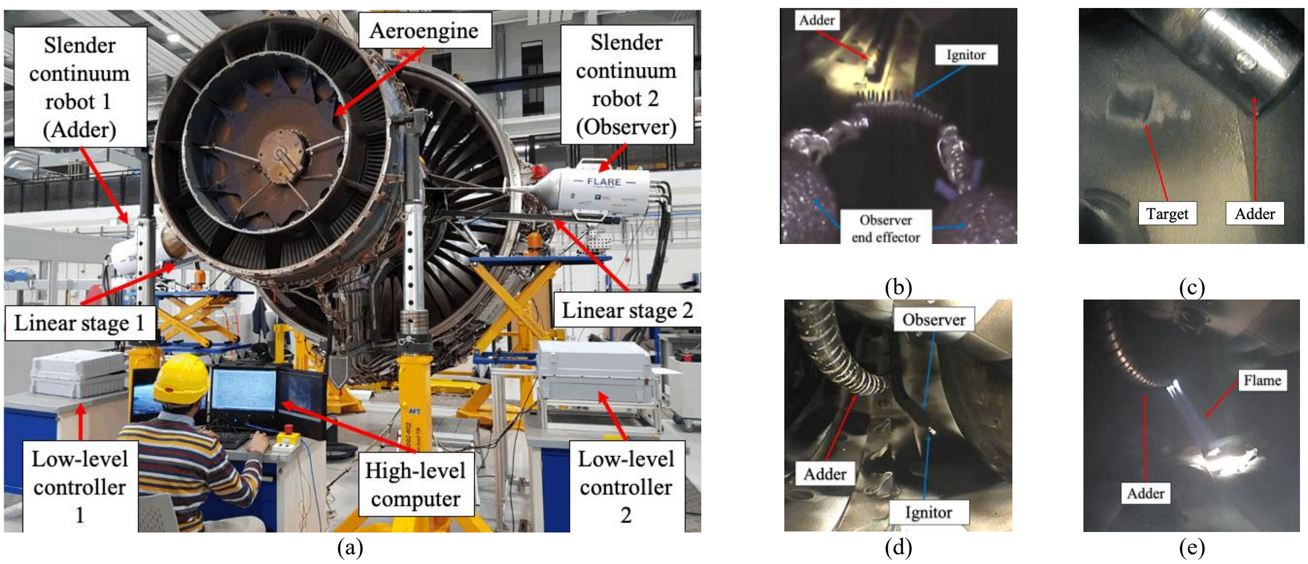

Fig. 3. A demonstration of the collaborative continuum robots for repair in a full gas turbine engine: (a) Overall setup of the robotic system on the engine for performing thermo-barrier coating repair; (b) View from the front camera of the Observer for supporting the navigation of the Adder in the engine; (c) View from Observer side camera, showing the collaboration for setting up the Adder against the target surface to be repaired in the engine; (d) View from the additional camera, showing the collaboration of the continuum robots for flame ignition in the engine; (e) The Adder spraying the coating on the target.

As an example, some of the key steps of the thermo-barrier coating repair with two continuum robots are selected and presented in Fig. 3b-e. First, the Observer enters the aeroengine combustor to guide the Adder by using the proposed collaboration strategy to maintain its position on the pre-planned path towards the target zone (Fig. 3b). After the Adder reaches the work zone, the Observer is instructed to set the end-effector of the Adder up against the target with the prescribed stand-off distance (Fig. 3c). Then, the Observer swipes beneath the Adder to ignite the thermal spray yielded by the spray nozzle (Fig. 3d). Subsequently, the Observer is positioned on standby for supervising the Adder that conducts coating repair for approximately thirty-minute (Fig. 3e), with stoppage intervals to enable the visual inspection of the target surface by the repair specialist by using the images provided by the Observer. Once the repair completed, with the support of the Observer, the Adder navigates out of the engine. Finally, the Observer is retracted out of the engine, with guidance from its own visual feedback.

IV. CONCLUSION

In this paper, a robotic system consisting of two 16-DoF continuum robots sharing identical design [5] and control system [7] is presented, which can collaborate for collision-free navigation, setting-up and operations within narrow environments exposed to extreme temperatures for keyhole industrial surgery (e.g., aeroengine combustor). The idea is to use one of the continuum robots, called 'Observer', equipped with vision systems and ancillary tools, to help the 'blind' one, i.e., Adder, with its tool (i.e., thermal spraying nozzle) to execute tasks in spaces difficult to access and observe by human and tools. The collaborations between the Adder and Observer were demonstrated successfully under different scenarios, including semi- (combustor rig - Fig. 2) and fully closed (a full gas turbine engine - Fig. 3) spaces, respectively, which is the first in-situ repair executed in aeroengine combustor by robots.

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