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Development of a slender continuum robotic system for on-wing inspection/repair of gas turbine engines

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ABSTRACT

The maintenance works (e.g. inspection, repair) of aero-engines while still attached on the airframes requires a desirable approach since this can significantly shorten both the time and cost of such interventions as the aerospace industry commonly operates based on the generic concept "power by the hour". However, navigating and performing a multi-axis movement of an end-effector in a very constrained environment such as gas turbine engines is a challenging task. This paper reports on the development of a highly flexible slender (i.e. low diameter-to-length ratios) continuum robot of 25 degrees of freedom capable to uncoil from a drum to provide the feeding motion needed to navigate into crammed environments and then perform, with its last 6 DoF, complex trajectories with a camera equipped machining end-effector for allowing in-situ interventions at a low-pressure compressor of a gas turbine engine. This continuum robot is a compact system and presents a set of innovative mechatronics solutions such as: (i) twin commanding cables to minimise the number of actuators; (ii) twin compliant joints to enable large bending angles ($\pm 90°$) arranged on a tapered structure (start from 40 mm to 13 mm at its end); (iii) feeding motion provided by a rotating drum for coiling/uncoiling the continuum robot; (iv) machining end-effector equipped with vision system. To be able to achieve the in-situ maintenance tasks, a set of innovative control algorithms to enable the navigation and end-effector path generation have been developed and implemented. Finally, the continuum robot has been tested both for navigation and movement of the end-effector against a specified target within a gas turbine engine mock-up proving that: (i) max. deviations in navigation from the desired path (1000 mm length with bends between 45° and 90°) are ± 10 mm; (ii) max. errors in positioning the end-effector against a target situated at the end of navigation path is 1 mm. Thus, this paper presents a compact continuum robot that could be considered as a step forward in providing aero-engine manufacturers with a solution to perform complex tasks in an invasive manner.

1. Introduction

The in-situ repair of gas turbine engines while they are installed of the aircraft requires sets of specialised inspection/repair tools to be delivered to the desired positions without disassembly. Long term service agreements increase the importance of in-service inspection and subsequent repair activity. Early or unplanned removal causes significant customer disruption; this means that taking an engine off-wing not only results in significant disassembly/assembly costs but also in penalties for non-operational time. Thus, in a highly competitive business such as aerospace power systems, the development of mechatronic/robotic systems able to navigate deep inside the geometrically intricate/crammed spaces of the engines and then, perform complex paths with end-effectors (e.g. cutting tools) could be of high technical advantage. Nevertheless, this is not an easily achievable task since it requires robots of "slender" designs, i.e. low diameter-to-length ratios, with many degrees of freedom to avoid collision with multiple obstacles (e.g. aerofoils), perform complex paths of end-effectors while being able to carry relevant payloads (e.g. tools) and position them accurately against target areas within the engines.

Despite of many reports in continuum robots that could be regarded as suitable systems to address these technical challenges, up to now, mostly borescopes and rigid-segmented boreblending tools are employed in most cases by the aero engine repair teams; commonly, through inspection holes positioned on the side of the engine casing, they can reach the target component and perform some corrective action. Some of boreblending tools [1] are

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constructed with small diameter (5–12 mm) rigid links that generally present one Degree-of-Freedom (DoF). Others are flexible and have generally two DoFs [2,3], which allows the end of the tool bend in two directions. However, the current design of these invasive tooling are unable to cover a wide range of repair and maintenance works as they present limited DoFs and articulated lengths (10–30 mm), that prevent them to reach intervention places far away from the accessing ports while suffering from reduced accessibility in crammed spaces.

On the other hand, over the years, the research work in the field of continuum robots have endeavoured to improve the capability of these systems in accessing constrained spaces by utilising increased number of degrees of freedom.

In this respect, some solutions using single/multiple rigid-joints per section for constructing continuum robots are available at various diameters (9–60 mm) and lengths (200–1.5 mm). These robots can access through small openings to enable inspecting jobs [4,5]. However, the rigid links could limit the accessibility within more intricate/crammed spaces [6] especially in those with tight succession of sharp bends.

Other approaches [7–11] use a series of super elastic NiTi alloys as backbone of continuum robots to enable enhanced articulation capabilities. Commonly, on these designs, one NiTi alloy rod is located at the centre of a succession of the disks that are actuated by cables to provide the bending of the continuum robots [12]. Furthermore, using this concept, it has been reported [7] that two/three NiTi rods can be used instead of actuating cables. Thus, enabling increased stiffness of the continuum robot. Although working continuum robotic solutions based on a central backbone have been reported, this design takes up the space in the centre of the manipulator, which prevents the passing through of utilities/end effectors, e.g. camera, illumination and machining spindle, which are of key importance to perform useful invasive operations. This is not to mention the tendency of such design to significantly twist around the central backbone when the continuum robot needs to take torques around the central axis [13]. Further, an improved design was developed by using three elastic backbones for structuring the arm section [10,14], which has the central space for delivering the tools to the tip of the arm. However, it needs to employ redundant backbones, bellows and woven outer tubes to decrease the same twisting phenomenon [15]. Nevertheless, the reported solutions do not have an integrated feeding system, i.e. facility without which their autonomous utilisation for performing real (more advanced than presented simplified scenarios) in-situ repairs/inspections within complex geometrical environments such as aeroengines is difficult. Another approach to avoid the twisting problem of the continuum robots, could by employing twin-joints (e.g. made of NiTi alloy rods) positioned alternatively at 90° in a succession of segments [13].

Furthermore, other solutions utilise a triplet of pneumatic actuators combined as articulated sections to build a flexible trunk [16] which can generate large longitudinal movement (ca. 45% extension) and bending angle and thus, being used as handling assistant with appropriate (0.5 kg) payloads. Although this design presents high dexterity, with its large diameter of the bellows to ensure appropriate actuation forces, it renders as dimensionally unsuitable for repair/maintenance tasks within highly constrained environments such as aeroengines.

To address these needs and challenges, this paper reports on a design, mechatronic solutions and control methods of a slender (diameter/length of 0.023) continuum robot that provides adequate number (25) DoFs at small tip diameter (15 mm) and high length (1270 mm), which make it able to perform inspection and machining tasks inside highly confined spaces, e.g. aeroengines. Thus, Section 2 of the paper details on the novelty of the design concept that consists in a succession of tapered segments of twin-compliant joint structures, which can significantly enhance the torsional stability while enabling the system to take appropriate payloads (max. 200 g) at its tip. Section 3 details the static and kinematic models of the system, which have been utilised for the electro-mechanical design of continuum robot and the selection of the actuation system; additionally, it reports on the modelling of the compliant joint buckling was used to support the design criteria of the NiTi alloy twin compliant joint. Section 4 presents in detail key aspects of the mechatronic design and realisation of the continuum arm, actuation pack, end-effector and architecture of the control system. Section 5 deals with the main modes of control that generates key commands to the continuum robot: tip-following (to enable the navigation); feeding-in/out (to enable advancement); machining (to enable path generation of the end-effector). In Section 6, sets of targeted experiments to characterise the performance of the proposed continuum robot, including payload, navigation and inspection and machining tests are described. Finally, the conclusions are summarised in Section 7.

2. Concept of slender continuum robot for in-situ repair of aeroengines

The design concept of the continuum robot has been driven by the technical requirements for performing in-situ (i.e. on-wing) repairs of aeroengines by accessing it from its front, i.e. fan section. Thus, to perform the required set of repair tasks, the slender of continuum robot was defined by the following limit specifications:

- min overall arm length 1200 mm – to reach the second stage of low-pressure compressors of the engine;
- max. tip diameter 15 mm (for at least 400 mm measured from its end) – to allow access in the crammed environment formed by the succession of static and rotating aerofoils of the engine;
- min. bend angle per section $\pm 90°$ – to ensure that tight change in direction during the navigation into the engine;
- min. payload at the tip 0.250 g – to ensure appropriate end-effectors (e.g. machining spindle) can be carried;
- different section lengths from 150 mm/section to 50 mm/section: from the engine fan to the compressor stage, the space gets increasingly confined. Hence, the section lengths were determined to decrease from the proximal to the distal end for enabling it pass through the gaps between the compressors and minimising the required DOFs.
- min 25 DoF – according to the min overall length of the arm and the section lengths, the min DoFs was decided;
- max dimension and weight of the actuation: pack 250 mm diameter (with 161 mm height) and 7.5 kg respectively – which is constrained by the size and the load capability of its carrier, a walking hexapod, which is the other subsystem in MiRoR project [17].

To achieve these technical challenges, the slender continuum robot relies on a concept which key characteristics are discussed below and partially captured in schematic representation of Fig. 1.

The preliminary simulation of the most challenging location into the aeroengine environment where the in-situ intervention could take place lead to the conclusion that the continuum robot would need to have 24 DoFs allocated to twelve-section, each of them actuated by steel cable. To ensure the high bending angles while enhancing torsional stability relative to the axis of the structure, a twin compliant joints (alternating at 90° to account for 2 DoF each section) structure has been adopted (see Fig. 1(a)). In order to make the deflections of the structure more uniform along its length, when the payload is applied at the tip, a tapered design has been adopted. For enhancing the stiffness of the structure at