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A modular mobile robotic architecture for defects detection and repair in narrow tunnels of CFRP aeronautic components

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ABSTRACT

Advanced composite structural components in aeronautics are characterized by very high production costs because of their dimensions, complex shapes and expensive forming equipment. For these components, such as horizontal stabilizers and wings, a defect occurrence is often critical because large part of inner surfaces, made of long and tapered narrow tunnels, are not reachable for repair operations. In these cases, the part is rejected with a relevant economic loss and high production costs. For this reason, aircraft constructors plan huge investments for defects avoidance during the forming processes of CFRP and to develop effective, robust and reliable repair tools and methods. Mobile robotics can play an important role, with specific systems capable of moving into narrow channels of wings structures (i.e. multi spar boxes) and repair it in accordance to technical standards. This paper describes an innovative mobile robot architecture for bonded repair scarfing operations on CFRP components. Targeting and responding to the demanding machining requirements, the functional-oriented design approach clearly highlights the advantages of a modular robotic solution. The mobile robotic architecture can be also applied in other fields with similar challenging manufacturing operations for further inspection, detection and machining operations.

1. Introduction

Working in narrow space is a typical issue for the repair process of aeronautical structural components. Carbon Fiber Reinforced Plastic (CFRP) components, as wings and horizontal stabilizers, are often realized in the form of multi spar boxes assemblies. A typical example is the Boeing 787 Dreamliner horizontal stabilizer (tailplane) which has a multi-spar boxes structure and its cross-section is composed by a plurality of longitudinal tapered narrow tunnels. During the manufacturing process of these components some defects may occur. In order to reduce the high cost of discards, the necessity for an efficient and robust repair process arises. In literature, different technological processes and techniques for CFRP aircraft structures repair are available [1]. This paper deals with the application of such techniques in narrow spaces, as the multi spar boxes structures.

Currently, the CFRP repair techniques are typically performed manually [2] and sometimes the damage is not accessible by the operator. In large CFRP multi-spar boxes structural components, indeed, human operators are able to repair internal damages only if localized in proximity of the wing tip or root. In all the other cases there are no fix strategies currently available and the components, often very expensive, must be discarded [3]. Thus, the position of the damage is crucial, as it causes a large number of discards in aeronautics manufacturing, with consequent increase of the production costs.

Due to the lack of solutions of applying fixing techniques in narrow multi spar boxes, in this paper a strategy for the automation of such a process is described. Mobile robotics is identified as the key enabling technology that makes it possible. As a further advantage, some studies, remarked the importance of automated machining of CFRP and the advantages in terms of accuracy, quality and reliability compared with a manual operation [4]. Nevertheless, there are no available solutions for the repair of internal defects. The proposed approaches, indeed, consider either new specific devices to be manually fixed in proximity of the damage [5,6], or the use of conventional robots, too big for this purpose [7]. In [8] a robotic inspection cell is presented, composed of three industrial manipulators performing both, photogrammetry acquisitions and ultrasound-based NDT inspection. The robots can move along linear guides and the inspection of large components is enabled;

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Table 1
Main features of the listed robotic architectures for operations in narrow spaces.

Robot	Application	Modular (Y/N)	Functionality	Duct section [mm]	Tethered (Y/N)	Locomotion System	Autonomy level
GE Inspection Robotics [9]	Oil, Gas, Power Plant	Y	Inspection & Cleaning	Ø 400	Y	Magnetic Wheels	Manned
Pipeline Explorer [10]	Gas Pipeline	Y	Inspection	Not specified	N	Retractable Wheels	Manned
Robotic Pipeline Inspection [13]	Water & Wastewater	Y	Inspection	Ø 305	Y	Crawlers	Manned
Solo Robot [15]	Wastewater	N	Inspection	Ø 200 ÷ 300	N	Crawlers	Self-Operating
Rover X SAT [15]	Wastewater	N	Inspection	≥ Ø 100	Y	Wheels	Manned
Versatrax [16]	Wastewater	Y	Inspection	≥ 370 × 480	Y	(Retractable) Crawlers	Manned
Piping Insp. Camera [17]	Wastewater	N	Inspection	Ø ≥ 150	Y	Wheels	Manned
ANATroller ARI 100 [18]	HVAC	Y	Inspection & Cleaning	215 × 127	Y	Wheels or Crawlers	Manned
JettyRobot [19]	HVAC	N	Inspection, Cleaning, Repair	Ø ≥ 360	Y	Retractable Crawlers	Manned
Rail Runner X (RRX) [20]	Shipbuilding Industry	N	Welding	≥ 600 × 800	Y	Crawlers	Semi-Autonomous
Fraunhofer Prototype [21]	Aeronautics	N	Wing Assembly	Not specified	N	Anthropomorphic Robot + Snake Arm	Not specified
Scarfing Robot by CNR-ITIA	Aeronautics	Y	Wing Inspection & Repair	≥ 150 × 150	Y	Omni-Directional Wheels + Pushing Rods	Semi-Autonomous

however, there is no possibility for internal defects detection.

An extended survey of the state-of-art of mobile robots for applications in confined spaces is hereafter reported. Table 1 reports a detailed summary, as well as the main features of the architecture presented in this work. The following fields are considered: power plants inspection, piping maintenance (oil & gas, water and wastewater) and HVAC (Heat, Ventilation and Air – Conditioning) applications.

The power plant maintenance field is led by General Electric Inspection Robotics [9]. This manufacturer builds small mobile robots to perform preventive services of power plants selected components, such as electric generators, turbines, boilers, tanks and piping. These robots are based on modular components, which can be standard, modified, or even customized upon request. The main operations are remote visual inspection (RVI), not destructive inspections (NDI – as ultrasonic inspection or eddy current) or even cleaning, polishing, grinding and painting. However, this kind of robot is too big to navigate inside the narrow tunnels featured by aeronautical components. Moreover, they lay on magnetic wheels that are not suitable with CFRP products.

The second application concerns piping inspection, required by several fields, as chemical plants, oil & gas pipelines, water and wastewater treatments and transportation. The "Pipeline Explorer" mobile robot by the "National Robotics Engineering Center - Carnegie Mellon University" [10] is the first untethered, remotely-controlled robot for inspecting live underground natural gas distribution pipelines. This robot represents the state of the art in remote-controlled inspection systems for low-pressure and high-pressure natural gas pipelines. The battery-powered Explorer robot can perform long-range, extended duration visual inspections of cast-iron and steel gas mains. As innovative feature, the pitch-roll joints are highlighted, used in place of pitch-only joints. These specific-designed joints allow orientation of the robot within the pipe, in any direction needed. Furthermore, three radial retractile legs are linked to custom-molded driving wheels, aimed to the correct positioning in the tube cross-sectional planes [11,12].

PureRobotics™ commercializes the "Robotic Pipeline Inspection" [13] to inspect pipes down to diameters of 30.5 cm (12″). The PureRobotics pipeline inspection system performs multi-sensor surveys in dry pipe or while submerged, with an operation range of up to 3 kms away from the access point. The subsystems are remotely-operated tracked vehicles tethered by a fiber optic cable.

However, the above described devices do not fit the narrow spaces typical of aeronautical components, due to their sizes. The "Solo Robot", by RedZone Robotics [14], represents a solution conceptually similar, but complying with the typical inner dimensions of aeronautical structures, but it is not sufficiently stiff to allow light machining and cleaning operations.

Other relevant examples (with similar limitations), are the robot "Rover X SAT" by Envirosight [15], the robot "Versatrax" by Inuktun [16] and the "Piping Inspection Camera" by Schroder [17]. In particular, the "Versatrax" robot implements a locomotion system that mixes up the concept of crawlers and that of arms pushing upon pipe walls.

In the field of HVAC service robots, a wide range of solutions exists, due to the high diffusion of HVAC systems in the last decade. A relevant feature is the transversal rectangular section of several HVAC piping systems, more comparable to the inner shape of aeronautical components than the circular one.

The ANATRoller robot family, by Robotic Design [18], consists of mobile tethered robots, developed in various sizes, able to move inside HVAC ducts, capable to overcome relevant slopes and perform specific tasks (i.e. spraying solvents for cleaning purpose) in a wide range tunnel shapes. However, this kind of architecture is not suitable for performing machining operation due to the underweight of the subsystems.

A very particular application in HVAC mobile robot service is the JettyRobot by Neovision [19], extending some concepts of the already described "Versatrax" robot. Its specific mechanical architecture, characterized by six multi arms equipped by six crawler units, is suitable for all circular ducts: horizontal, vertical, ascent and descent, and