Nuclear Plant Containment Building Inspection via Long-Reach Cable-Driven Hyper-Redundant Robot

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***Index Terms*—robotic inspection and maintenance, harsh environment inspection, long-reach manipulator, hyper-redundant robot, cable-driven robot**

I. Introduction

Nowadays, the use of robotic systems represents a game-changer strategy in the context of industrial inspection. Indeed, robots can perform tasks or activities that are impossible with traditional methods, significantly increasing the safety of human operators. Robots can move into environments too hazardous to access, such as vessels, tanks, pipelines, nuclear power plants (NPP), and nuclear waste sites.

Moreover, regular and adequate maintenance activity is fundamental to let industrial facilities safely operate and possibly extend their expected lifetime. The benefits of an accurate and well-defined inspection plan are increased safety and efficiency, leading to an overall advantage in economic terms [1]. This is especially the case in the context of NPP. In fact, a study conducted by the Organisation for Economic Co-operation and Development [2] confirms that the long-term operation of the existing nuclear fleet is one of the most cost-competitive options for providing low-carbon energy, which is crucial for emission reductions as requested by current international policies to face global warming.

In recent years, long-reach cable-driven hyper-redundant manipulators have been widely employed in the field of industrial inspection [3]–[5], as well as in the nuclear sector [6], [7]. Such robots are suitable for the mentioned applications due to the implementation of hyper-redundancy and cable actuation. The cable design keeps the actuators safe from the environmental conditions of the workspace and reduces the weight of the manipulator structure, while the kinematic redundancy allows the robot to perform multiple tasks at the same time, like moving into constrained environments on a specific trajectory avoiding possible obstacles.

In addition, due to the March 2011 accident at Fukushima Daiichi NPP in Japan, the necessity to develop specific long-reach robotic arm for decommissioning nuclear reactors has risen. Some examples are the Fukushima Repair Manipulator (FRM) [8] and the robotic arm developed by Veolia Nuclear Solutions (VNS) and Mitsubishi Heavy Industries (MHI) [9].

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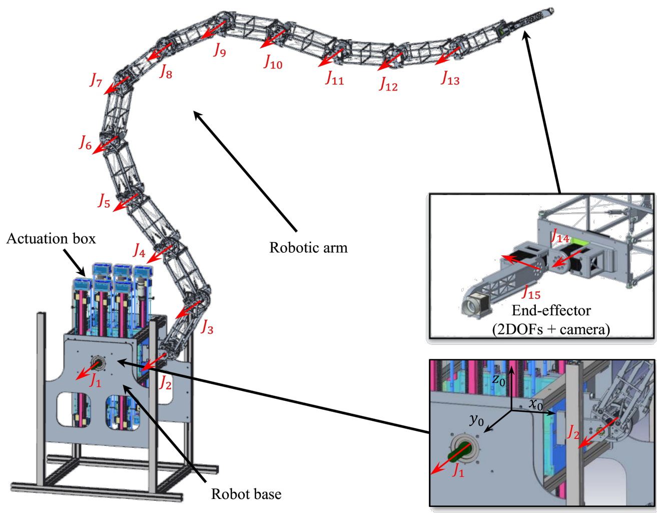

Fig. 1. CAD drawing of SLIM.

This paper shows how SLIM (Snake-like Manipulator for Inspection and Maintenance) [10], a long-reach cable-driven hyper-redundant robot designed for inspection and maintenance of industrial sites, can be employed in the exploration and surveillance of the containment building of NPP.

II. SLIM application in nuclear facilities

This Section describes in detail SLIM, compares its characteristics with other robots developed for the inspection, maintenance, and decommissioning of NPP, and finally presents its capabilities to inspect the containment building of NPP.

A. SLIM design and performance

The original design of SLIM, shown in Fig. 1, consists of the following four main components:

- a robotic arm;
- an actuation box;
- a robot base;
- a dedicated device acting as the end-effector.

The robotic arm comprises 12 moving modules, each composed of a rigid link and a circular pulley acting as a revolute joint, as depicted in Fig. 2. Each pulley is driven by a cable fixed on both sides to a linear actuator. The power is transferred to the module through the friction between the

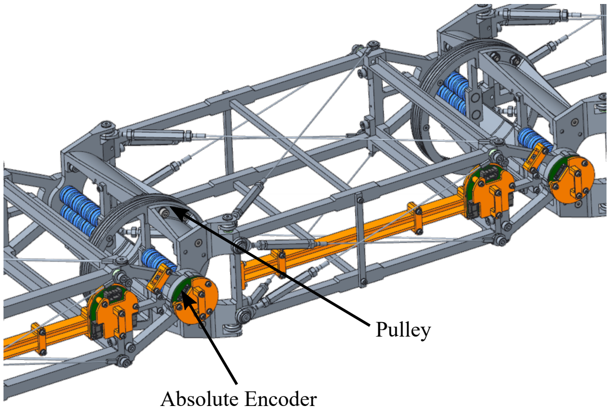

Fig. 2. Details of a single module of the robotic arm.

pulley and the cable. The 12 parallel revolute joints allow moving the end-effector in a specific Cartesian position on a plane, up to 4.8m from the base centre. The first joint of the arm (J_2) is connected to the actuation box, which contains all the linear actuators. The actuation box can rotate around the axis (J_1) that is parallel to the axes of the other joints. This design allows the robotic arm to wrap on itself in a compact configuration and unroll as needed. In contrast with most long-reach cable-driven hyper-redundant manipulators, SLIM owns as many actuators as degrees of freedom (DOFs). The robot base supports the whole robot and is fixed to the ground. For the task of positioning the end-effector in a bi-dimensional Cartesian space, SLIM has 11 degrees of redundancy. A dedicated device acting as the end-effector, able to carry a 1kg payload, is integral to the tip of the last module of the robotic arm. Such a device can be replaced or customised to suit other requirements.

Concerning the components of SLIM, the employed 3mm diameter cables are made of a synthetic fibre called Zylon PBO [11], which is characterised by higher tensile strength and lower mass density with respect to traditional steel. The joints angular position, whose limits are $[-\pi/3, \pi/3]$rad, is measured by a magnetic absolute encoder whose resolution is 18 bits with an accuracy of 0.0017rad. The robot base and the actuation box consist of structures made of Ergal. Each linear actuator is composed of a three stages planetary gearbox and a two poles brushed DC motor, which is controlled by a dedicated motor driver. The linear motion is indirectly measured using an incremental encoder, whose resolution is 500 pulses per turn. The actuation box motion, whose limits are $[0, 4\pi]$rad, is driven by a eight poles brushless motor, controlled by a dedicated motor driver. Finally, the electronic architecture of SLIM is based on a real-time system that can be placed in proximity of the robot base. The chosen materials and components for the robotic arm make SLIM suitable for the inspection of objects and environments characterised by high temperatures, up to 105°C. The cable actuation keeps the actuators, their drivers, and the control system far from the object under investigation preventing damages due to possible extreme conditions.

Exploiting a non-linear controller implemented to deal with the elasticity and friction effects introduced by cable-driven actuation, whose details are reported in [10], the errors in terms of position and attitude measured on the target pose are always within the uncertainty margins due to the sensors. Given the information on the data sheets of the mounted motors and sensors and considering the deformation on the modules length computed via FEM analysis, the position accuracy on the end-effector is $\sigma_{ee} = 0.003$m, while the attitude accuracy on the end-effector is $\sigma_\alpha = 0.006$rad, $\sigma_\beta = 0.005$rad, and $\sigma_\gamma = 0.005$rad, where α, β, and γ are the Euler angles in the YXY representation.

B. Comparison amongst robotic solutions for NPP

The most relevant robotic solutions developed for inspection, maintenance, and decommissioning of NPP are AIA, Super Dragon, FRM, and the robotic arm by VNS and MHI, whose characteristics are described in [6]–[9], respectively. The main differences between them and SLIM are:

- *AIA*: all motors are mounted on-board requiring the aid of liquid cooling systems.
- *Super Dragon*: each joint is driven by two independent cables, then two motors per joint are needed.
- *FRM*: this robot is not hyper-redundant, exploits hydraulic actuation, and was developed to inspect a specific area of Fukushima Daiichi NPP.
- *the robotic arm by VNS and MHI*: this robot, made by boom links and a telescopic robotic arm, has on-board motors and was developed to operate in a specific area of Fukushima Daiichi NPP.

C. Containment building exploration and surveillance

International Agency for Atomic Energy provides specific recommendations on maintenance, testing, surveillance, and inspection of NPP to ensure that the levels of reliability and availability of all structures, systems, and critical components follow the assumptions and intentions of the design [12]. Some of the required activities focus on the surveillance and maintenance of the integrity of the containment building. Given the environmental parameters of a common containment building in terms of temperature, relative humidity, pressure [13], [14] and radioactivity [15], in virtue of its above-mentioned characteristics, SLIM can safely operate within the containment building. Then, if equipped with adequate tools, SLIM can accomplish many inspection tasks, for instance:

- monitoring the conditions of the containment environment such as temperature, relative humidity, pressure, atmospheric composition, and radioactivity level;
- monitoring the mechanical behaviour of the containment as to deformation and displacement;
- monitoring the structural integrity of containment walls.

Considering the robot length and the typical containment building size, about (20-40) m $\times$ (20-40) m $\times$ (30-60) m, to inspect the whole volume, SLIM should be installed on a moving mechanism, like cranes, rails, or wheeled platforms.

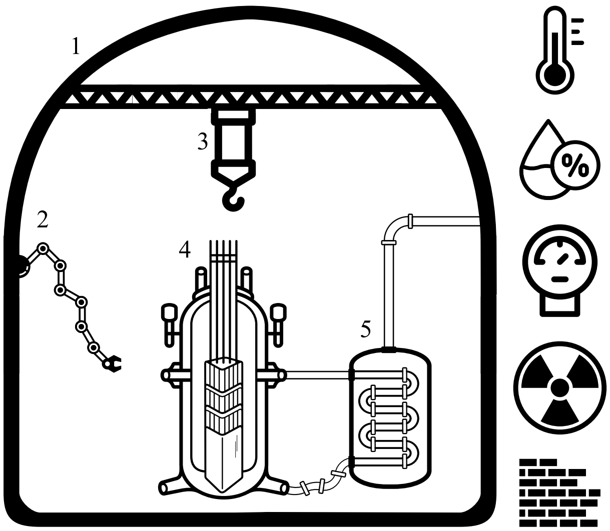

Fig. 3. Schematic representation (not to scale) of a hypothetical inspection of the containment building (1) performed by SLIM (2). The main crane (3), the reactor vessel (4), and the steam generator (5) are also reported. The icons in the right side of the picture represent some of the possible type of measurements: temperature gradients, relative humidity, pressure and atmospheric composition, radioactivity level, and structural integrity of containment walls.

Fig. 3 shows a hypothetical situation in which SLIM is mounted on some moving mechanism fixed to the walls of the containment building. In this scenario, depending on the mounted tools and sensors (e.g. optical camera, thermal camera, barometer, etc.), SLIM could perform different inspections and measurements, such as temperature gradients, relative humidity, pressure and atmospheric composition, radioactivity level, and structural integrity of containment walls. Considering the accuracy on the target pose reported in Section II-A and the hyper-redundancy, SLIM is qualified to inspect and explore even the most cramped parts of the containment building.

III. Conclusion

This extended abstract presents an application of a long-reach cable-driven hyper-redundant snake-like manipulator, called SLIM, for the exploration and surveillance of the containment building of NPP.

The proposed robot is composed of a fixed base that houses an actuation box, able to rotate, connected to a 12 DOFs robotic arm, constrained to move on a bi-dimensional Cartesian plane, on whose tip can be installed a wide variety of mechanisms to carry tools and sensors.

The robot can reach objects approximately 5m far from the centre of its base and, exploiting the kinematic redundancy, can move along elaborated paths, pass through small entrances, and avoid obstacles inside the explored area.

The performance so far obtained in terms of position and attitude accuracy on the end-effector suggest that SLIM is capable to monitor complex, confined, and harsh environments like the containment building of NPP.

A hypothetical situation in which SLIM is fixed to the walls of a containment building to perform different inspections and measurements, such as visual exploration, temperature gradients, relative humidity, pressure and atmospheric composition, radioactivity level, and structural integrity of containment walls, is proposed.

Future works will focus on developing a new design of SLIM to allow movements in the 3-dimensional space and on increasing the size of its workspace. Furthermore, the control algorithm will be improved to prevent vibrations and drifts induced by the cable actuation. Finally, SLIM will be equipped with radiation-tolerant components to allow the inspection of the whole NPP.

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