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MiRoR - Miniaturised Robotic systems for holistic in-situ Repair and maintenance works in restrained and hazardous environments

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***Abstract*— This paper presents the novel concept of a miniaturised robotised machine-tool, Mini-RoboMach, consisting of a walking hexapod robot (WalkingHex) and a Slender Continuum Arm (SCArm). By combining the mobility of a walking robot with the positioning accuracy of a machine tool, with its 24 + 25 degrees of freedom (DoFs), camera-based calibration system, laser scanner and two end-effectors of opposed orientations, the proposed system can provide a versatile tool for in-situ work (e.g. repair) in hazardous/unreachable locations in large installations.**

***Index Terms*— robotised machine tool; walking hexapod; continuum robot; in-situ inspection/maintenance; navigation; multi-axis manipulation of end-effectors**

I. Concept of The Mini-RoboMach

Due to the challenging (e.g. geometrically intricate, hazardous) environments existent in some key industrial sectors (e.g. nuclear power generation), maintenance and repair work is preferably performed in-situ and thus, the use of "off-the-shelf" tooling/machine tools to carry out such tasks is frequently impossible. There is no simple engineering solution to having an adequate tooling system if holistic in-situ interventions are required. Considering the large tooling setups often used for industrial repairs, a niche enabling-technology is presented in the form of a Miniaturized multi-axis Robotised Machine tool, the Mini-RoboMach, whose systems specifically address the need for inspection and repair work in hazardous environments.

Some attempts have been made to develop robots capable of performing in-situ manufacturing and/or repair, such as ROWER [1] and REST [2], designed for welding in hard-to-reach places and ODEX-II [3] for nuclear inspection and maintenance. Although successful, these robots were developed for specific purposes, lacking the flexibility and/or accuracy that are required for the kind of niche applications described above. From the published literature, it appears that for performing in-situ maintenance and repair (e.g. inspection, machining) tasks, highly versatile robots capable of performing active manipulation of end-effectors in large open spaces as well as intricate environments have not been reported.

The Mini-RoboMach (Fig. 1A) proposed here is configured as a "walking and snaking" system, capable of performing holistic in-situ multi-task operations in challenging environments. A wide set of in-situ tasks can be achieved by each constitutive unit independently, or the system can be used as a single combined unit for even more complex tasks. MiRoR system consists of two robots that are now, for the first time, reported of working symbiotically to achieve unique in-situ tasks:

a) The WalkingHex (Fig. 1B), a 24 DoFs parallel kinematic configuration, is utilised for providing both walking and 6-axis movement of the end-effector for performing in-situ operations over large workspace volumes [4, 5];

b) The SCArm (Fig. 1C), with its 25 DoFs, enables "snaking-in" capability for penetration into dense structures and the use of its last 6 DoFs to manipulate end-effectors for post-production operations in confined workspaces [6, 7].

While detailed information about the construction and performance of WalkingHex and SCArm are available [4-7] this paper focusses on the unique capability of the combined 49 DoF system, Mini-RoboMach.

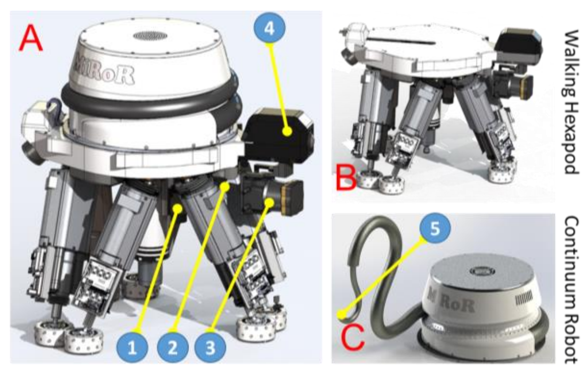

Figure 1. Generic representation of the main constitutive elements of Mini-RoboMach (A): WalkingHex (B) and SCArm (C); **Note**: (1): IDS® USB 2 uEye; (2): SmartRay™ 710; (3) Hokuyo UTM-30LX-EW planar laser scanner; (4) D-Link® DCS-2103/2130; (5) AWAIBA® NanEye;

As a combined system, the WalkingHex (i.e. the body) can execute a variety of the in-situ tasks on the base surface (ground) of the working environment and also act as a carrier for delivering the SCArm to desired locations, thus enabling the completion of in-situ works in otherwise unreachable positions in hazardous zones. Further, by utilizing an intelligent controller, Mini-RoboMach is able to autonomously schedule

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the tasks for its main operation modes depending upon the conditions found in the working environments.

II. Example working scenario

Figure 2 illustrates (with overall dimensional details) one of Mini-RoboMach's working scenarios: part of a nuclear power plant (Fig. 2A) with a series of locations where machining tasks on the ground (Fig. 2B) and on specific features (Fig. 2C) need to be carried out, and a reactor pressure vessel (RPV) head on the floor (Fig. 2D) ready for inspection of the top pipe welds.

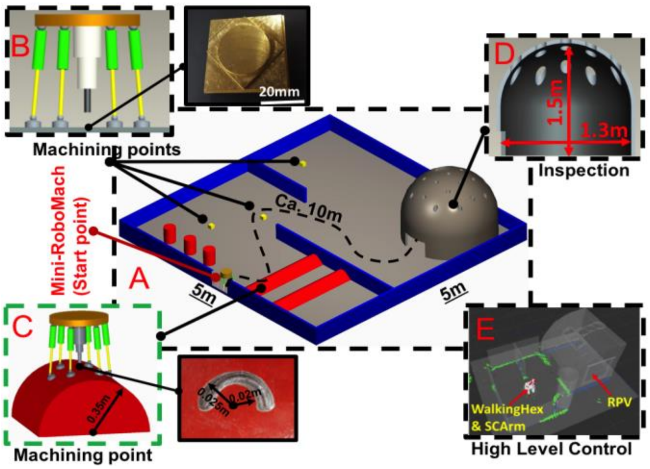

Figure 2. A working scenario for Mini-RoboMach system: part of a nuclear power plant (A); machining on the flats (B) and on pipes (B) and inspection of welds (D) utilising a high level controller (E)

To perform the required inspection of the welds of the RPV and other machining operations on the ground, the Mini-RoboMach's system was defined by the following limit specifications: 1) Minimum reachable height 1500mm: to access the top of RPV head for inspection; 2) Minimum walking range 10m: to allow the system navigate from the safe environment to the terminus point under the RPV; 3) Minimum mobile speed: 0.1m/min which was considered appropriate considering that the propulsion mechanism is actually a machine tool of high precision; 4) Maximum height of the system Ø 560mm: to allow the Mini-RoboMach's to slip-under the RPV. To achieve these technical challenges, the Mini-RoboMach relies on key robotic concepts whose main characteristics are discussed below and partially captured in the schematic representation of Figure 1.

III. Key Features of The Mini-RoboMach

A. *Walking Hexapod*

The WalkingHex robot (weight: 20 kg; platform diameter: 400 mm; able to climb over max 30 mm steps and 20 degrees slopes) derives its structure from the FreeHex machine tool [8] which is based on a Stewart configuration where the base platform has been removed. Compared to the FreeHex, the WalkingHex robot [9] provides a higher level of autonomy by means of: (a) a Self-propulsion ability for entering the location where the in-situ intervention is needed. This is provided by actuating each of the spherical joints on the platform with three wires (up to 700N pulling force monitored via motor current); when WalkingHex is used as a machine tool the wires are slackened. Additionally the WalkingHex has: (i) a laser stripe sensor (SmartRay™ 710) to map the working environment and support the navigation; (ii) autonomous calibration and referencing systems for aligning itself against features on the ground before starting the intervention. This is achieved by a set of three cameras (IDS® USB 2 uEye) aimed downwards and a novel calibration method [9]. A high-speed machining spindle (Jaeger® Spindle Z42-M160.20 S5: 0.3 kW at 60 krpm), oriented towards the ground is mounted on the platform. The WalkingHex feet have been realised to actively hold the system while walking and machining by utilising permanent magnets that can be demagnetized using an electromagnetic coil.

B. *Continuum Robot*

To address the need of reaching tightly packed locations (e.g. narrow labyrinth structures), the SCArm, which relies on pairs of compliant joints (alternated at ±90º), has been developed. From simulations of the required in-situ interventions, the following key specifications for the continuum robot emerged: length > 1.2 meter; 24 DoF allocated to 12 sections; maximum tip diameter of 15mm for a minimum length of 100mm. 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 (from ϕ12mm at the tip to ϕ40mm at the base). As the actuation pack (25 motors: 24 for cable actuation; 1 for rotational feeding) needed to be compact, the large strokes of the actuating cables required a special design of spooling system to allow for winding/unwinding of equal cable lengths for a given rotation was adopted [7]; the tension in the actuating cables has been monitored via motor current. The SCArm is equipped with a torque cable driven spindle and 2 miniaturized cameras (AWAIBA® NanEye) to allow for observation and machining at it distal end.

C. *High Level Control software with its main abilities*

The High-Level Controller (HLC) of the Mini-RoboMach assists in controlling this complex robot by providing fully- and semi-autonomous functionalities to the end-user. Furthermore, using a task-planning capability, the HLC semantically specifies goals which are then translated into task sequences to be executed by the robot.

1) *WalkingHex Navigation*

The system was designed to work in known environments utilizing pre-defined gait sequences (e.g. planar, rotational) triggered by the HLC. Path-planning is performed on a global map while reacting to unknown obstacles, for which a local planner based on the elastic band approach [10], has been adopted. This is enabled by a Hokuyo UTM-30LX-EW planar laser scanner mounted on a tilting unit to build a 3D point cloud. The scanned data is combined with an octree-based OctoMap [11] which represents a discretized full 3D space, similar to Occupancy Grid Maps, enabling comparison with CAD data of the environment to assist with the navigation.

2) *SCArm Navigation*

Navigation of SCArm is based on longitudinal advancements into the environment, i.e. tip following by minimizing the deviation from the path travelled [12]. Given a Cartesian goal pose in the environment, a probabilistic planner (RRT-Connect) has been used to generate a path to the goal while

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checking for collisions using the OctoMap representation and considering the constraints stemming from the design of the hardware. A Transitioning Mode is used when switching from the navigation mode to performing 6-axis end-effector manipulations for which both an IK-solver is employed. Finally, a Homing Mode is provided for convenience in order to allow for retracting the SCArm back out of the environment independent from previously performed motion sequences.

IV. Demonstration of The System

The capability of the Mini-RoboMach has been tested in a mock-up nuclear plant scenario (Fig. 2) that allows the testing of the system for autonomous navigation over a 10m walking distance while dragging the power cables (at max. speed of <0.4m/min; with a positioning accuracy of 2mm/500mm – checked by a Leica AT-402 Laser Tracker) to specified targets and then to perform key intervention tasks: (i) machining stress relief features on the ground utilizing the "lower" spindle contained on the WalkingHex (Fig. 3A) – the time to complete this stage of the task is ca. 35min; (ii) inspection of welds of a reactor pressure vessel utilizing the end-effector contained on the SCArm (Fig. 3B) – the time to complete this stage of the task is ca. 45min. The machining task proved the ability of Mini-RoboMach to calibrate itself against features of the ground [7], to react to machining forces (<100N in x,y,z direction), and to machine at high accuracies <0.070mm [5], features that have subsequently checked by a Coordinate Metrology Measurement machine. The inspection tasks proved that Mini-RoboMach was able to identify the opening of the RPV and navigate under its dome, extend the SCArm and inspect (in a ±15° sector with a positioning accuracy of ±1mm – checked utilising IMETRUM® video gauge system) the quality of welds of the upper pipes with the cameras of the end-effector. Conventionally such tasks would require an engineer in Hazmat suit equipped with a specialist machine tool and an inspection toolkit. In contrast with this, Mini-RoboMach is a self-sufficient system that proved its capability to tackle all these tasks without human supervision.

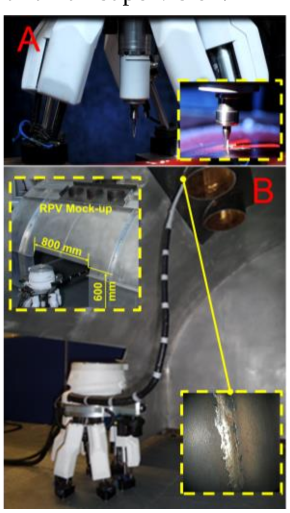

Figure 3. Mini-RoboMach performing high accuracy machining task (stress relief feature) on the ground with the "lower" end-effector (A) and inspection of welds under the RPV at a height of 1.5m above the ground using the "upper" end-effector (B).

V. Conclusions

This paper reports on the concept, development and demonstration of a miniature robotised machine tool, the Mini-RoboMach, that is hybrid in structure and capability, i.e. it can navigate through complex environments and then perform the multi-axis manipulation of end-effectors. The Mini-RoboMach has an outstanding versatility to tackle inspection and repair tasks in a wide range of applications due to the fusion of two units with complementary capabilities: (i) a walking hexapod with 24 DoF, the WalkingHex, capable of navigating to a particular location, calibrating itself, and performing a multi-axis manipulation of an end-effector, such as a cutting tool, relative to features on the ground; (ii) a Slender Continuum Arm with 25 DoF, SCArm, that is able to navigate into tightly-packed/difficult-to-reach environments and then perform complex multi-axis manipulation of end-effectors at high accuracy. Apart from having the capabilities of each constitutive unit verified, the Mini-RoboMach was successfully demonstrated as a unitary system by navigating under a mock-up of a nuclear environment to machine complex features on the ground and inspect pipe weld quality at heights, operation that would be considered hazardous for manual intervention.

Although for some in-situ interventions the system might be considered as over-engineered, the Mini-RoboMach gains an unprecedented versatility and combination of capabilities belonging to both robots and machine tools which can be utilized in various intervention scenarios with little or no setup modifications and a short response time.

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