The SPIR: An Autonomous Underwater Robot for Bridge Pile Cleaning and Condition Assessment

Khoa Le, Andrew To, Brenton Leighton, Mahdi Hassan, and Dikai Liu

Abstract— **The SPIR, Submersible Pylon Inspection Robot, is developed to provide an innovative and practical solution to keep workers safe during maintenance of underwater structures in shallow waters, which involves working in dangerous water currents, and high-pressure water-jet cleaning. More advanced than work-class Remotely Operated Vehicles technology, the SPIR is automated and required minimum involvement of humans into the working process, thus effectively lowered the learning curve required to conduct work. To make SPIR operate effectively in poor visibility and highly disturbed environments, the multiple new technologies are developed and implemented into the system, including SBL-SONAR-based navigation, 6-DOF stabilisation, and vision-based 3D mapping. Extensive testing and field trials in various bridges are conducted to verify the robotic system. The results demonstrate the suitability of the SPIR in substituting humans for underwater hazardous tasks such as autonomous cleaning and inspection of bridge and wharf piles**

I. INTRODUCTION

Routine inspection and maintenance of underwater structures such as bridges and wharf piles are crucial to ensure the integrity and prolong the lifespan of the structures required by government agencies and private companies. In order to inspect the condition of a pile, the covering crustaceans and other marine or aquatic growth need to be cleaned off either by high-pressure water cleaning or hand scraping. These operations, described in Fig. 1[1], are particularly arduous tasks as divers have to work in strong water currents and poor visibility and expose in awkward poses for a long period, let alone the large reaction force of the blasting nozzle with load over 50 N.

The latest technological offering available for cleaning and inspection tasks is work-class Remotely Operated Vehicles (ROVs) equipped with a cleaning system. At current, these ROVs are large and expensive, typically designed to operate in large open water environments. Hence their hulls are large and heavy that prevents them from being deployed and work in narrow and complex areas, littered by obstacles, such as bridge pylons, wharf piles, etc. Furthermore, to operate these commercial ROVs requires trained operators who have undergone intensive and costly training procedures [1].

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[1]https://www.youtube.com/watch?v=uz1ZXV5Oths

Fig. 1: Diver on cleaning operations

This paper presents the design, development, and testing of SPIR performing underwater cleaning and inspection tasks. The SPIR (Fig. 2 consists of claw arms used for docking rigidly onto a pile, a 3 degree-of-freedom cleaning arm for positioning a high-pressure water jet, and a suite of cameras and sensors used to provide intelligent functions. Once navigated to a pile, the SPIR will autonomously clean the pile by systemically moving to different positions of the pile, identify the surfaces to be clean at each position, and execute a cleaning trajectory to direct a water jet to remove the marine growth. After cleaning, the SPIR collects high-definition images around the pile that is stored into a geographic information system and can be viewed by bridge inspectors for condition assessment. To the best of our knowledge, this is the first-of-its-kind system performing autonomous underwater bridge-structure cleaning and assessment.

In Section II, we present the overall system and detail of the system designed to achieve the pre-defined operations. Section III focuses on the methodologies to make the SPIR operate autonomously and effectively in uncertain environments. Section IV describes the outcomes and results obtained from labs and site trials, which demonstrate the effectiveness of the system.

II. SYSTEM OVERVIEW

A. Functionalities of the SPIR

In order to conduct the inspection efficiently, the main functionalities of the SPIR are developed and implemented as follows:

- Autonomous localisation and navigation: This function allows the robot to maintain the position and track the pre-defined trajectories under the water current, up to 3 knots (1.5 m/s). Operators

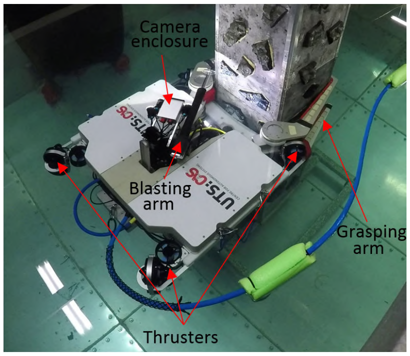

Fig. 2: SPIR and the main components

only need to select a target pile displayed from the user interface then order the SPIR to navigate towards it.

- Remove marine growth: The SPIR equips a 3 DOF manipulator which carries the high-pressure water jet nozzle to clean underwater structure from growths. The vision-based marine growth identification technique is also implemented to plan the trajectory for the nozzle optimally. Besides, a special docking mechanism is also designed to prevent the SPIR from floating away during blasting.
- Vision-based 3D reconstruction: Stereo-vision-based algorithm (ORB-SLAM2) [2] is implemented to reconstruct the accurate 3-D model of underwater structures to detect failures such as deformations, cracking spots.

B. Hull design and manoeuvring system

Water current speed in bridges pylon nearby estuaries is varying from 0.2-4 knots (0.1 m/s to 2 m/s) [3]. According to the consultations with diving experts, manual underwater structure inspection operations are paused when the current speed, causing by tidal, exceeds 3 knots (1.5 m/s), therefore shortening the working time. To enhance the capability of operating in high water currents attacking from all directions, the hull of the SPIR is carefully designed and optimized using both numerical analyses, using the computational fluid dynamics (CFD) technique, and experimental approach to minimise the fluid drag force affecting on the body. Furthermore, various geometrical constraints of pylons, i.e., piles size and shape, interval gap dimension, etc. are also considered in the designing process to make the SPIR design neat and efficient.

Twelve T200 thrusters, allocated as in Fig. 2, are incorporated to the SPIR, providing enough thrust force to overcome the disturbances from the water around bridges pylon. The arrangement of the thrusters makes the SPIR a fully-actuated vehicle that capable of maneuvering in narrow environments such as bridge piles. Given each thruster provides 5 kgf at 300 W, that total thruster system consumes nearly 3.5 kW in full throttle.

C. Marine growth removing manipulator

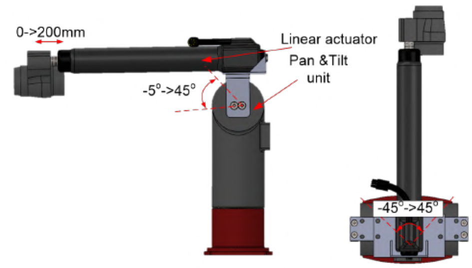

Fig. 3: Marine growth removing manipulator

As the underwater structures are usually covered by a thick and stiff layer of marine growth, which in some cases reaches 20 cm, removing this layer is required as an important phase of the condition assessment. The high-pressure water blasting method is selected to incorporate to the SPIR due to its efficiency and economy. The high-pressure water pump (SCUD400) with the nozzle creates the jet whose pressure is up to 4000 psi, is proven to efficiently clean marine growth from pile surfaces at a distance between 5-10 cm. However, the large reaction force from the jet, up to 50-70 N, caused the challenges to design a proper robot manipulator to handle this force.

As the payload of the SPIR is 6.5 kg in water, the miniature underwater robot manipulator, which can handle 50-70 N at the end-effector is required. However, there is no existing product on the commercial market [4]. Therefore, the design solution that combines a high torque pan and tilt unit (SS109HT) with the linear actuator (UltraMotion) is selected, creating a 3-DOF spherical robot manipulator, whose workspace is described in Fig. 3.

Regardless of the wide range of disturbances, the SPIR body is demanded to be stable during the marine growth removing operation to ensure efficiency.Inspiring from the safety belt of divers to engage to bridge piles, the pile docking mechanism, including 4 grasping arms, is designed, assisting the SPIR to firmly attach to the inspected structures. Actuated independently by four motors, the docking mechanism always provides four contacting points, hence being highly compliant to the wide range of bridge pile dimensions in different shapes. The current control mode of the motors is used to generate the constant grasping force in every grasping pose.

The grasping arms can be set in a loose-engaging mode in the inspection phase, where the tips of the arms assist the SPIR to maneuver around bridge piles without being drifted away. The profile of the grasping arms are designed to be compatible with the most popular bridge pile shapes, i.e., cylinder, square, hexagon and octagon, those sizes range from 350 mm to 550 mm. The grasping arms are removable and replaceable in the case of dealing with piles in different dimensions.

TABLE I: Sensory system of the SPIR

Sensor type	Model name
9-DOF Inertial Measurement Unit (IMU)	Advanced Navigation Orientus
Pressure Depth Sensor	Bar30-BlueRobotics
Acoustic Positioning System	WaterLinked
Sonar Scanner	Tritech Micron
Stereo Camera	DuoM - Duo3D
Monocular Camera	Blackfly BFS-U3-31D4C-C with 2mm lens

D. Sensory system

To achieve the fully autonomous objective, the SPIR has implemented a sensory system that is used to estimate the robot body state, and to build up an awareness of the surrounding environment. TABLE I shows the list of sensors implemented on the SPIR.

Robot body state estimation uses IMU (roll, pitch, yaw), pressure depth sensor (heave), and acoustic positioning system (surge, sway). This combination of sensors is typical for ROVs and performs well with certain limitations for the bridge environment. Limitations include acoustic dead zones created by the narrow structure of piles, and the metal structure influencing magnetic readings.

Environmental awareness building uses sonar scanner to locate piles and avoid obstacles, the stereo camera to create 3D maps of pile structures, and the monocular camera to capture images of surface conditions. The stereo and monocular cameras have been selected to have a wide field of view for capturing images close to the surfaces, which is necessary in turbid waters.

E. Power and data setup, operator control

The signal conditioning, vision processing, and closed-loop control processes are implemented in an embedded computer, installed in the SPIR enclosure, making the SPIR reduce the communication with the control console. Video stream and signal conditioning results are transmitted over Ethernet and displayed on the console monitors only for supervisory purposes.

An onshore power supplying solution is selected instead of using batteries to optimise the weight of the SPIR. As the power is transmitted over 100 m cable length, the voltage is boosted from 240 VAC to 400 VDC at the power supply box before transmitting to the SPIR to reduce the thermal dissipation. Here, the voltage is stepped down to be suitable for the devices, including embedded computers, sensors, and actuators. Fig. 4 describes the SPIR setup to conduct operations.

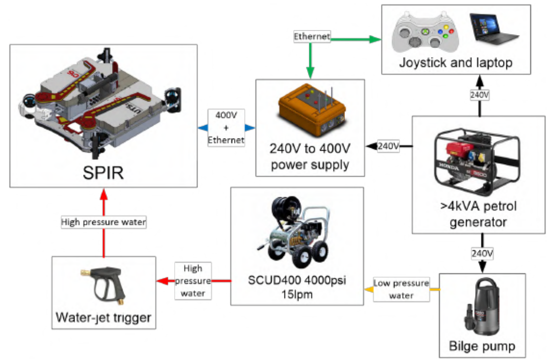

Fig. 4: General view of SPIR setup

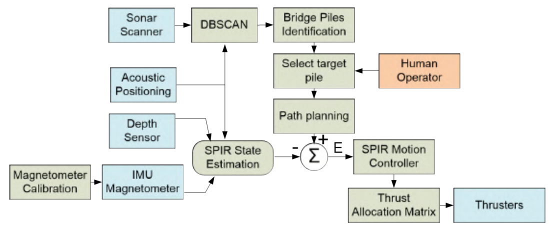

Fig. 5: Navigation in open water control scheme

III. Localisation, navigation and marine growth identification methodologies

A. Localisation and navigation in open water

A navigation controller was developed for the SPIR to drive toward the target piles autonomously (Fig. 5). The sensory system, including the inertial measurement unit, depth sensor, magnetometer, and acoustic positioning system are fused to estimate the state the robots [5] while sonar scanning sensor, mounted in front of the SPIR, are applied to detect the relative position between the target piles to the SPIR. The detecting range and the field of view of the sonar sensors are set in 10m and 90 deg, respectively, providing the 2-D point cloud data set at the sample time of 2.5 seconds. Then, the Density-based Spatial Clustering of Applications with Noise (DBSCAN) algorithm [6] is applied due to the efficiency in terms of processing time to process the raw data set, recognizing the targets to generate the desired path towards them.

SPIR operators select the target pile from the sonar scanning feedback and plan the robot to the destination [7]. Defining **E** as the errors between the current robot states and the desired path toward the target pile, the goal of the SPIR motion controller is to generate the control signals to minimise **E** under the large disturbance of environments. Several control algorithms such as anti-windup PID controller, reinforcement learning [8], and adaptive controller [9] were studied and successfully designed for this objective; those results are specifically described in Section IV.

B. Underwater Simultaneous Localisation and Mapping (SLAM) around bridge piles

Once the SPIR is in the vicinity of the pile, vision is used to localise in relation to the pile, so that inspection and cleaning can be performed. For inspection of the pile, a full 3D model of the pile as well as high quality images geo-referenced to the 3D model are desired.

The 3D model can be used to keep a record of marine growth on the pile, and the high resolution images are required for inspecting cracks or damage to the pile structure.

A combination of a grayscale, relatively low resolution stereo camera, and a colour high resolution monocular camera was used. The stereo camera is used for acquiring a 3D reconstruction of the scene from a single view point, and for determining the trajectory of the camera. Given the trajectory of the camera, single view point reconstructions can be combined into a full 3D reconstruction of the pile. The monocular and stereo cameras are attached together rigidly and the transform between the two is known, so that the high resolution colour images from the monocular camera can be localised to the full 3D reconstruction generated generated from the stereo camera.

There are a number of challenges for vision in the underwater environment around a bridge pile.

- Highly turbid water with visibility of 1 m or less
- Varying amounts of floating material
- Difficult lighting conditions where sunlight may illuminate the object or dominate the background

To capture a full 3D reconstruction of the pile the SPIR moves around the pile spiral path while the grasping arms are in a loosely engaged configuration. Starting from a position just below the water surface, the SPIR rotates completely around the pile, then increases depth by a distance that ensure that images collected at the previous depth share some overlap with newly collected images, and rotates back to that starting face. This process is repeated until the entire pile has been viewed by the camera.

ORB-SLAM2 is used to determine the trajectory of the camera as the SPIR moves around a pile [10]. ORB-SLAM2 is a publicly available visual SLAM system, which gives an online estimate of the camera's movement from stereo images. Visually the pile and marine growth tends to be repetitive, which makes it difficult to match image features detected in overlapping images of the pile. ORB-SLAM2, and many visual SLAM systems in general, use an estimate of the motion of the camera to predict the position of features in a new image. This is done to reduce the number of feature pairs that are compared to improve performance, but we believe it also improves the accuracy of feature matching for features with low uniqueness.

After the entire pile has been captured the key frames selected by ORB-SLAM2 are saved. The data saved for each key frame includes a stereo pair of images and a camera pose. Offline, a single viewpoint reconstruction is generated for each key frame, which are then merged together using the pose of the key frame to create a full reconstruction of the pile. A good quality 3D reconstruction can be produced despite the poor quality of the input images.

To capture high resolution images of cracks in the concrete or other damage to the pile structure, the monocular camera is used. Floating material and sunlight flicker are removed by securely attaching to the pile with the grasping arms, capturing multiple images over a period of a few seconds, and merging the images into a single median image. This is done while ORB-SLAM2 is in operation, so that the pose of the captured image relative to the full 3D reconstruction is known.

C. *Marine growth identification*

The SPIR identifies areas on a pile that is covered by marine growth to intelligently clean only those sections. Marine growth identification is performed by comparing the 3D map created during a pre-cleaning inspection with the pile dimensions provided from bridge construction drawings. Fig. 6 shows a reconstructed 3D map of a pile (green) registered using ICP (Iterative Closest Point) algorithm [11] onto the ground truth of the pile (purple). After registration, any points on the 3D map that is outside of the ground truth pile are considered marine growth and can be extracted based on the point-to-pile distance (refer to left graph in Fig. 7). The extracted marine growth points are further filtered based on cluster size being greater than a predetermined size (refer to right graph in Fig. 7).

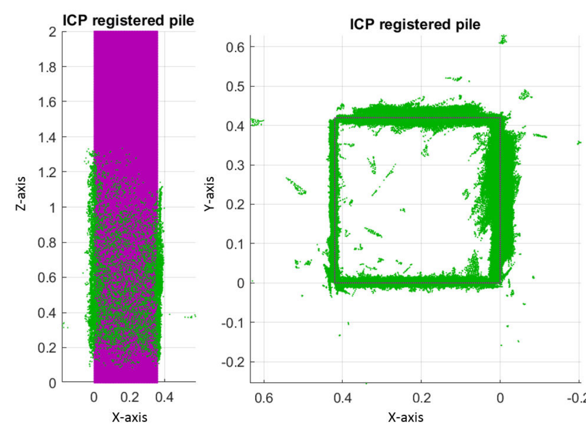

Fig. 6: ICP registration of a 3D map (green) onto a ground truth pile (purple), side view (left), top view (right)

IV. Field trials and results

The field trials were performed on various bridges in New South Wales, Australia, such as Peats Ferry Bridge, Mullet Bridge, Narrabeen Bridge, Windang Bridge, with the support of Road and Maritime Services (RMS). Fig. 8 shows the SPIR and working team on sites. Multiple tests were conducted to evaluate the operation procedure and the efficiency of the SPIR.

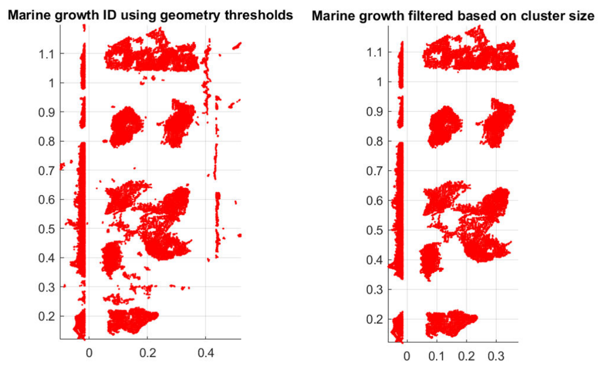

Fig. 7: Marine growth identification based on thresholding point-to-pile distance (left) and further thresholding the cluster size of extracted points (right)

(a) SPIR in Narrabeen bridge

(b) SPIR in Windang bridge

Fig. 8: SPIR on field trials

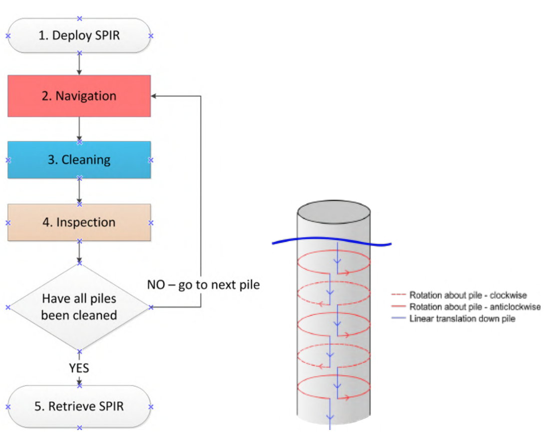

Fig. 9: Operation procedure

A. Operation procedure

The operation procedure of the SPIR is summarised in Fig. 9. After being launching, the navigation in open water mode, using the dynamic positioning controller, is activated to maintain the SPIR desired poses against water disturbances. SPIR operators select a bridge pile to inspect from the console monitor and order the SPIR to start the operation. SPIR navigates toward the selected pile and firmly engages in it using the grasping arms. Next, the marine growth removing process is started. To clean the entire piles without being caught as the cable wraps around the pile, SPIR follows the spiral sequence described in Fig. 9 until reaching the maximum depth. After completing the cleaning phase, the pile inspection routine is conducted by following a similar trajectory, from the bottom to the initial position. Data, such as SPIR trajectory, high-resolution surface snapshots of the pile surfaces, are processed and stored in real-time for further assessment. As the SPIR returns to the initial poses, the operators can select a next bridge pile to work on, and the procedure is repeated until completed.

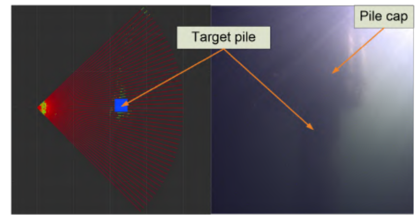

Fig. 10: Bridge pile detection using sonar scanning

B. Autonomous navigation in narrow environments

The tests, described in this section, were conducted in Narrabeen Bridge, which is built upon piles and pile caps. This environment is complicated as the vertical bridge piles are hidden in water, up to 1.5 m in high tide, and covered by the underwater caps, hence causing challenges to the localisation and navigation tasks. Furthermore, the interval between the vertical piles is approximately 2 m, creating a narrow working environment to operate the SPIR.

After setting up the position for the acoustic positioning receivers, the SPIR was deployed from a manual crane of the site trial boat (Fig. 8a); then the sensor calibration, mentioned in Section III, was conducted. The dynamic positioning of SPIR was activated to maintain the position of the robot under the disturbances of water current, measured around 0.2-0.4 m/s, while the sonar sensor was applied to identify the targets. Fig. 10 shows the result of the sonar signal processing in which a pile was located around 2.5 m ahead of the robot, which is difficult to be detected using purely visual feedback.

Operators selected the target and triggered the navigation mode to move towards the pile. The tracking performance, presented in Fig. 11, includes 3 phases: identifying a target, navigating, and grasping pile. It is seen that the SPIR position fluctuated in the range of

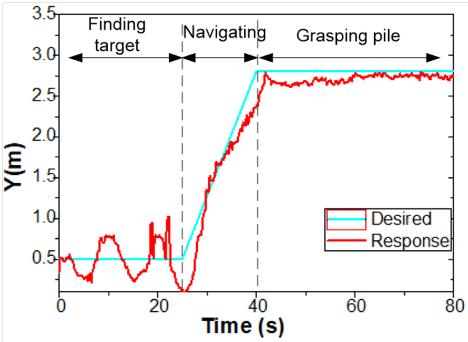

Fig. 11: Navigation towards the target pile

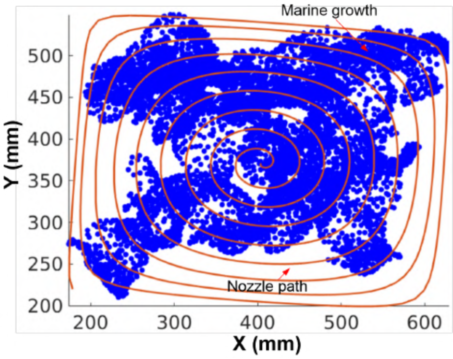

Fig. 12: Deformable spiral path

±0.3m around the desired position during the identifying target phase. As the SPIR successfully engaged to the pile using the grasping arm, the body was stayed still, showing minor fluctuations at the desired pose.

C. Vision-based autonomous marine growth removing process

The tests of the marine growth removing process were conducted in Windang Bridge (Wollongong, Australia) where the marine growth thickness is more than 20 cm (Fig. 8b). As the growths flourishing on the surface are extremely stiff and condense, the maximum water pressure (4000 psi) and the big nozzle were used for this scenario. Besides, the desired distance between the nozzle and surface, and the motion speed are set up at 5 cm and 20 cm/s, respectively.

To efficiently clean bridge piles from marine growth, the distance between the water-jet nozzle and the surface has to be maintained from 5 to 10 cm. If the distance is overly close, the high-pressure water stream could damage the structures during blasting; vice versa, if being excessively far, it is not powerful enough to remove hard marine growths such as barnacles, corals, etc. For this reason, the profile of the surfaces needs to be accurately identified to generate the proper tracking trajectory for the nozzle, mounted in the end-effector of the blasting arm. The stereo-vision-based system is applied to scan and restructure the surface profile before blasting. After firmly engaging to the pile, first, the blasting manipulator is controlled to follow the pre-defined box-shape trajectory, keeping the safe distance to the surface, while the stereo camera collects images of the surfaces. The images are then registered to centre of the SPIR body and aggregate to form the broader 3D view of the surface, including marine growth. To prevent damage to the structure surface and avoid frequent or aggressive deceleration and acceleration due to sharp turns of the cleaning nozzle, a Deformable Spiral Coverage Path Planning (DSCPP) is utilised to generate a spiral path based on the 3-D model constructed from the stereo camera [12]. The DSCPP algorithm deforms a spiral path to wit within any size rectangle and appropriately maps a smooth spiral path generated inside a circle to a spiral path inside a Minimum Bounding Rectangle, hence making the path remaining smooth while minimising the path length.

A deformable spiral trajectory was generated by applying DSCPP algorithm (Fig. 12), following by the blasting phase. The blasting performance, shown in Fig. 13, was assessed by a professional diver to be accepted as the marine growths on the structure were completely removed, and the core of the bridge pile was exposed for the condition inspection. It is observed from the IMU feedback that the fluctuation of the robot poses is small (below 0.5 deg), showing the effectiveness of the grasping arm in maintaining the SPIR stability against the reaction force from the water stream. After completing a surface, the SPIR sequentially moved to the next face of the structure and repeated the process until reaching the seabed.

Fig. 13: A surface before and after blasting

D. Inspection and marine growth identification

The bridge pile inspection and marine growth identification routine were extensively tested on piles from several bridges. The key challenges faced during the

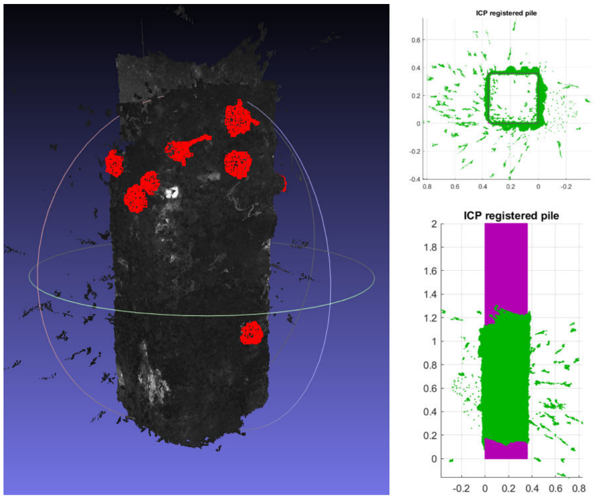

Fig. 14: 3D map of Narrabeen bridge pile and identified marine growth shown in red

site trials conducted in shallow tidal zones were low visibility (about 50 cm) due to high turbidity after a rain period and vortex water current around the pile, stirring particles around the pile. The robustness of SPIR's hardware and software procedures against these challenges were thoroughly demonstrated. Including the robustness of the stereo and monocular cameras with wide field-of-view to capture images at close viewing distances, the 3D mapping procedure using SLAM for a stereo camera described in Section III, and the high-resolution image capture procedure also described in Section III.

The following result shows the 3D map and marine growth identified for a pile on the Narrabeen bridge. The 3D map of the pile is shown in Fig. 14, and the marine growth that is identified on the pile is shown in red on the 3D map. The ICP registration result of the 3D map with the ground truth model of the pile that is used to identify the marine growth is also shown in Fig. 14

V. Conclusion

In this paper, we presented the SPIR, a world-first autonomous robotic system for underwater structures cleaning and inspection. The SPIR hardware and the control systems are optimally designed to substituting humans in conducting operations in hazardous environments. The robots have been successfully tested in various field trials, demonstrate that the SPIR is, in general, a feasible technology to clean and collect high-quality data for profound assessment.

In the future work, due to the autonomous features of the SPIR, one operator is able to supervise multiple robots simultaneously, hence possibly increasing the efficiency of the operation [13].

Appendix

Video summary of the SPIR project is available online: https://www.youtube.com/watch?v=hFtW2cXaHYk

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