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Author(s):
Gehring, Christian; Fankhauser, Péter; Isler, Linus; Diethelm, Remo; Bachmann, Samuel; Potz, Marcel; Gerstenberg, Lars; Hutter, Marco

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ANYmal in the Field: Solving Industrial Inspection of an Offshore HVDC Platform with a Quadrupedal Robot

C. Gehring, P. Fankhauser, L. Isler, R. Diethelm, S. Bachmann, M. Potz,
L. Gerstenberg and M. Hutter

Abstract Offshore HVDC converter stations for transportation of offshore wind energy to the coast need regular human inspection. Automated surveillance of such a platform by a mobile robot has high potential of improving the speed and quality of decision making while reducing operating expenses and risk of unmanned operation of the platforms. However, the challenging environment of such platforms has prevented operators from making use of mobile robots to this date. Recent progress in legged robotics resulted in systems that are becoming feasible for such tasks nowadays. For this reason, the quadrupedal robot ANYmal was tested on a platform in the North Sea for automated inspection. This paper presents the results of the field tests and discusses the challenges of industrial inspection of offshore sites.

1 Introduction

Offshore wind energy is one of the fastest-growing energy sources in the world, but the exploitation of the renewable energy imposes a number of technical challenges. To transport offshore wind energy to the coast over more than 200 km efficiently, the AC current from wind turbines needs to be converted to DC current on a so-called offshore High Voltage Direct Current (HVDC) converter platform. These platforms are built of a complex integration of various electrical and mechanical equipment such as pumps, water treatment systems, and several safety and backup systems. All of these components can potentially fail and lead to a shutdown of the converter station, which is extremely costly for the operator. To provide electricity to

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C. Gehring, P. Fankhauser, L. Isler, R. Diethelm, S. Bachmann, M. Hutter
ANYbotics AG, Weinbergstrasse 35, 8092 Zurich, Switzerland,
e-mail: `cgehring@anybotics.com`

M. Potz, L. Gerstenberg
TenneT Offshore GmbH, Eisenbahnlängsweg 2a, 31275 Lehrte, Germany,
e-mail: `marcel.potz@tennet.eu`

Fig. 1: The quadrupedal robot ANYmal was deployed for autonomous inspection and surveillance on a wind energy HVDC converter platform in the North Sea.

millions of people reliably, such offshore converter stations are regularly inspected by human operators. Due to high expenses for trained personal, transportation, and supplementary infrastructure required, manned platforms are highly undesirable for operators of such platforms. Health and safety considerations of a manned operation lead to the same conclusion. Modern platforms are thus equipped with various digital sensors which are supervised from onshore. However, additional usage of a mobile robot for inspection is desirable for three main reasons: First, the monitoring capability of the robot is very similar (and even better in certain aspects) in comparison to the capacity of humans and significantly favourable compared to fixed installed cameras. The likelihood that a camera, mounted at a fixed position, provides an insufficient perspective for a situational judgment is high. Moreover, a fixed setup is often useless in case of a major incident due to lost communication or damaged equipment. Installation costs and operating expenses of fixed sensors are high, especially for retrofitting older existing sites. A second advantage of the mobile system is that issues can be detected earlier due to more frequent visits of the robot compared to manned inspection routines. Furthermore, modern sensor technology allows the mobile system to perceive conditions that are not perceptible for humans. The robot can detect leakages, hot spots, gas leaks, and deteriorating machines before a major problem occurs due to the high accuracy and repeatability of its measurements. Hence, the risk of consequential damage and costs can be reduced substantially. The robot can inspect a problem from different viewpoints and the right specialist for repairing can be sent from the beginning – saving additional costs. The third benefit is the automated collection of vast sensory information. For instance, 3D mapping of the environment is a by-product of the robot's navigation system, but is also highly valuable for the operator. Ultimately, predictive maintenance based on the gathered data can reduce downtime of the site and optimize capital expenditure for back-up equipment.

To this date, no robots have been used on offshore HVDC converter stations for surveillance and inspection. One of the main underlying reasons is that these platforms were mainly designed for humans and pose a challenging setting for state-of-the-art mobile robots. In this paper, we present the first findings from extensive field tests for the industrial inspection and surveillance with an autonomous mobile robot on an offshore platform. The tests were performed with ANYbotics' quadrupedal robot ANYmal, which is designed to navigate through difficult environments with the superiority of its legged locomotion in comparison to wheeled or tracked actuation. The deployment took place on one of TenneT's offshore HVDC platforms in the North Sea in 2018 as shown in Fig. 1.

2 Related Work

Due to the complexity of deploying a mobile robot on an offshore platform, only a few attempts have been reported so far. In 2011, [9] conducted a feasibility study with the mobile platform MIMROex on a shallow water offshore gas platform in the South Chinese Sea. The system was programmed to automatically follow a predefined path with help of reflective poles for localization and take readings of gauges and gas concentrations. With its four-wheeled design, the robot was restricted to flat ground with a maximum of 20 mm bumps. Similarly, the Sensabot robot [5] was shown to perform remote controlled inspection task on an onshore oil and gas facility. To overcome the limited mobility of the wheeled actuation, a customized elevator and cog rail ladder were proposed. Another approach to mobility in robotic industrial inspection was presented by [1], which proposed to use a rail-guided system where the robot would travel along a metal tube.

In 2014, the company Total and ANR initiated the ARGOS Challenge (Autonomous Robot for Gas and Oil Sites) which required the systems to autonomously perform various inspection tasks and navigate over difficult terrain including stairs [7]. Out of the five approved teams, four robots were built as tracked vehicles with movable flippers (e.g., [6, 8]), while our group participated with the legged robot ANYmal [4]. These demonstrations showed that autonomous industrial inspection for offshore plants is feasible without requiring to adapt the environment or install special equipment.

3 Problem Statement

The environment of the HVDC platform and its difficulties for mobile robots as well as the inspection tasks are outlined in this section.

(a) Stairs (b) Leakage protection (c) Step up

(d) Door sill (e) Pipes (f) Cable protection

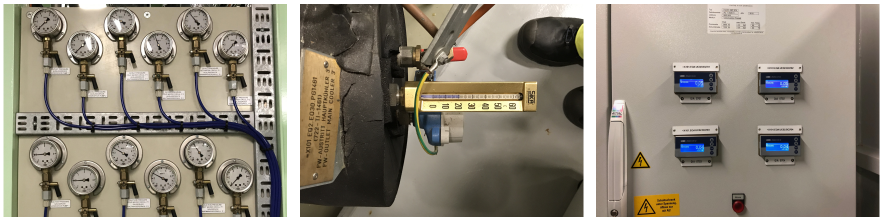
Fig. 2: Even though most of the ground is flat, various obstacles on the ground makes the locomotion of the robot difficult.

3.1 Description of the Environment

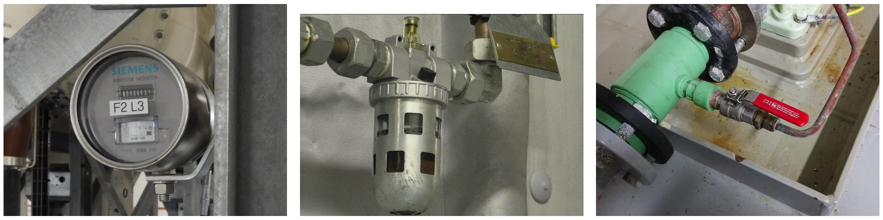
The working area on the platform has an overall length of 80 m, width of about 60 m and a height of 30 m. The decks of the platform are connected by staircases and an elevator. About 50% of the site cannot be accessed by humans or the robot during operation due to potential electrical discharges. These rooms can only be accessed once per year when the site is shut down for revision. During normal operation of the site, 50 of the ca. 200 rooms of the platform including GIS, transformer, pump, water treatment, AC&DC, fire-fighting, and battery rooms are interesting for robotic inspection.

Most rooms and corridors of the platform have flat ground, but there are numerous areas where the terrain is difficult to overcome by most wheeled or tracked systems. Fig. 2 shows some examples of obstacles that can be expected on the platform. In addition, although the platform is usually clean and tidy, the pathway could be obstructed by installed equipment or movable objects.

A further challenge for a mobile robot are the doors of the rooms, which are usually closed. For some doors, even a badge is required to open them. Some of the doors facing outdoors are opening and closing automatically. The seven lower decks of the platform are connected by four indoor and two outdoor staircases as well as an elevator. Some areas of the platform relevant for inspection are only reachable by stairs.



(a) Manometers (b) Thermometer (c) Digital displays



(d) Analog counters (e) Oil level (f) Valve

Fig. 3: Various instruments need to be read out to monitor the equipment on the platform.

The floors of the rooms with machinery are made of painted metal while other rooms are covered by linoleum. Some corridors and stairs are built with checker boards and gratings. Water, oil and fine dust can be expected on the ground which can thus become very slippery.

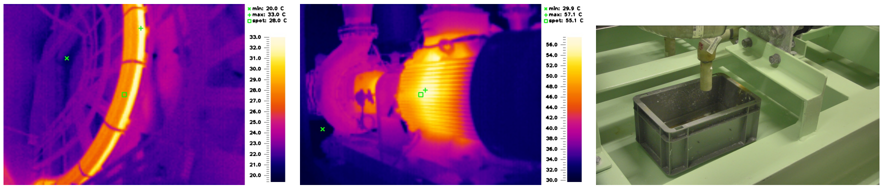
Typical room temperature is 25 °C, but some rooms are not isolated and thus could reach temperatures of 5 °C. Other rooms like the Diesel generator room can become rather hot with 35 °C to 45 °C. The rooms are air conditioned with low relative humidity in normal operation. In case of a failure of equipment, it can become high. On the top deck precipitation can be expected.

The communication between offshore and onshore is enabled by a fiber cable. For continuous monitoring or tele-operating the robot, a reliable wireless network needs to be installed. No wireless network is available in the working areas of the platform. For this reason, WiFi routers were installed for the feasibility tests.

3.2 *Robot's Mission*

Daily surveillance tours of the robot included visits of specific points of the plant. During these missions, the robot's tasks were reading instruments, checking the health of the equipment of the site, monitoring environmental changes, and detecting anomalies.

On a HVDC platform there are numerous instruments which are usually read out by technicians. Fig. 3 showcases some typical instruments like manometers, oil



(a) Cables (b) Pump (c) Fluid container

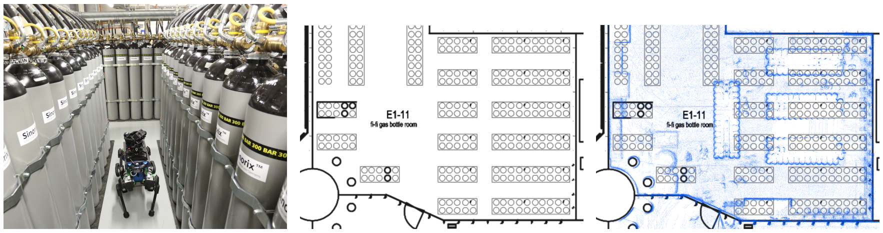
(d) Oil leakage (e) Expire date of fire extinguisher (f) Indicated label

Fig. 4: The health of the equipment is monitored by thermal imaging, visual inspection and sound assessment.

levels, valves, displays and panels. Using cameras and computer vision algorithms, the images can be processed automatically and the measured values can be reported with a confidence level indicating how good the recording and interpretation was.

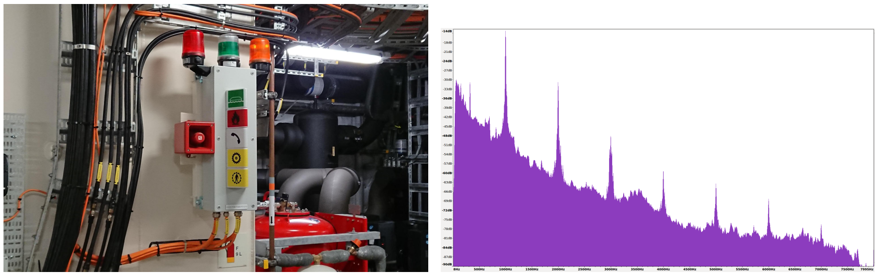
While instruments provide some information about the operational state and health of the machinery, the equipment can be further examined by the robot using thermal imaging, visual inspection and sound assessment as depicted in Fig. 4. The thermal camera allows to estimate the temperature of cable trails, pumps and electrical components. The optical camera enables screening the environment for oil leakages. Malfunctioning pumps and fans as well as gas leakages can be early detected based on sound measurements with the onboard microphone. Another typical task of the human service team is to review the expire date of the fire extinguishers (Fig. 4e). The robot can take pictures of the fire extinguisher and extract the label with the expire date and highlight it as shown in Fig. 4f. This can be done with generic visual inspection points. If the robot does not find the label or something it was trained to look at, it can inform the remote operator who can take over and have a closer look by tele-operating the robot.

While construction or maintenance work is ongoing on the platform, the environment can change. Since the robot maps the environment with its sensors for navigation, the same data can be used for visualizing these changes. The bottles in the room shown in Fig. 5a are arranged differently as illustrated in the floor plan depicted in Fig. 5b. The 3D points in blue measured by the robot's laser sensor drawn in Fig. 5c visualizes the environmental changes. The sensory information of



(a) Actual room (b) Floor plan (c) Recorded map

Fig. 5: The bottles (a) have been placed differently as indicated by the floor plan (b). The blue points recorded by the robot's laser sensor show the correct map (c).



(a) General platform alarm (b) Frequency analysis

Fig. 6: The robot can record the general platform alarm (a) with its microphone and detect the alarm according to the identified frequency peaks (b).

the robot can also be used to check if any escape routes are blocked or equipment is missing. Additionally, events and anomalies can be detected by the robot. For instance, the ambient temperature can be monitored to detect fire. With the microphone, the robot can also check if the general platform alarm shown in Fig. 6a is operational as expected by analyzing the frequency response as depicted in Fig. 6b.

4 The Robotic Inspection System

The robot system which was used during the field tests on the HVDC platform is a newer version of the quadrupedal robot ANYmal as described in [4, 3] with stronger actuators for climbing steep stairs up to 40°. The ANYmal is an electrically-driven quadrupedal robot designed as a general-purpose platform. With the size of $800 \times 600 \times 700\,\text{mm}$ in standing configuration, the weight of about $30\,\text{kg}$, and a payload capability of $10\,\text{kg}$, the robot is well suited for unmanned inspection tasks. Onboard computers provide power for complex optimization and vision tasks, and

(a) ANYmal (b) Interim Inspection Payload

Fig. 7: The robot ANYmal B300 (a) together with the prototype inspection payload (b) has been used for the field tests.

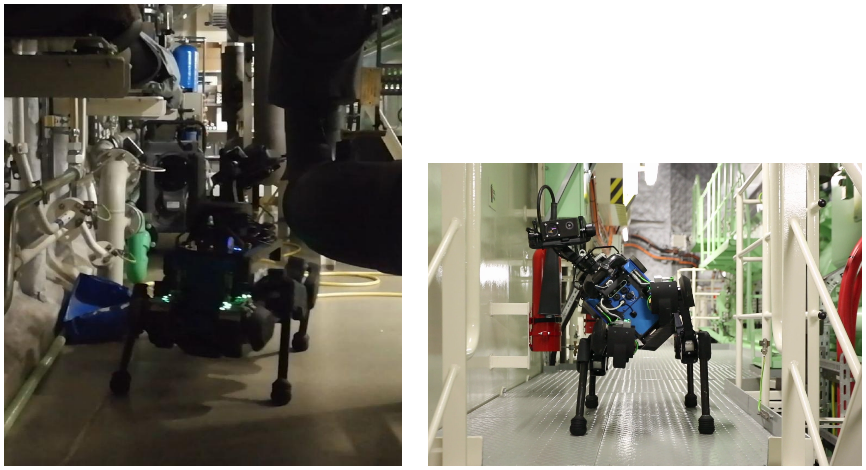
the battery ensures about 2 h to 4 h autonomous operation. The system is completely sealed against dust and water ingress (IP67).

4.1 Sensors and Actuators

Numerous sensors are mounted on the robot for navigation, inspection and diagnostics. The robot is able to post-process sensor measurements onboard. This allows the robot to operate even in areas with limited connectivity.

For inspection of the offshore site, it was carrying a prototype sensor payload for inspection as shown in Fig. 7. An actuated gimbal with a visual and thermal camera as well as a flashlight are mounted on the top of the robot. The actuated gimbal increases the workspace of the inspection sensors, because the cameras can be aligned to the inspection goals independent of the robot's posture. This allows inspection of the ceiling right above the robot. The robot features microphones for audible and ultrasonic sound recording of machineries like pumps or fans.

To navigate through the environment, the robot uses perception sensors to localize itself in the environment and to avoid obstacles. For far-field perception up to 100 m, a Velodyne Puck LIDAR sensor with 16 lasers beams creates a point cloud of the environment at 10 Hz to map the environment and localize the robot. For near-field perception up to 7 m, an assisted stereo camera, the Intel RealSense D435, records depth information around the robot. The dense information of the ground is used for accurate foothold planning and obstacle avoidance.



(a) Crawling through narrow corridors (b) Pose adaptation for inspection

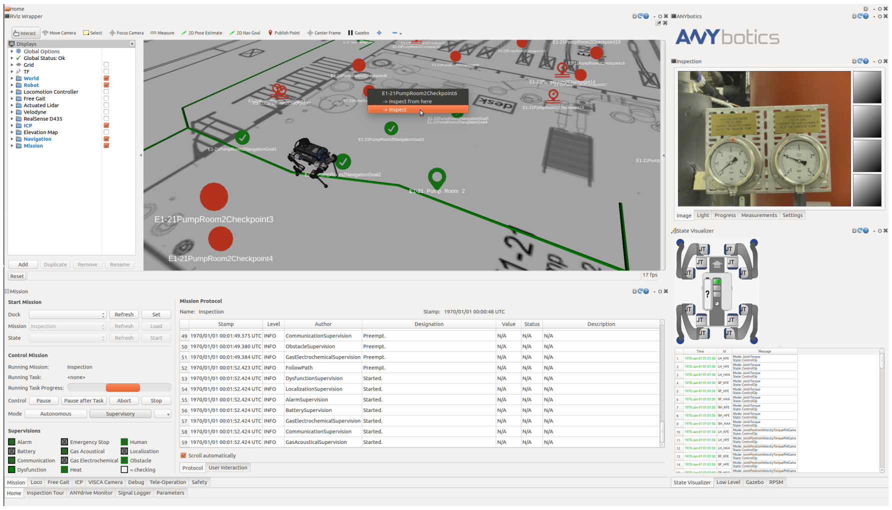
Fig. 8: ANYmal employs different gaits for locomotion and can adapt its posture for optimal inspection.

4.2 Mobility and Navigation

The robot fuses the 3D point cloud information from the LIDAR sensor and depth camera for mapping and localization. Employing an ICP-based localization method as described in [4], the robot determines its current position and orientation with respect to a previously recorded map. A pose graph is used as a map representation to roughly define where the robot can move within the 3D point cloud of the environment. The robot's pose of the navigation goals, via-points and checkpoints are stored in such a pose graph as illustrated in the user interface in Fig. 9. The poses are inter-connected with edges (green lines) to indicate that the robot can move between these poses. When a node of the pose graph is selected as a goal, the robot searches the pose graph for the shortest path from its current location to the target pose using an A* algorithm.

Knowing the path from the pose graph, the robot plans a smooth trajectory from its current position along that path. The trajectory is generated online using the robot's perception sensors such that obstacles are automatically avoided.

Depending on the terrain and speed, the robot uses different gaits for locomotion. The robot employs a trotting gait on smooth and flat terrain for fast walking up to $1.0\,\mathrm{m/s}$. In more challenging terrain, the robot makes use of a slower walking gait as depicted in Fig. 8a, which even enables crawling underneath suspended obstacles. To overcome unknown obstacles, the robot relies on its perception capabilities to safely plan its footholds and adapt its body pose [2]. If obstacles are known like steps, special maneuvers can be also pre-programmed. To inspect a checkpoint, the



Mission: Inspection

Running Mission: Inspection

Running Task: <none>

☑ Scroll automatically

Mission Protocol

Name: Inspection

Stamp: 1970/01/01 00:00:48 UTC

	Stamp	Level	Author	Designation	Value	Status	Description
49	1970/01/01 00:01:49.375 UTC	INFO	CommunicationSupervision	Preempt.	N/A	N/A	N/A
50	1970/01/01 00:01:49.380 UTC	INFO	ObstacleSupervision	Preempt.	N/A	N/A	N/A
51	1970/01/01 00:01:49.384 UTC	INFO	GasElectrochemicalSupervision	Preempt.	N/A	N/A	N/A
52	1970/01/01 00:01:52.423 UTC	INFO	FollowPath	Preempt.	N/A	N/A	N/A
53	1970/01/01 00:01:52.424 UTC	INFO	DysfunctionSupervision	Started.	N/A	N/A	N/A
54	1970/01/01 00:01:52.424 UTC	INFO	LocalizationSupervision	Started.	N/A	N/A	N/A
55	1970/01/01 00:01:52.424 UTC	INFO	AlarmSupervision	Started.	N/A	N/A	N/A
56	1970/01/01 00:01:52.424 UTC	INFO	BatterySupervision	Started.	N/A	N/A	N/A
57	1970/01/01 00:01:52.424 UTC	INFO	GasElectrochemicalSupervision	Started.	N/A	N/A	N/A
58	1970/01/01 00:01:52.424 UTC	INFO	CommunicationSupervision	Started.	N/A	N/A	N/A
59	1970/01/01 00:01:52.424 UTC	INFO	GasAcousticalSupervision	Started.	N/A	N/A	N/A

Fig. 9: The Graphical User Interface (GUI) shows the state of the robot, the measurements of the onboard sensors, and the progress of the ongoing inspection tour.

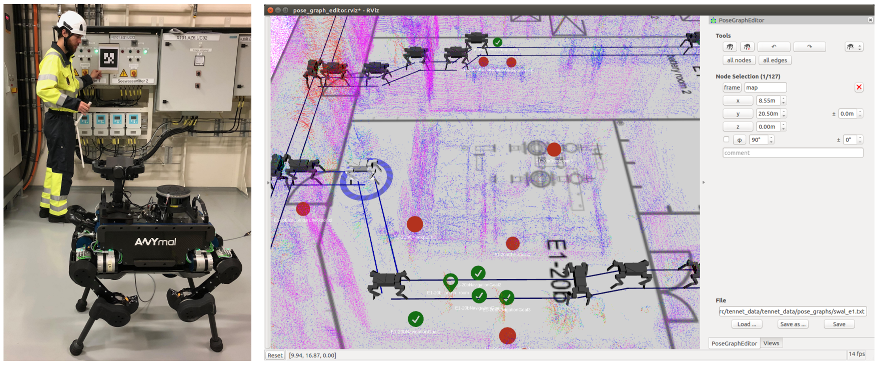
robot walks to a defined viewpoint in the 3D map and adapts its posture if required as shown in Fig. 8b.

4.3 *Robot Control and User Interface*

The operator commands the robot via WiFi link. For teleoperation, the robot is controlled by the graphical user interface (GUI) shown in Fig. 9. The GUI visualizes the robot in 3D together with the environment, planned path and inspection points. The state of the robot including the health of all sensors and actuators as well as the charge of the battery is shown on the front page. Scheduled tasks and progress of an ongoing inspection tour can be observed remotely. For deployment of the robot on a new site, a remote control is additionally provided to steer the robot.

5 Field Tests

Autonomous inspection tours similar to the ones performed by human operators have been evaluated on the offshore platform. A mission usually starts and ends on the charging station. Missions are easily programmable by a qualified operator through the graphical user interface described in Fig. 4.3. The operator can access the status of the system and the progress of the mission at any time and automati-



(a) Checkpoint Recording (b) Mission Editor

Fig. 10: The location of an inspection point (a) is recorded by holding an AR tag next to the point of interest. After recording the checkpoints, the path of the robot can be adapted in a GUI (b).

cally receives a post-mission report as soon as the mission is completed. The report includes information about state of the system, locomotion, localization, navigation, inspection, and unexpected events. During an autonomous mission, the operator is able to take direct remote control of the robot at any time. This enables the operator to control the robot in difficult situations or send it to any point on the map to have a closer look at its environment.

To conduct any field tests on the offshore platform, the field engineers needed to successfully pass a safety training. After installation of the WiFi network and charging system on the platform, functional tests of the robot's localization and navigation system were conducted before the robot was sent on fully autonomous missions. The deployment of the system in a new environment required the following steps: First, the robot is manually steered through the environment using a remote control. While scanning the environment with the LIDAR sensor and depth camera, the robot automatically builds a 3D map of its environment. The recorded point cloud is then stored on the robot and can be inspected by the operator in the GUI. In a second round, the robot is steered to the points of interest. The operator holds an AR tag next to the checkpoint as shown in Fig. 10a. The location of the robot together with the location of the checkpoint is computed automatically as the robot knows its location with respect to the previously recorded map, and the pattern of the AR tag provides 3D pose information of the checkpoint relative to the onboard camera of the robot. The operator defines the type of checkpoint and programs its characteristics such as pressure range for a manometer or maximum temperature of a hot spot. For navigation, the checkpoints and via-points are defined in the pose graph. An editor is available to modify and adapt the path of the robot in 3D for the mission as shown in Fig. 10b. The robot's reactions to unexpected events such as communication loss are programmed in a next step. The robot, for instance, waits for further instructions from the operator when it found an unknown obstacle or goes back to

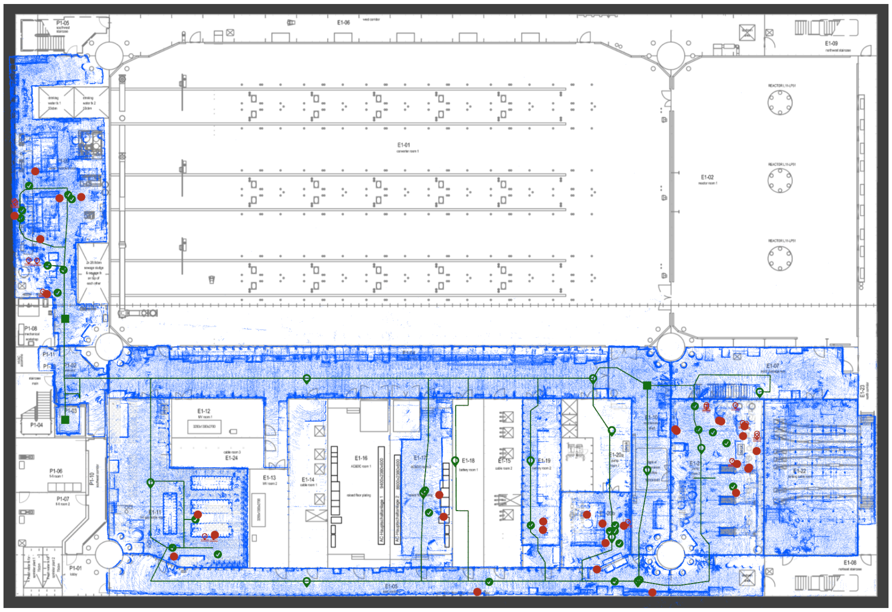


Fig. 11: The path (green) and inspection points (red) of the autonomous inspection mission is shown on the floor plan with the overlayed recorded map of the robot's sensors (blue dots).

the starting point when communication is lost. A physical simulation of the robot is provided to thoroughly test navigation and inspection before deploying it on the real system. Errors made by the operator such as unconnected locations can be simply found before costly experiments are conducted. Once the mission is configured and tested in simulation, tests on the actual site are made to check the reliability of navigation and inspection.

6 Results of the Feasibility Study

During the field tests of two weeks, ANYmal was executing more than 30 autonomous missions. The robot's path and the 19 points of interest of one of the autonomous missions is illustrated on the floor plan in Fig. 11. The inspection tour took about 25 min including 6 min for inspection on average.

The coverage of points of interest by ANYmal has been analyzed in a pump room, water treatment room, and HVA/C room. 385 instruments like manometers, thermometers, valves, displays, panels, flow meters, pump sound and pneumatic lubricators have been evaluated in these rooms. While 92% and 85% of the points of interest can be successfully inspected in the pump and water treatment room,


(a) Inspection in the darkness (b) Inspection with and without flashlight

Fig. 12: In case the lights are off as in (a), the robot can use its onboard flash light for inspection. The onboard flashlight also improves the inspection when the lights are switched on (b).

respectively, 54% can be scanned by the robot in HVA/C room. Many valves in the HVA/C room are very difficult to see because they are hidden and facing the wall.

The rooms with installed equipment typically have no windows and thus no natural light. However, all rooms of the platform are illuminated by lamps. By default, about one third of the lamps are always switched on for emergency situations. The remaining lamps can be switched on by pushing a toggle switch which could be used by the robot with additional manipulation skills. Fig. 12a shows the robot inspecting a room in complete darkness with its onboard flashlight. Tests showed that the onboard light can improve visual inspection as shownin Fig. 12b. While the illumination is usually good enough for visual inspection if all lamps are on, the noise level of images becomes critical when the emergency light is only available. In conclusion, an onboard flashlight is recommended for inspection.

In addition to the visual inspection tasks, acoustic and thermal inspection was successfully tested. The alarm for emergency situations of the siren shown in Fig. 6a was successfully identified by the robot's microphone and onboard frequency analysis. Thermal images of cables and pumps as depicted in Fig. 4a were automatically recorded by the robot during its inspection tours.

7 Conclusion

The presented study addressed the feasibility of using a legged robot for automated and unmanned inspection tasks on the offshore platform. The mobility and inspection skills of the robot ANYmal were demonstrated on a HVDC converter station. For illustration, we collected a video summary of the field tests[1]. In conclusion, the quadrupedal robot ANYmal is well suited for autonomous inspection of a HVDC platform. The robot can overcome various obstacles with its legs, pass through nar-

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[1] `https://youtu.be/DzTvIPrt0DY`

row passages due to its slim design, and can observe the environment from a visual, thermal, auditory, and geometrical perspective. The only major impediment to solve is how to open and pass doors. Due to safety considerations regarding fire, not all doors could be automated in both directions. Apart from opening doors, the robot could also use a manipulator to push buttons, toggle switches and fuses, and turn valves. Integrating the inspection sensors in a robotic arm would further increase the coverage of points of interest for inspection.

While human operators inspect the platform monthly, the robot can survey it more often, even daily, in the future. To make this happen, the integration of the robot's software into the existing control system of the platform and the long-distance communication need to be addressed in the future.

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