Two Pilot Experiments on the Feasibility of Telerobotic Inspection of Offshore Wind Turbines

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***Abstract*—With cyber-physical systems, it is not necessary to be physically present at a location to perform work there. Inspection of offshore wind farms is a task that would be beneficial to do remotely, due to the time and high cost required for accessing the turbines for manned inspections. Such remote inspections must be equally effective at finding errors in the turbines, since errors that aren't found can cause expensive failures. This paper describes a remote inspection robot prototype, and how it was used to compare participants' ability to identify errors using remote and manned inspections in two experiments. The results demonstrated that errors with both known and unknown symptoms were successfully identified using remote inspections, although not as effectively as manned. This is considered promising for remote inspections, and what we have learned in these experiments is used in the planning of a larger experiment, and in the development of an improved prototype.**

***Index Terms*—Robotic inspection, Human-robot interaction, Wind energy, Cyber-physical systems**

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I. INTRODUCTION

There are many challenges for installing and operating wind turbines in offshore areas, causing problems for the ambitious plans for offshore wind. Especially operation and maintenance is difficult, as access is expensive and unpredictable. There are limited operational data available from offshore wind turbines, but it has been estimated that between 25% and 30% of the total energy cost of offshore wind energy will be from operation and maintenance (O&M), compared to only 10% to 15% on land [1].

Operation of wind turbines on land typically relies on information from manned inspections for planning maintenance. This is possible because of the relatively easy and inexpensive access, while frequent manned inspections of offshore wind turbines would be prohibitively expensive. Offshore wind turbines are located in areas with high average wind speeds for maximum energy production. Since the turbines are inaccessible when the wind speeds and wave heights exceeds a certain threshold, there can often be long periods where manned inspections, and maintenance operations, are impossible to be performed.

In this paper we investigate whether remote inspections with a cyber-physical system is a feasible alternative to manned inspections. A remotely controlled robot, or telerobot, can be equipped with sensors for inspecting the equipment inside the turbine. The use of robotics for inspections has typically been to bring an expensive robot to the site and have it access an area that are impossible or dangerous for humans to access, e.g. inside generators [2] and for examining the blades of wind turbines [3].

The main motivation for using remote inspection for offshore wind turbines is to reduce the need to visit the turbine, thus it would be counterproductive to bring the robot to and between turbines. One or more robots should be permanently installed inside the nacelle of each wind turbine. This is the room where all the equipment used for electricity production and auxiliary systems are located, thus most failures that can be detected during inspections originate from here. Since each turbine requires its own robot, the cost of the robot must be low for it to be economically viable for the low margin wind energy industry. The robot must also be able to operate unattended for long periods, so it should be highly reliable.

Before robotics can be introduced on an offshore wind farm or similar, the concept should be evaluated in a laboratory environment. Two experiments have been performed with a remote inspection robot prototype as the first part of such an evaluation. The purpose of these was to determine whether remote inspection is feasible as an alternative to manned.

II. EQUIPMENT

A. The Robot Prototype

A robot system that is permanently installed in a wind turbine must be low cost and highly reliable, thus we want to build it as simple as possible. A prototype of such a robot for laboratory testing has been designed and built at our department (figure 1). It moves on a rail, because we consider this advantageous when doing inspection tasks in an enclosed area, like a wind turbine nacelle, which are packed with equipment. It is a simple way to get the robot up from the floor, and closer to the equipment that is being inspected. A freely moving robot would need to climb to achieve the same, which increases the cost and complexity, while the reliability will be reduced. Because the robot grips to the rail, similarly as a roller coaster, it can't fall off the rail and cause damage to itself or nearby equipment. This is considered an important safety feature. The rail also makes it easy to know the robot's position and the robot can be powered through the rail, both simplifying the robot and reduce its cost.

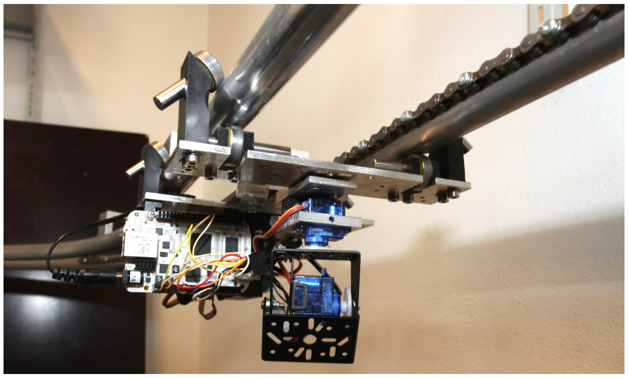

Fig. 1. The robot prototype (without camera attached).

The prototype is equipped with a 1080p USB camera from Creative, on a pan and tilt mechanism. It faces forward by default, and can turn approximately 90 degrees to each side as well as up and down. Since this is the only sensor available on the prototype, the evaluation will be limited to visual inspection. Other sensors will be added in future versions of the robot, including thermographic camera, microphone, temperature and vibration sensors. Especially theromigraphic cameras are expected to be useful for inspections of actual wind turbines, as it is a common tool during manned inspections.

The robot is controlled by a Beaglebone development card, with an ARM processor. It uses an Angstrom Linux distribution, which is intended for embedded applications. With many GPIO and PWM pins, the Beaglebone can connect to the motor encoder, the motor driver and the servo motors controlling the pan and tilt, with only a few additional passive electronic components. The control system is implemented in C, and communicates with a client using UDP. The camera video is streamed to the client using a small open source program called mjpg-streamer.

The robot is controlled from a desktop computer using a keyboard, mouse or a gamepad. The gamepad is considered the best control interface, and was used in the experiments. The user interface is a Java application running on a 24-inch monitor with a 1920x1200 resolution. As seen in figure 2, the interface is a typical telerobot control interface, with a large video display and a control panel on the side. Since it can be difficult for the user to be aware of the direction the camera faces, this was indicated on the screen as green lines overlaid on the video stream [4].

An inspection robot would be used by personnel with experience from inspections, who will not necessarily have expertise in controlling robots. Thus, it is important that the robot is easy to use and suitable for doing inspections, i.e. high usability [5]. One of the goals of the experiments is to improve the usability of the robot and the control interface through user centered design [6].

B. The Laboratory

To evaluate inspections, there must be something to inspect. For this purpose, we have created a laboratory environment [7], shown in figure 3. It is intended to be a mock-up of visually similar equipment as one might find in an industrial system that can be observed during inspections. However, it is not considered a replication of a wind turbine. Around this equipment, a rail for the remote inspection prototype is installed. It consists of an upper part, lower part and a transition between these. Only the larger upper part is used during the experiments.

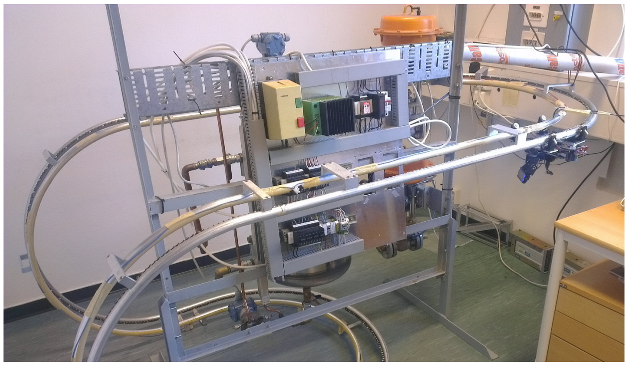

Fig. 3. The laboratory environment

The purpose of inspections is usually to identify wear, damage and other problems before they cause more serious failures. We divide these problems into two groups; errors that can be identified by recognizing known symptoms or patterns, and errors that have unexpected symptoms or symptoms unknown to the inspector.

To evaluate the participant's ability to find errors with known symptoms, a number of paper clips were positioned in the laboratory before each of the inspections. Paper clips were used since they are easily recognizable, but small enough to be hard to find. They are also easy to attach to most objects. The number of paper clips that were found during an inspection was used as a measure for the effectiveness for finding errors with known symptoms.

Evaluation of the ability to find errors with unknown symptoms is more complicated. We have defined eight error makers that represent wear, damage or other errors in the equipment, based on information from actual inspection procedures and interviews with maintenance personnel. Each of these was unique, as finding one should not give an advantage when looking for the others. The markers were designed to be

Fig. 2. The user interface

recognizable as error conditions for the untrained participants in our experiments, but were not intended to represent authentic errors. Even though actual errors often would be more subtle and difficult to identify, we consider untrained participants' ability to identify our error markers to be a reasonable approximation to trained inspectors' ability to find actual errors. Thus the number of error markers that were found was used as a measure of the effectiveness for finding errors with unknown symptoms.

Two groups (A and B) of errors were created, with four paper clip locations and four error markers in each group. They were divided with the intention that the two groups should have various types of errors at various locations, but that the combined difficulty of each group should be as similar as possible.

III. METHODS

A. First Experiment

There were four participants in the experiment, three PhD-students and one post.doc. recruited from the Department of Engineering Cybernetics were the experiment took place. None of the participants have been involved in the development of the robot and the laboratory, or used the robot before. The participants were first given 2 minutes to look and familiarize themselves with the equipment without any visible error markers. Personnel doing inspections is expected to know the original condition of the equipment. This was performed without using the robot.

Before the inspections, the participants were told that they had two tasks. The primary task was to look for signs of wear, damage or other conditions that would require maintenance. The secondary task was to look for paper clips that were hidden in the laboratory. Each participants performed two inspections, one manned and one remote. For manned inspections the participants could move freely in the room with the equipment to look for error markers and paper clips. With remote inspections the same task was performed by controlling the robot from an adjoining room. Both inspections lasted four minutes.

For each inspection the paper clips and error markers from one of the two groups were shown. Two participants had group A during their remote inspection while the other two had that group during their manned inspections. The participants did not know how many items they were supposed to find. Two of the participants performed manned inspection first, and the other did remote first, so the learning effect would skew the results as little as possible.

If there was a technical problem with the robot during remote inspections, the system would be restarted and the inspection continued with an additional 10 second time to compensate for the loss of concentration.

After both inspections were performed, the participants were given the opportunity to comment on the experience and suggest improvements in a short informal interview.

B. *Second Experiment*

The second experiment was performed with four new participants, three master students and one PhD student. As in the first experiment, all were from the department were the experiment took place, but none of them had been involved in the development of the robot and the laboratory, or used the robot before. This experiment was performed as the first one, except:

- Before inspecting, each participant were given 2 minutes to look at the equipment both with and without the robot, instead of just without the robot.
- Only the primary task of searching for error markers was given to the participants, the secondary task of finding paper-clips was not used.

IV. RESULTS

The results, sorted for remote and manned inspections, are shown in figure 4. There is a significant difference between the number of found error markers in the first experiment ($t = -2.45$, $df = 6$, $p < 0.05$), but not for paper clips in the first experiment ($t = -1.94$, $df = 3.5$, $p = 0.074$) or error markers in the second ($t = -0.655$, $df = 5.9$, $p = 0.27$).

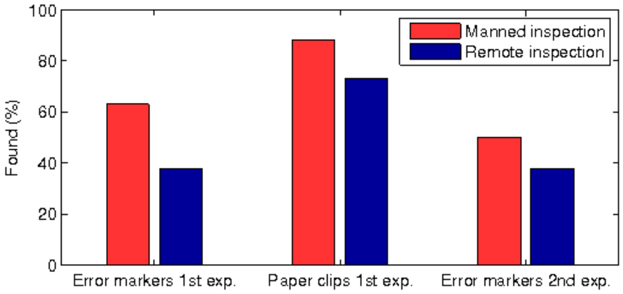

Fig. 4. Results comparing remote and manned inspections

V. DISCUSSION

A. *Discussion of the Experiments*

Due to the low number of participants, the results can only be considered preliminary and not conclusive. But there is a trend, especially in the first experiment that remote inspection with our early prototype was less effective than manned. The participants of the first experiment complained that they would have performed better if they were allowed to test the robot before starting the inspection. It was observed that they wasted time in the start of the inspections to learn how to control the robot. Some of the reason for the low effectiveness of remote inspection in the first experiment can be attributed to this.

When the participants were able to test the robot beforehand, there was a smaller difference in the number or error markers. This is also realistic, as the operator of such a system would have, at least, basic training in its use.

The results demonstrate that the error markers were of suitable difficulty. All markers were identified by at least one participant, while none were found by all. The comments by the participants, both during and after the inspections, indicated that the error markers represented unknown symptoms the participants did not expect. While when the markers were noticed, the participants did understand that they were indications of errors. Thus we consider them to be suitable replacements for real errors in this application. Real errors might be more subtle in their nature and more difficult to identify, but the personnel doing real inspections would also be more experienced than the participants in these experiments.

The task of looking for paper-clips where removed from the second experiment because it was observed that some participants prioritized finding paper clips and ignored the errors with unknown symptoms. A likely reason for this was that the participants found the task of looking for unknown symptoms frustrating, and it was easier to focus on the more clearly defined paper clip task. In the second experiment, it was observed that when getting frustrated, the participants tended to give up. This is not the effect we intended to accomplish by removing the paper-clips, thus we advise keeping the paper-clips in future experiments. If nothing else, the paper-clip task keeps the participants from giving up.

B. *Usability Issues*

Based on the results from these experiments and comments from the participants, we have identified the following usability issues in our prototype:

- The camera could only be turned approximately 180 degrees, which limited its use.
- The robot movement are controlled by moving the left joystick forward or backward. When the camera looked to the side, this forward and backward movement of the joystick would create a sideways motion from the user's perspective, which was reported to be confusing.
- The map and controls on the side of the user interface use a large portion of the screen size, which instead could be used to show a larger video display.

VI. CONCLUSIONS

Inspection of offshore wind turbines performed remotely with a cyber-physical system can be less expensive and more predictable than traditional manned inspections. There is a large potential economic benefit of this, especially because of the high cost of transportation offshore. The experiment presented in this paper is the first of a series of planned experiments for determining how effective remote inspection, using an inexpensive telerobot, can be compared to manned inspections.

The laboratory used for the two experiments is not a realistic representation of an offshore wind turbine, but the inspection task given to the participants is considered to be an adequately realistic inspection task. Although the results show that remote inspection is less effective than manned inspections, we consider the results promising for inexpensive remote inspection of offshore wind turbines. The comments from the participants will inspire improvements in the prototype that will be evaluated again in a new and larger experiment currently being designed. The larger number of participants will give results of higher precision, so the difference in effectiveness between the methods, if any, can be determined with more confidence.

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