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The Capabilities and Effectiveness of Remote Inspection of Wind Turbines

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Abstract

This paper evaluates the effectiveness of remote inspections of wind turbines. The first part of the paper presents a usability test where remote inspections with a robot prototype have been directly compared to manned inspections. The experiment had 31 participants that did inspections with and without the robot in a laboratory environment. As expected, it was challenging to remotely operate the robot, and the remote inspections did not perform as well as the manned. However, the difference was not very large and some possible improvements were identified. Concerns with remote inspections of wind turbines that were not addressed by the experiment is discussed in the last part of this paper. These will be evaluated in upcoming field trials.

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1. Introduction

Over the last years a large number of offshore wind turbines have been installed or planned. Advantages for offshore wind turbines are the large available areas with favorable wind conditions that are far from population. Unfortunately, offshore wind energy is significantly more expensive than onshore wind energy [1], due to large additional costs for installation, infrastructure and maintenance. A reduction in the cost of energy is necessary for making offshore wind less dependent on subsidies and a viable alternative in the future.

Maintenance is estimated to contribute to typically 20-25% [2] of the total cost of energy from offshore wind turbines, which is significantly more than onshore. One challenge is that the maintenance of wind turbines is dependent on several visits to each turbine every year, each with at least two technicians for safety reasons. The transfer to and from the turbine can be difficult and dangerous, even with advanced access systems. The turbines are often considered

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inaccessible when there are more than 2.5 m of significant wave height, which for parts of the North Sea will be as much as half of the days in a year [3]. In the winter access can be impossible for long periods. A failure could therefore result in a long downtime while the wind conditions are favorable for energy production.

This paper considers remote inspections of wind turbines, which is an alternative to the manned inspections that are performed today. A robot installed inside the turbine nacelle can be used to do inspections on behalf of a technician on land. The robot can be equipped with sensors similar to human senses, e.g. camera and microphones, thus it can gather similar information as a technician on site would be able to. It is not intended to be an autonomous system or an alternative to condition monitoring, but instead a tool for technicians to employ their experience without having to access the turbine, i.e. at a low cost and regardless of the weather conditions. A robust economic benefit for remote inspections [4] was found using the NOWIcob cost-benefit simulation tool [5].

Section 2 describes a usability experiment performed to compare remote and manned inspections. Section 3 discusses the capabilities of remote inspection in a realistic setting and how this can be evaluated in field trials.

2. Experimental comparison of remote and manned inspections

Usability testing [6] is a method for evaluating participants' ability to use a system, as a remotely controlled robot, to solve relevant tasks. The experiment presented here is the last of a series of such usability tests that has been performed to evaluate whether remote inspections with a low-cost system could perform as well as manned inspections. Compared to the previous experiment [7], the number of participants has been increased to 31 and the prototype used in the experiment has been improved.

2.1. Laboratory for comparing remote and manned inspections

To evaluate inspections, there must be something to inspect. For this purpose, we have built a laboratory, shown in Fig. 1b. It is a mock-up of an offshore wind turbine nacelle, with visually similar equipment that is intended to be used to compare the probability that an error is found with remote and manned inspections. In the laboratory this can be evaluated with a large number of participants and with full control over the equipment. The experiments performed in the laboratory should be followed up by tests in a wind turbine, as some aspects of the evaluation would require a more realistic environment.

The purpose of the laboratory is to measure the participants' ability to detect targets that represent errors or problems with the equipment. This is measured as the ratio of the targets that are found during an inspection, i.e. the detection rate, which can be seen as an indicator of the effectiveness of the inspection method. 12 error markers and 16 paper clip locations were defined for the experiment. The error markers mimic actual errors found in industrial equipment, and the participants did not know what these looked like prior to the inspections. They were

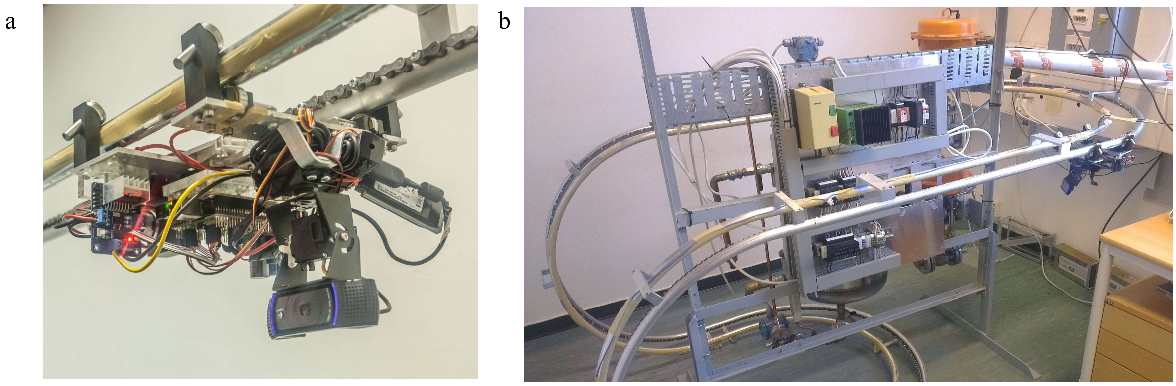

Fig. 1. (a) robot prototype; (b) prototype in laboratory

designed to be as realistic as possible, but they also had to be possible for the inexperienced participants to identify and feasible to add and remove to the laboratory between inspections. The paper clips represented errors with known symptoms of failures. Four groups, named A to D were defined, with 3 error markers and 4 paper clips in each. The groups were designed to have similar combined difficulty based on experience from earlier experiments where some of the same targets were used.

2.2. Prototype for laboratory evaluation

A robot prototype (Fig. 1a) was developed for the laboratory evaluation. It has not been built to be sturdy and reliable enough to be used in a turbine, but it has an intentionally simple design so future implementations can be highly reliable at a low cost. The robot's onboard computer is an ARM based Beaglebone development board. It runs Ubuntu Linux, with Xenomai real-time patches. While future systems are intended to have several sensors for inspection, the prototype only has a 1080p web-camera on a pan and tilt mechanism for visual inspections.

The prototype moves on a rail, because we consider this advantageous when doing inspection tasks in a known, enclosed area, such as a wind turbine nacelle. It is a simple way to get the robot up from the floor, and close to the equipment that is being inspected. A freely moving robot would need to climb to achieve the same, which would increase the cost and complexity, and likely reduce the reliability. A rail solution also have advantages as powering the robot through the rail, accurate positioning and that the robot can be attached to the rail to prevent it from falling and cause damage to itself or other equipment.

The user interface is a Java application running on a desktop computer, and is shown in Fig. 2. It connects to the robot as a client, and use a 1920x1200 resolution 24-inch monitor. The client has been developed with a user centered design process [8] consisting of several usability tests. The video from the camera is shown in full screen [9][10], as this is considered the most important information for the operator during inspections.

A Samsung Galaxy 10.1 tablet was used as a touch screen control interface for the robot. A touch screen interface was used because it is highly customizable for the developers, and since most people today are using touch interfaces on smart phones or tablets on a daily basis. The robot is moved between pre-defined positions in the laboratory, with a common touch gesture called *swipe*. This control scheme is considered to be a higher level of autonomy than the direct teleoperated control used in the previous experiment [7]. Even if the control of our robot

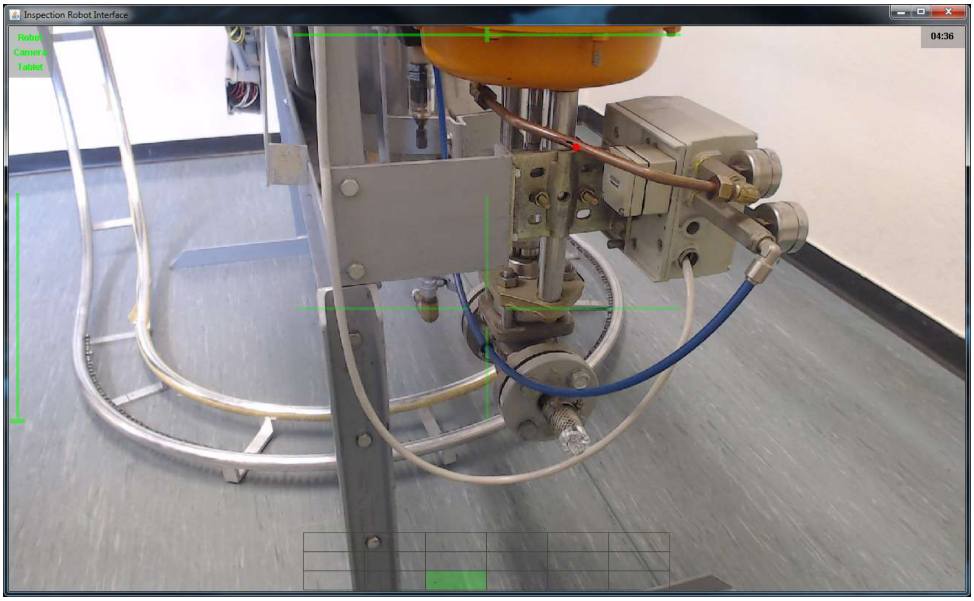

Fig. 2 user interface, with an identified error marker indicated with a red dot

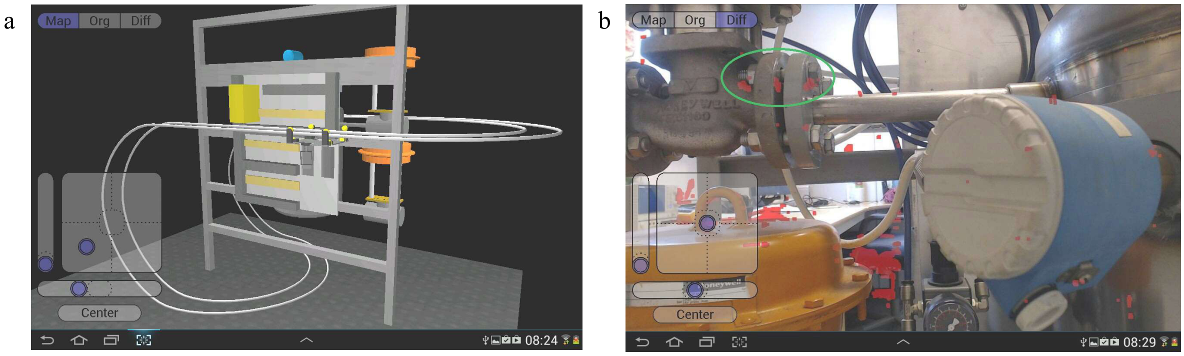

Fig. 3 (a) “map view” on tablet; (b) “difference view” on tablet, with differences between historical and current image highlighted in red.

is simpler than for many other robots, as it moves on a rail, the same benefits from higher autonomy are expected. These are typically reduced workload, better effectiveness and that the users find the system easier to use [11][12].

The pre-defined positions for the experiment were set up using a simple grid of the laboratory, without concern for where the targets were located. In a real application, these would instead be defined based on the location of equipment that should be observed during inspections. Since the robot will visit the same positions during each inspection, it is easy to store historical information. This can be used in future inspections to study how the equipment has evolved over time. The interface also allows the user to manually control the robot around the pre-defined positions with the controls on the left side of the tablet screen.

In addition to being a control interface, the tablet was also used as a *secondary* screen, where additional context dependent information could be displayed to the user. This is similar to concepts in modern game consoles, as the touch screen on Nintendo Wii U and the SmartGlass smart phone application that can interact with the Microsoft Xbox consoles. Three different views could be shown on the tablet. The first was a map view of the robot's environment shown in Fig. 3a. The second shows a historical image from the robot’s location. In the experiment, images from when no targets were visible were used. In a real setting the user would be able to browse between images from different points in time. The third view is shown in Fig. 3b. It is the same as the second, with the addition of an image analysis algorithm that highlight the difference between the historical and current image.

2.3. Methods

The experiment was performed at the Norwegian University of Science and Technology over a 2-week period. 31 engineering students participated in the experiment. One of the participants had previously worked with inspection of equipment similar to what was used in our laboratory. The rest of the participants did not have any experience with inspections. 12 randomly selected participants received a gift certificate from an electronic store after the experiment had completed.

Each participant performed four inspections, two manned and two remote, following a within-subjects design. The participants were given 3 minutes for the manned inspections, which had been observed to be a suitable amount of time to investigate the whole laboratory in the previous experiments. The remote inspections were expected to take longer to perform, and the participants were given 5 minutes for these. For each of the inspections, one of the four groups of targets was present in the laboratory. All participants performed one inspection with each of the groups, but in different order. To counterbalance any learning effect, half of the participants did inspection 1 and 3 remotely, and the others did 2 and 4. Each participant used approximately 45 minutes in total.

A pre-written script was read to the participants with information about the experiment. The error markers were described to the participants as unknown symptoms that should be obvious when noticed. They were told to look for symptoms like wear, damage or missing components. Next, the participants completed a survey with background information and confirmed that they participated willingly and were properly informed. The participants were then given the opportunity to investigate the laboratory without any visible targets and to test the robot, before starting on the four inspections.

The detection rates for both the error markers and the paper clips were measured for each participant. In addition to these measurements, a NASA-TLX survey [13] was given to the participants after each inspection. This is a subjective evaluation of operator workload, which consists of rating six different aspects of workload on a scale from 0 to 100. A high value correspond to a high workload, which is considered negative.

2.4. Results

The presented results are based on 30 participants doing 4 inspections each, a total of 120 inspections. The results of one of the 31 participants were not used due to technical problems with the robot prototype that significantly impaired both of his remote inspections. The detection rates for the different inspection methods are shown in Fig. 4a, and the results from the NASA-TLX survey are shown in Fig. 4b. The error bars in the graphs represent 95% confidence intervals. A summary of paired t-tests comparing each of the remote inspections for each participant with the corresponding manned inspection is shown in Table 1.

The time each participant spent waiting for the robot to move and adjust the camera was estimated. It was on average 72 seconds with a 5.5 seconds 95% confidence interval. This estimate is based on the number of moves each participant did with the robot, and the measured average duration of these.

For each remote inspection it was registered which of the pre-defined locations that was visited. On average 90% of the 18 locations were visited during an inspection. Only 42% of the participants had time to visit all 18, and 62% visited 17 or 18. The estimate in Fig. 4a was found by calculating the detection rate for the remote inspections of each participant, when only considering the targets that were visible from the observation points that had been visited.

Table 1 Summary of paired t-tests (mean difference calculated as $\mu_{MANNED} - \mu_{REMOTE}$)

Measurement	Mean diff.	Standard dev.	T-test	P-value	Significance
Error markers	6.7%	40%	t(59) = 1.286	.203	No
Paper clips	10%	32%	t(58) = 2.451	.017	Yes
Mental workload	-6.5	19	t(59) = -2.601	.012	Yes
Physical workload	30	25	t(59) = 9.177	<.001	Yes
Temporal workload	-8.6	19	t(59) = 3.467	.001	Yes
Performance	-3.9	21	t(59) = -1.405	.165	No
Effort	0.1	17	t(59) = -0.039	.969	No
Frustration	3.0	21	t(59) = 1.086	.282	No

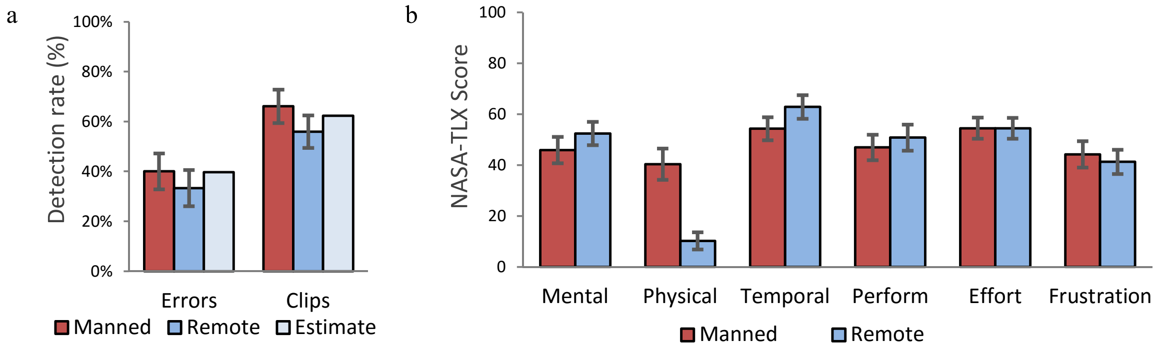

Fig. 4. (a) results for found targets; (b) NASA-TLX results

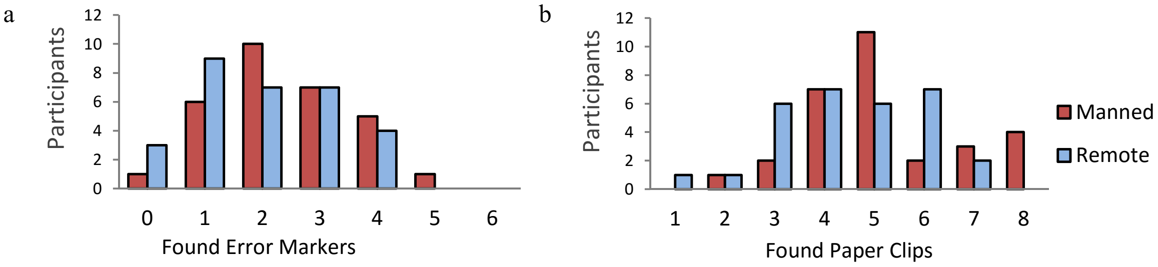

Fig. 5 Participants sorted on number of found error markers (a) and paper clips (b)

Alternatively the participants can be shown by sorting the number of targets they found, as shown in Fig. 5.

2.5. Discussion

It is considered more difficult to do a task remotely than in person, which is also suggested by the results in this experiment. However, the differences between the effectiveness of the inspections methods are small enough for remote inspections to be considered as a promising alternative, especially with further improvements to the system.

A large number of participants ran out of time before they were able to complete their remote inspections. This could be seen from the participants' comments, the high temporal workload ratings, and since less than half of the participants were able to visit all the possible positions within the given time. In a real setting, it is unlikely that inspections would have been aborted before all of the equipment had been inspected properly. The estimate presented in Fig. 4a is an extrapolation of how each participant performed in the part of the laboratory he had time to inspect. It suggests that if enough time had been available to complete the remote inspections properly, there would be little or no difference between the two inspection methods. Unfortunately, the reliability of this estimate is unknown.

It is challenging to have a *fair* comparison between manned and remote inspections with respect to the time available for each inspection. It is acceptable for remote inspections to take longer, because in the real world the planning and logistics of manned inspection will require a significant overhead time. This makes a comparison with the same amount of time irrelevant, but at the same time it introduces possible confounding factors to allow for longer time for the remote inspections. The chosen solution in this experiment was that the remote inspections were 120 seconds longer, but since the robot was busy moving for some of the time, the effective inspection time was only 48 seconds longer than for manned, which is negligible compared to the large expected overhead of manned inspections. One could argue that the additional time for remote inspection should have been significantly longer due to this overhead, and since it was so common to not have time to complete the inspections. In retrospect, it would perhaps have been better to not limit the available time, but instead let the participants continue until they thought they were finished, and then measure the time use. However, this would have made it more difficult to schedule and perform the experiment.

The improvements in the robot control since the previous experiment made controlling the robot easier. Unfortunately, none of the participants had time enough to properly test the interface for manual control. It was observed that the robot control method allowed the participants to browse systematically through the laboratory, which was the intention. This systematic approach should be beneficial for the inspections, and are easy to combine with inspection checklists etc. However, several participants had a very thorough approach, and spent a large amount of time at each location. This usually resulted in very good results for the visited locations, but unfortunately this was a time consuming process and it was usually not enough time to do this for all locations.

Even if it is acceptable that remote inspections take longer, it should be a prioritization to improve the remote inspection system on this point. Some limitations of the camera properties were observed, especially with the ability to differentiate between similar colors, as indicated by one error marker that was never identified during the remote inspections. The most likely reason for this was that it was almost impossible to notice this error on the images from the camera.

Table 2. Possible inspection methods

Method	Sensor	Description	Examples of identifiable symptoms
Visual	Normal Camera	The use of a normal camera to get images and video to the technician, which will be similar to what he would see if he was on site. Stereoscopic cameras for 3D are an option for increased realism.	• Visible wear and tear • Visible cracks and fissures • Spills • Cable problems (loose, damage to isolation, etc.)
Thermographic	Thermographic camera	Thermographic cameras create images that describe the surface temperature of the objects in the image. It is useful for detecting hot spots, and can replace a large number of temperature sensors by instead having one mobile camera.	• Mechanical problems that generate heat • Insufficient cooling or lubrication • Electrical short circuits or overloads that generate heat
Vibration	Vibration sensors	Vibration sensors are important for condition monitoring of rotating machinery, which consist of vibration sensors embedded in the equipment. For remote inspection it is possible to have vibration sensors that can be located at different locations depending on demand. Vibration measurements are often analyzed in the frequency domain.	• Dents or fractures in bearings • Damage and wear in gearbox • Rotor imbalance
Audible	Microphone	Equipment with moveable parts will often change their sound depending on their condition. Vibrations also manifests as sound, thus audio analysis can be used similarly as vibration analysis.	• Same as vibration • Changes in sound from motors

3. Evaluation of the capabilities of remote inspection

The experiment presented in section 2 evaluates how effective remote inspection is compared to the alternative of manned inspections, meaning how likely a person is to correctly identify an error in the turbine during an inspection. However, the experiment did lack in realism and there are concerns that it was not able nor intended to address. These concerns are discussed here, and will be evaluated in upcoming field trials, where the functionality and reliability of an improved prototype can be evaluated in a realistic environment.

3.1. Inspection methods

The experiment only evaluated one method of inspection, namely *visual inspection* with a camera. There are however other possible methods for doing remote inspections, each relying on a different type of sensor. The ones that are considered most important are described in Table 2.

All the inspection methods, except for visual, were not part of the experiment mainly because it would have been difficult to replicate the heat, sound and vibration necessary in the laboratory. Field trials in an actual wind turbine in operation are therefore necessary to evaluate these.

3.2. Ability to identify realistic errors with remote inspection

A potential problem for remote inspections of wind turbines is that errors that are identifiable during manned inspections for some reason are impossible or difficult to identify remotely. There can be several reasons for this, one being that it is difficult or impossible for the robot to move to a position with a good view. This means that if a rail is used for moving the robot, it is important that it is configured to allow the robot to access all the important locations of the nacelle. This can be a challenge since the interior of the nacelles vary with the turbine models. It is, however, common that most or all turbines in a wind farm have the same type of turbine.

It is also possible that the error is not detectable with the sensors on the robot. An example of this was encountered in the experiment, where one of the error markers was very difficult to detect with the camera that was used. In a field test the sensors will be tested in a realistic environment, thus it will be possible to evaluate the quality of the sensors and whether they are able to observe what was intended. Sensor information can also be stored, thus it is possible to replay it to experts after the fact for further analysis.

There are however problems with field tests. Even if failures are a large concern with wind turbines, they are still rare enough that it is difficult to measure the ability to predict them. This problem was encountered in the CleverFarm project [14], where condition monitoring systems were installed in three turbines for three-and-a-half years without any failures of these turbines, thus it was not possible to determine whether the condition monitoring would be able to predict a failure. Similarly it will be difficult to evaluate remote inspection's ability to predict actual failures if they are unlikely to occur.

4. Conclusions

The experiment presented in this paper demonstrates the use of remote inspection as an alternative for manned inspections. Due to the high cost for visiting offshore wind turbines for maintenance task, there is a considerable potential for cost savings with remote inspections. The total time for remote inspections will usually be much shorter than for manned inspections, even if the time needed for the inspection itself is longer. Since the experiment was performed in a laboratory environment, it was not intended to evaluate how such a system would perform in a wind turbine. To evaluate concerns regarding the operation in a realistic environment we suggest, and are currently planning, for field tests inside a turbine nacelle.

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