

CLIMBING RING ROBOT FOR INSPECTION OF OFFSHORE WIND TURBINES

HERNANDO LEON RODRIGUEZ, BRYAN BRIDGE AND TARIQ P. SATTAR

Research Centre for Automated and Robotic NDT

Faculty of Engineering, Science and the Built Environment

London South Bank University, 103 Borough Road, London, SE1 0AA, England

A rapid expansion of wind turbine farms for sustainable electric power production is planned in Europe by 2020. At least in the UK, these will largely be located offshore to meet growing concerns about the visual intrusiveness and noise generation produced by onshore based farms. The necessary structural integrity inspection of offshore wind turbine blades poses tremendous problems of access, danger to human operatives and costs in the event of blades having to be taken out of service and transported on shore for scheduled inspections. For these reasons robotic in-situ blade inspection of offshore wind turbines has been proposed and micro/nano focus computed axial X ray tomography (MNCAT) has been identified as the optimal if not the only solution for identification of safety critical defects in the thickest blade sections. The weight of such an inspection system is very high, typically 200kg and typical cross sectional scanner dimensions of 1m x 2 m to encircle a blade, clearly involve very high destabilizing moments to be countered by the deployment robot. The solution is a climbing ring robot completely encircling a turbine tower, typically 3 meter in diameter, to provide the necessary adhesion forces and anti-destabilizing force moments. Because of the size and thus development costs of such a huge robot the optimal design path is to prototype a small scale model. First results on such a model are described and from its performance the load carrying capabilities of a full scale version can be computed and the scale model can then be refined by 'reverse engineering' to guarantee that a full scale construction is able to meet requirements. The key design innovation is that the adhesive forces between the robot and climbing surface are provided entirely by mechanical means rather than by using the usual methods of vacuum suction or magnetic force, making the system much cheaper and easier to manipulate. Furthermore the design is entirely modular.

1. Introduction

The largest wind turbines planned for the future will generate 5MW and involve fibre reinforced composite (FRP) blades up to 100m in length. These blades will be subject to enormous stresses, especially in storm conditions in offshore locations. At the same time the use of FRP in safety critical structures located in such extreme environments is relatively new and it is likely that structural defects of a previously unknown nature may arise. Effective regular inspection for structural integrity inspection is thus essential. An automated on-site inspection solution with the blades remaining on their axles is desirable to

avoid the costs of dismantling the blades and moving them to an onshore inspection laboratory. Robotic deployment is also desirable to avoid dangers to manual operatives and the costs of using manual operatives in such dangerous activities. In robotic deployment the nondestructive inspection instrument needs to be transported to every part of the turbine blades in order to achieve 100% volume inspection coverage [1].

Concerning the method of inspection, using real time photon detectors x rays can penetrate the thickest sections of FRP blades but conventional through transmission radiography (TTR) alone would produce results that are very difficult to interpret. In computerized tomography (CT) images (i.e x ray absorption maps) of any cross section of the object under inspection, orthogonal to the x ray direction, can be obtained. So images of all defects in the cross section are displayed without mutual overlap (unlike TTR) and obviously the defect images will thus be of much higher contrast than corresponding images in TTR. One way is to take multiple real time TTR radiographs at smaller angular intervals ranging through 180 degrees, after digitization of such data commercial software packages exist to routinely convert such data sets into CT images [2-4].

This paper describes results on a prototype scale model, which will be scale up to carry the X-ray source and detector.

2. Requirements and defects to be scanned

Wind farms on land are located in remote areas; access to site is always suitable for mobile plant, and some roads only consist of two thin gravel paths. Some fence sections have to be removed for larger vehicles. The ground at the bottom of the wind turbines is uneven. Some sites have a policy that any damage to the ground due to crane pads is re-seeded. It is possible on most sites to get lifting platforms close to the blades operating off the site roads.

Some of Eon's wind farms are located offshore and this leads to the possibility of more adverse conditions and unstable working platforms and reduced resource availability onsite.

The wind turbine blades can be fixed in the 6 O'clock position, not all positions are able to be locked into but these may be attainable if a safe working practice can be agreed with the site. When stopped the blades can flex in high wind but no working in height must be undertaken in high winds (>12m/s).

Traditionally the material used to construct WTB is glass reinforced plastic (GRP), the fibre properties of the GRP are determined by manufacturing process, ingredient chemistry and coatings. The fibres range in diameter of 3.5 to 24 micrometers and are made primarily up of silica sand (50%), metal oxides and other ingredients can be present. E-glass is the most common form of fibreglass, making up 90% of all glass-reinforced plastics. E-glass is an excellent electrical insulator and its chemical make up is mostly silicon oxide (50%), aluminium oxides, boron, calcium, limestone, boric acid and clay.

3. Types of defects

The RWE portfolio of wind farms have been in operation for around 10 years, the inspection techniques that are presently in use are remote visual inspections at various timescales and at specific times due to local environmental changes and the use of conditional monitoring techniques.

Wind Turbine Blade sizes vary and blade failures have been reported, blades/blade sections have been reported to have been thrown up to 400m after failure.

Figure 1 shows assessment damage to composites is often hidden to the eye. Where a metal structure will show a “dent” or “ding” after being damaged, a composite structure may show no visible signs of damage, and yet may have delaminated plies or other damage within

Impact energy affects the visibility, as well as the severity, of damage in composite structures. High and medium energy impacts, while severe, are easy to detect. Low energy impacts can easily cause “hidden” damage.

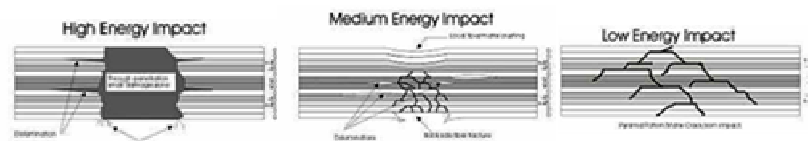


Figure 1. Typical damages in wind turbines.

The biggest numbers of incidents found were due to blade failure. “Blade failure” can arise from a number of possible sources, and results in either whole blades or pieces of blade being thrown from the turbine. A total of 98 separate incidences were found:

Nine incidents were reported in 2005 and seven in 2006 to date. This data makes nonsense of an operator's statement regarding “a one off event” for the incident at Crystal Rig, Berwickshire, Scotland and confirms that there is a need for an effective inspection technique for the projected higher usage of wind power. Pieces of blade are documented as travelling over 400m, typically from much smaller turbines than those proposed for use today. In Germany, blade pieces have gone through the roofs and walls of nearby buildings. This is why CWIF believe that there should be a minimum distance of at least 1km between turbines and occupied housing – and preferably about 5km to address other problems such as noise.

4. Specification of the CONcEPT Prototype tomography scanner

A portable NDT scanning system is required to detect internal defects in the wind turbine using **X-Ray tomography technology**. In tomography images in the form of spatial X-Ray absorption maps of 2 dimensional sections of a test

object are produced and three dimension absorption maps are then reconstructed from successive two dimensional tomography images.

Consider a small area in a two dimensional slice of an object as an image pixel. The pixel dimensions can be defined by the scanning intervals used in the x-y scans of the source-detector assembly. In order for a tomographic image to be obtainable it is necessary for rays to pass through each pixel from source to detector in multiple directions.

A wind generator is an enormous steel tower with about 45m separating the hub or centre of rotation and the end of a wind blade and about 150m in length.

Several options are considered for a scanner configuration that can allow X-Ray tomographic imaging to be carried out on wind turbine blade without take them out of service.

Figures 2 show what could be described as a traditional method of scanning a wind turbine just after manufacture. It consists of a Cartesian Scanner in which the source and detector array move relatively to the blade in two orthogonal directions, one direction being parallel to the blade axis.

This method can be consider the most obvious option for scanning the blade at periodic inspections, but it requires repeatedly to be dismantled from its tower and them moved it to NDT facility for examination exam, a process which is very expensive and carrying a high risk of further damage to the blade during transport.

In-situ tomographic inspection can be carried out without having to construct a rotation mechanism because the rotation of a blade round its longitudinal axis used for pitch adjustments can be exploited. Altogether there will need to be three orthogonal axes of movement, a vertical motion of a climbing robot combined with two orthogonal linear movements of a source – detector scanner.

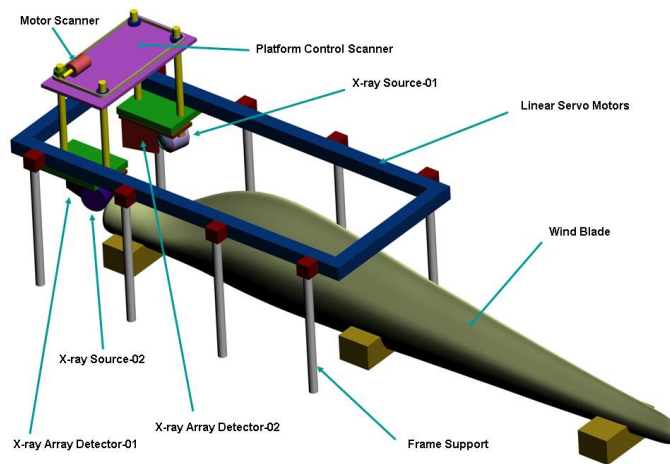


Figure 2. Conceptual Design of scanning automated system –(laboratory based system).

The image resolution will depend on the range through which the blades can be rotated, the narrower the range, the lower the resolution. However, in view of the additional complexity that would be introduced by adding external rotation mechanisms, the possibilities of using blade rotation needs to be considered seriously.

Figures 3-4 show a ‘ring’ climbing robot with a payload capability allowing it to climb around the cylindrical tower and scan the blades in situ.

The climbing robot can carry a heavy payload of the full NDT equipment and control system. The robot is a ring system who itself can divide the forces around the tower; this robot can be development by several modular frames in order to decrease the diameter from 4.5 m to 3 m in the top of the tower and climb up. The system has a Cartesian scanning arm in one of the side to be able to scan the blades from the top of the tower to the bottom. A possible proceeding can be:

1. Climb the robot to the top of the tower and set up the position.
2. Move the X-ray source and the array detector to defined the home position
3. Get the NDT date on this first position
4. Rotate the blade “pitch” to second angle in order to obtain new NDT results.
5. Move the robot to a new position to obtain new results a long of the blade with different angles.

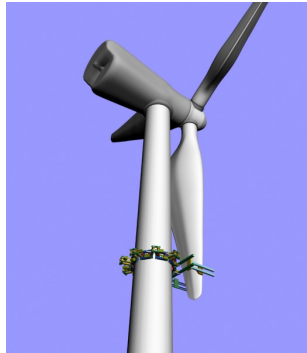


Figure 3. Ring Climbing Robot with mobile NDT scan.

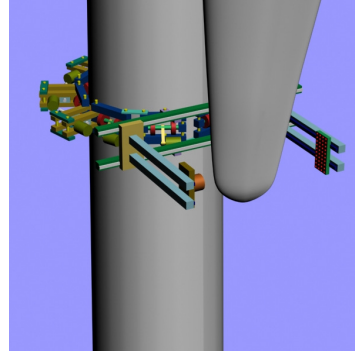


Figure 4. Close View - Ring Climbing Robot with mobile NDT scan- Tomographic scanner is obtained by exploiting the rotation capability of the blade along its long axis.

Figure 5 shows another option of for the climbing vehicle. This is a wall climbing robot with permanent magnet adhesive forces. It has been found through design experience on several projects that these magnetic systems can create a 600 kg force over an area of ferromagnetic steel wall about the size of an A4 sheet (0.3x 0.3 sq metre). Approximate calculations show that the robot could have a 100 kg payload and climb without expend any energy of the attach force and get the ability to scan the blade with the Cartesian scanning arm.

A final option is to dispense with a climbing robot and deploy the Cartesian Scanner via a crane or cherry picker. This might be a preferred option if such equipment happened to be available at the test site. However if all equipment needed to be transported to a given test tower in a given farm, this would be an unsatisfactory option as the overall equipment bulk would clearly be much greater than would obtain using a climbing robot.

Overall the use of climbing robots, if they can achieve the desired payload specification, is a much more satisfactory solution. For example the transport of a robot and scanner by sea to an offshore turbine would require far less cargo space than a crane or cherry picker capable of reaching to the top of a 100 or 200 metre tower.

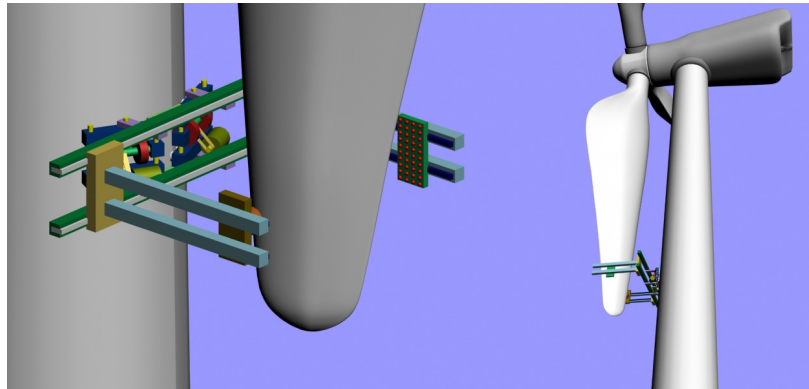


Figure 5. Wall Climbing Robot with mobile NDT scan and permanent magnets.

5. Payload feasibility considerations

The key stability factor for the climbing robot and scanner will be the force moments of the scanner about the points of contact of the robot with the turbine tower. These moments will tend to overturn the robot. These moments have to be balanced by the moment of the magnetic adhesive forces about the same points of contact.

For a simple order of magnitude calculation it will be possible to model the overturning effect in terms of a single force W acting through the centre of gravity of the scanner, being the weight of the scanner. If the scanner centre of gravity is located a distance d from a point the surface of the tower located centrally with respect to the robot platform. The overturning moment about this point is Wd . Taking worse case scenarios of a source detector system with a 70 kg mass and $d = 4\text{m}$ (a possible case with 4 meter wide blades) this overturning moment is then about 2800 Nm. Let the adhesive force act from the centre of gravity of an adhesive plate and consider an adhesive plate of $0.3 \times 0.3 \text{ sqm}$, which could generate a force of about 6000N.

6. Climbing robot prototype

Figures 6-7 show a novel 'ring' climbing robot with a payload capability allowing it to climb around the cylindrical tower and scan the blades in situ with a Cartesian scanning arm. The key innovation is that the adhesive forces between the robot and climbing surface are provided entirely by mechanical means rather than by using the usual methods of vacuum suction, air vortex or magnetic force, making the system much cheaper and easier to manipulate.

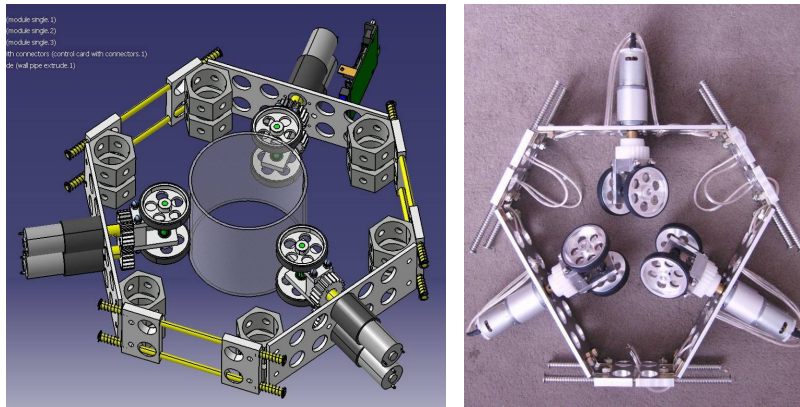


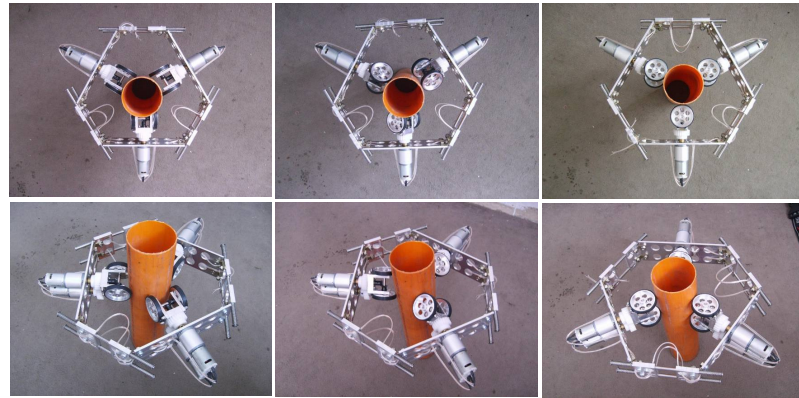
Figure 6. Pipe climbing robot prototype.

The prototype has three modules which are completely identical and can be easily joined together to climb on any circumferential tube. The tower has a tapering radius. The robot is placed around the tower and it uses spring forces to grip it. Active force control could also be used to adapt to changing radius but this method has not been used here.

Each module uses two motors, one for the drive motion and the other to turn the angle of the wheel so that the robot climbing trajectory is spiral. The robot has the capability to face the driver wheels in different angles which means that the robot can either climb along the tube, see figure 7 (column a), or with a certain pitch angle it can spiral around the tube, figure 7 (column b), or if the wheel is turned through 90 degrees then the robot will not climb but it will rotate around the tube in the same spot, figure 7 (column c).

The prototype has been built to a linear scale of 1:10 (for both the robot and test pipe) and tested successfully performing the three types of motion i.e. up/down, spiral, and rotation on the spot. The robot weight is 3kg, the payload capacity is 2kg with a safety factor of 2 and maximum speeds of climbing and circumferential motions are 10m/min. In the full scale model the cross sectional area over which adhesive forces between the wheels and turbine tower could be developed would increase by a factor of 100 (assuming the wheel widths and diameters to be scaled up by a factor of 10 and the payload capacity can thus be potentially increases in the same proportion to about 200kg, the target figure.

However, if necessary, adhesion forces can always be augmented in the full scale design by the inclusion of a number of rare earth magnet arrays.



(a) up/down motion (b) spiral motion (c) on-the-spot rotation

Figure 7. Prototype design in small scale of wind turbine climbing robot.

Acknowledgments

The support of the European Commission under project COOP-CT-2006-032949 is gratefully acknowledged, and Nueva Granada Military University of Colombia for sponsoring the PhD of Leon Rodriguez.

References:

1. European CRAFT project CONCEPT-INSPECT, "Computerised Open Environment Portable Tomography", 6th Framework Programme CRAFT COOP-SME: COOP-CT-2006-032949.
2. B Bridge, Climbing Robots for Non Destructive Testing: Historical perspective and future trends pp 25-32, Advances in Climbing and Walking Robots, Proceedings of 10th International Conference (CLAWAR 2007), World Scientific Publishing Co Pte Ltd ISBN-13 978-981-270-815-1, ISBN-10 981-270-815-4
3. S Chen, T Sattar, A Khalid, M Ralocevic and B Bridge, Pneumatic wall and ceiling climbing inspection robot able to handle diameters down to one metre with high payload capability, Proceedings of the 2nd International Conference on Climbing and Walking robots, Clawar 99, Portsmouth 1999, Professional Engineering Publishing Ltd, ISBN 1 86058 207 9.
4. Proceedings of the Second International Conference on NDE in relation to Nuclear and Pressurised components, New Orleans 2000, Published by the Electric Power Research Institute (EPRI) Palo Alto, CA, USA