Climbing robots: recent research and emerging applications

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Abstract

Purpose – This paper aims to provide details of recent research into robots capable of ascending vertical or near-vertical surfaces and to illustrate how the ability to climb is set to resolve a critical industrial need arising from the growth in renewable energy.

Design/methodology/approach – Following a short introduction, the first parts of this paper describe a selection of recent research activities that involve innovative concepts and designs. The second part discusses climbing robot developments aimed at the automated inspection, maintenance and repair of wind turbine blades. Brief concluding comments are drawn.

Findings – Robots that can ascend vertical or near-vertical surfaces are the topic of an extensive and technologically innovative research effort. Many developments take their inspiration from the climbing abilities of living creatures. Drones with the ability to adhere to and climb vertical surfaces are also being developed. Potential applications include inspection, surveillance and search and rescue. Climbing robots are poised to provide a solution to the need to de-man and reduce the cost of inspecting and maintaining composite wind turbine blades.

Originality/value – This provides an insight into recent innovations in climbing robot concepts and designs and shows how the ability to ascend vertical surfaces is being exploited in the robotic inspection, maintenance and repair of wind turbine blades.

Keywords Inspection, Robot, Climbing, Biomimetics, Wind turbines

Paper type Technical paper

Introduction

Climbing robots have been studied extensively and an important industrial application is the inspection and maintenance of large structures such as dams, bridges, ships' hulls and large industrial boilers where robotic systems act as alternatives to human operators, thereby reducing costs and timescales. Despite a growing number of commercial products there is a strong academic research effort and many technological approaches to climbing are being studied. These include a range of innovative biomimetic concepts which seek to emulate the abilities of living organisms, together with more conventional techniques involving magnets or vacuum technology. This article aims to provide an insight into this research effort and also to show how the ability to ascend vertical surfaces is addressing a critical industrial need arising from the growth in renewable energy.

Biomimetic design concepts

Many classes of robot have taken inspiration from living creatures and climbing robots are no exception. Workers from the University of Cambridge and Toyohashi University have recently reported a climbing robot inspired by the leech dubbed the LEeCH (Longitudinally Extensible Continuum-robot inspired by Hirudinea) (Kanada *et al.*, 2019). Land leeches have longitudinal, circular and oblique muscles which confer highly versatile body motions, including elongation and bending, together with anterior and posterior suckers which allow adhesion to highly varied and vertical surfaces [Figure 1(a)]. These capabilities have been mimicked in the LEeCH which is based on a soft actuator consisting of three 10 mm-diameter flexible metal tubes which are located at the vertices of an equilateral triangle. These have a minimum bending radius of 25 mm and feature helical grooves and are actuated by a rack and pinion mechanism by a drive unit comprising three DC motors (Figure 2). The body bends or elongates by controlling the lengths of the three tubes fed by the gear and a suction cup at either end of the body [Figure 1 (b)] allows adhesion to and motion on vertical surfaces. The robot has successfully climbed up and down a wall and also made the transition from one side of a wall to the other. The authors suggest that such movement could be useful in applications such as building inspection and maintenance and also in assisting with search and rescue missions. A video clip of the robot can be viewed at https://youtu.be/uCISNjwTLgU.

Workers from Osaka City University have taken inspiration from terrestrial hermit crabs to design a climbing robot for the inspection of the exterior surfaces of metal pipes (Imajo *et al.*, 2015). A key design issue was that the robot could overcome obstacles on the surface of the pipe and this was achieved through the use of rimless, spoked wheels. The spokes mimic the hermit crab's claws and each is tipped with a permanent, neodymium magnet which adheres to the pipe (Figure 3). The robot weighs 380 g and is driven by DC reduction motors fitted to a gearbox with planetary gears. It is also equipped with a

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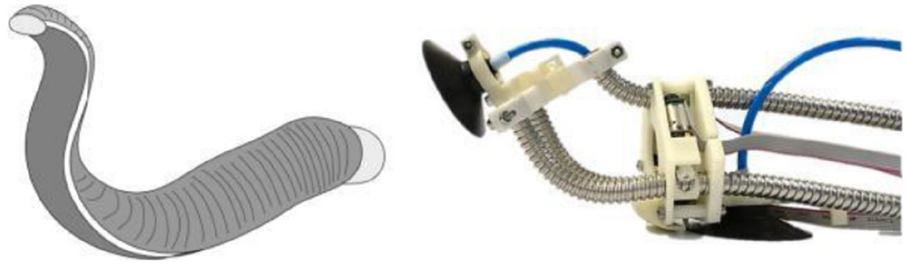
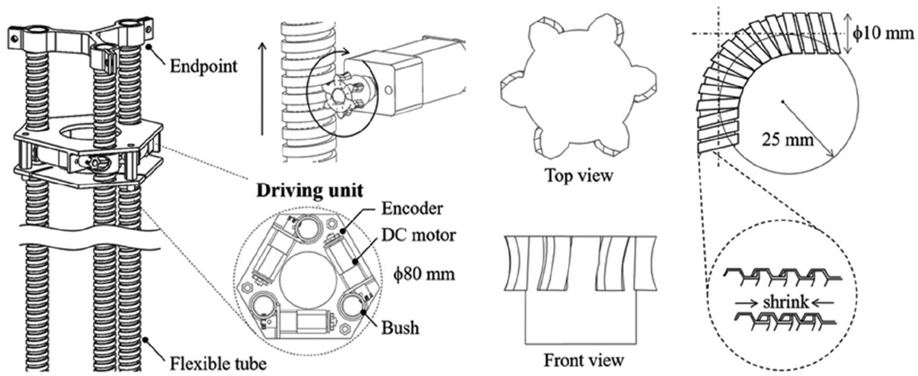
Figure 1 (a) Schematic of a leech showing the anterior and posterior suckers; (b) the robot showing the two suction cups



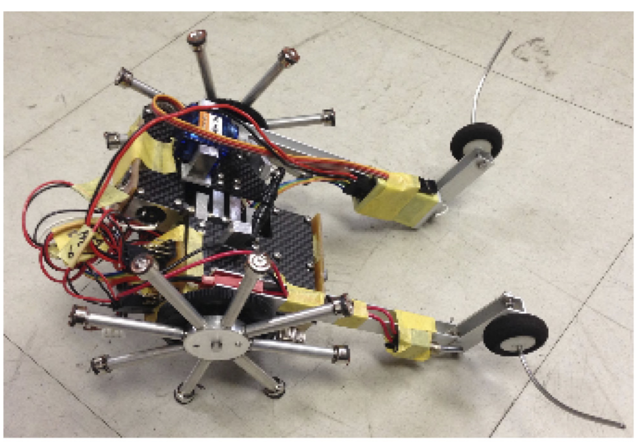
Source: Toyohashi University of Technology

Figure 2 Details of the drive mechanism



Source: Kanada *et al*. (2019), *Soft Robotics*, http://doi.org/10.1089/soro.2018.0115

Figure 3 The pipe climbing robot

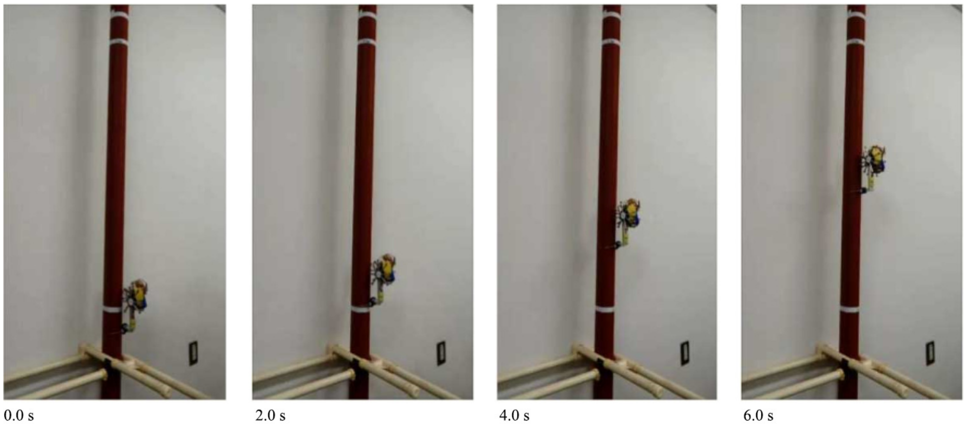


Source: Imajo *et al*. (2015). *Journal of Robotics*, Article ID 312780, http://dx.doi.org/10.1155/2015/312780

servomotor for adjusting the camber angle of the wheels and two small wheels are attached to the rear of the robot to prevent pitching motions. The robot's climbing ability was successfully tested on a selection of carbon steel pipes coated with corrosion-resistant paint with diameters ranging from 21.7 to 101.6 mm (Figure 4).

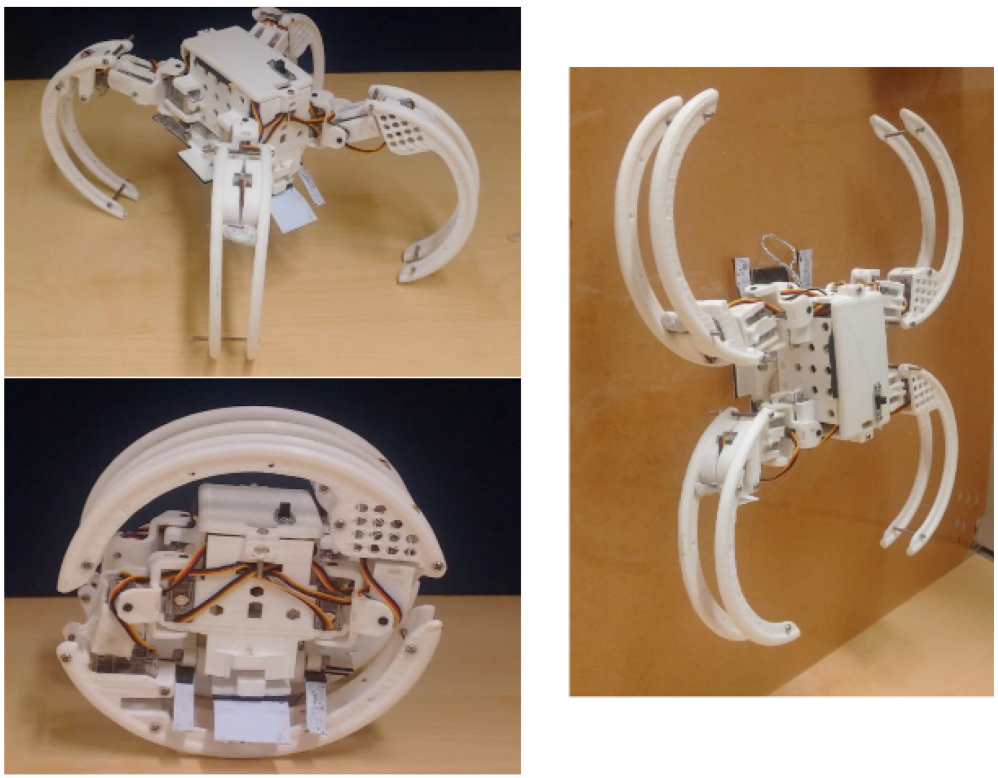
A group from the Singapore University of Technology and Design has developed a robot with multi-modal locomotion capabilities (Figure 5) inspired by *Cebrennus rechenbergi*, a spider that has rolling, crawling and climbing abilities (Yanagida *et al.*, 2017). Dubbed the Scorpio, the robot was fabricated using 3D printing in polylactic acid, a thermoplastic. The body has dimensions of 10×30 mm and houses the control unit, power supply and sensing unit. The limbs are multi-jointed, semi-circular structures with three DOF, powered by micro servo motors. The robot weighs 300 g and consumes less than 5 W at a working voltage of 7.4, supplied by a lithium-polymer battery. In contrast to more conventional techniques, adhesion during climbing is achieved through the use of AirStick micro-suction tape, an acrylic material whose surface features a multitude of microscopic air pockets that create partial vacuums between it and the target surface. The tape can be used repeatedly without losing its adhesive properties. In the climbing trials, the robot was attached to a cleaned glass wall and successfully performed ascending and descending motions while being teleoperated. The authors suggest that the multiple locomotion modes could allow the robot to play a role in urban reconnaissance and surveillance missions.

Figure 4 The robot climbing a steel pipe



Source: Imajo *et al*., 2019. *Journal of Robotics*, Article ID 312780, http://dx.doi.org/10.1155/2015/312780

Figure 5 The Scorpio robot showing its three locomotion modes

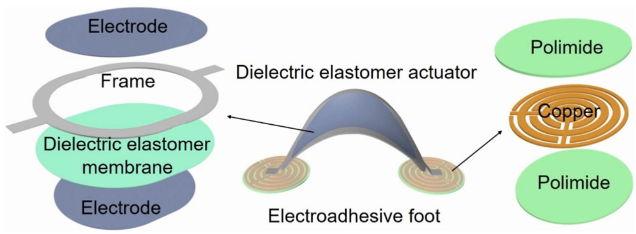


Source: Yanagida *et al*. (2017), *Applied Sciences*, 7, https://doi.org/10.3390/app7040342

Soft climbing robots

Soft design concepts have the potential to dispense with the complex electromechanical mechanisms and transmission components used in conventional robots and as such can be lighter and more flexible. Although many soft robots have been developed using materials such as pneumatic actuators, shape memory alloys and electroactive polymers which can move horizontally, crawl or grip objects, none could climb vertical surfaces, but this capability has now been demonstrated by workers from MIT and Shanghai Jiao Tong University. The robot is based on dielectric-elastomer artificial muscles and electroadhesive feet (Gu *et al.*, 2018) and a schematic is shown in Figure 6. The actuator consists of a biaxially pre-stretched dielectric-elastomer membrane with a thickness of 1 mm, sandwiched by two compliant electrodes and a 0.3 mm-thick

Figure 6 Schematic of the robot



Source: Jiao Tong University

flexible frame. After relaxing the pre-stretched membrane, the actuator buckles to a saddle-shaped structure. As an applied voltage on the actuator is increased or decreased, the body of the robot extends or contracts. Each electroadhesive foot consists of a copper electrode layer (thickness 0.018 mm) sandwiched by two polyimide layers with thicknesses of 0.02 mm. When a voltage was applied to either electroadhesive foot the foot could adhere to the wall. Motion was achieved by a control strategy governing the voltages applied to the actuator and the feet, thereby synchronising the body deformation and foot adhesion. The robot could climb wood, paper and glass walls at an angle of 90° and at a speed of 0.75 body lengths per second (63.43 mm/s). It could also crawl on horizontal planes with a speed of 1.04 body lengths per second (88.46 mm/s) and achieve spot-turning locomotion at 62.79° per second. The robot could also carry a payload while climbing. A small camera weighing 1 g was attached to the robot, allowing it to take videos while climbing a vertical confined tunnel, making it potentially suitable for inspection and surveillance tasks. A video of the robot in operation can be viewed at http://softrobotics.sjtu.edu.cn/vedios/爬壁机器人.mp4.

A body of work combines biomimetic and soft design concepts. For example, a group from Tufts University recently reported a soft climbing and crawling robot inspired by the motion of caterpillars (Rozen-Levy *et al.*, 2019). The robot is moulded from soft silicone rubber and actuated using remote motor-tendons coupled to the structure through Bowden cables. Grip is achieved passively through an elastic flexure that pushes a compliant finger against a dowel. Experimental results showed that the gripper is easily able to support the weight of the robot and that the body structure allows it to crawl horizontally and vertically. The group maintains that it has the potential to access locations such as wiring ducts and tree canopies that cannot be reached by humans or traditional rigid robots.

Combined flying and climbing robots

Several research groups have developed hybrid flying/climbing robots which are effectively drones that can land on, adhere to and ascend vertical surfaces. In 2015, a group at KAIST, the Korea Advanced Institute of Science and Technology, reported the development of a climbing drone, the CAROS (Climbing Aerial RObot System) (Myeong *et al.*, 2015). This is a fairly conventional quadrotor-based flying platform which is equipped with four wheels. When the drone approaches a wall, it re-orientates itself and the thrust generated from the rotors provides aerodynamic adhesion, allowing it to stick to the wall, while its wheels allow it to climb and move around. In 2018, the group reported improvements to this system which involved a new mechanism and control algorithm for perching on a vertical surface and a low speed pose change (Myeong and Myung, 2018) (Figure 7). This reduced the magnitude of the impact on the surface previously caused by a fast pose change and high landing speed.

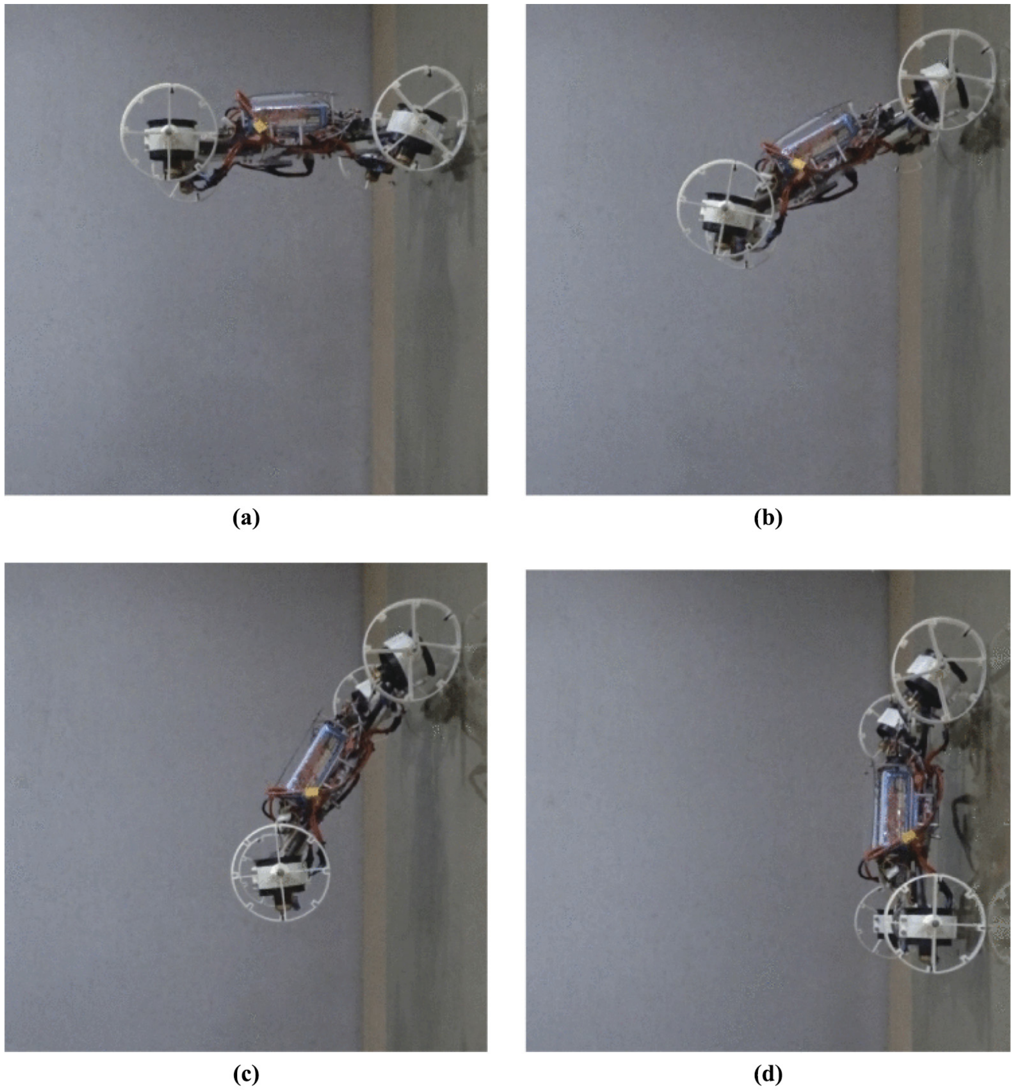
Workers from Stanford University have developed SCAMP (Stanford Climbing and Aerial Maneuvering Platform), a quad-rotor drone which is the first robot able to fly, passively perch, climb and take off again (Pope *et al.*, 2017). It is equipped with long, thin legs with microspines on its feet. To perch, it flies tail-first into the wall and detects the impact-induced acceleration spike and activates its rotors to maximum speed. The tail acts as a pivot and the robot attaches to the wall aerodynamically while its feet find places to grip. By alternating loads between its feet SCAMP is able to climb up the wall; it drags the unloaded foot along the surface until it engages on a foothold. This removes tension on the engaged foot, which then releases. If the robot misses a step, its on-board accelerometers detect the resulting free-fall and the rotors spool up to push it gently back onto the surface. Its feet then re-engage with the wall and it can resume climbing. A video showing the robot in operation can be viewed at https://youtu.be/bAhLW1eq8eM. A group from Shandong University of Science and Technology recently reported a multi-rotor climbing drone which achieved adhesion to surfaces through the use of a gecko-inspired dry material which relies on Van der Waals forces (Guo *et al.*, 2018). This technology was first used by a group from Stanford in its widely publicised climbing robot, the Stickybot.

Suggested applications for these types of robots include military reconnaissance and surveillance, search and rescue and structural inspection and maintenance. Several authors note that, as civil and engineering structures continue to increase in size, monitoring their health is becoming increasingly problematic and costly. This is certainly true in the case of wind turbines and although climbing drones require significant further development, more conventional robotic solutions are poised to address this problem.

An emerging application: wind turbine blade inspection and repair

Recent years have seen dramatic growth in wind turbine power generation, particularly from offshore installations and global capacity is predicted to double in the next five years. In the interests of efficiency, blades are getting progressively larger, with some now reaching 80 metres in length and this trend is set to continue. They are fabricated from composite materials such as glass fibre-reinforced polyester and epoxy and carbon fibre-reinforced epoxy. While corrosion resistant, tough, stiff and strong, blades can suffer from in-service defects such as cracking, delamination and erosion and routine inspection and maintenance is vital to ensure reliable, long-term operation. The traditional approach is to employ specialist rope access technicians who conduct visual and other inspection methods, but this is a costly and time-consuming, manual process that can only be conducted in good weather. A growing trend is the use of drones which can conduct visual inspection but cannot employ more sophisticated testing methods or conduct repairs.

Figure 7 (a) Once the drone contacts the wall, it starts to change the tilting angle of the thrusters adjacent to the wall, generating frictional forces between it and the wall, (b, c) In the pose change process, the drone rotates its body, (d) After the pose change, for the drone to stay on the wall with minimum thrust force, it enters the wall climbing mode

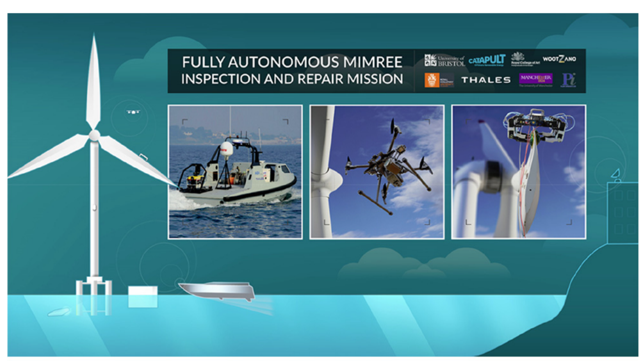


Source: Myeong and Myung (2018), *IEEE Access*, Vol. 7, doi: 10.1109/ACCESS.2018.2889686

With these considerations in mind, blade climbing robots that could deploy visual and other inspection methods and also conduct repairs have been widely investigated by both academic and corporate organisations. These are yet to see routine deployment but a growing number of activities are now poised to make this vision a reality.

In 2019, the two-year MIMRee (Multi-platform Inspection, Maintenance and Repair in Extreme Environments) project commenced in the UK and aims to demonstrate that offshore wind turbine inspection and maintenance can be conducted by robots. It involves autonomous marine vessels, aerial vehicles and a crawling/climbing robot (Figure 8). The climbing robot, the BladeBug (Figure 9), was developed in the UK by a former turbine blade designer and uses suction to achieve adhesion to the blade. It has six legs, a design that was eventually adopted to accommodate the complex shape of the blades, including their

Figure 8 Overview of the MIMRee project

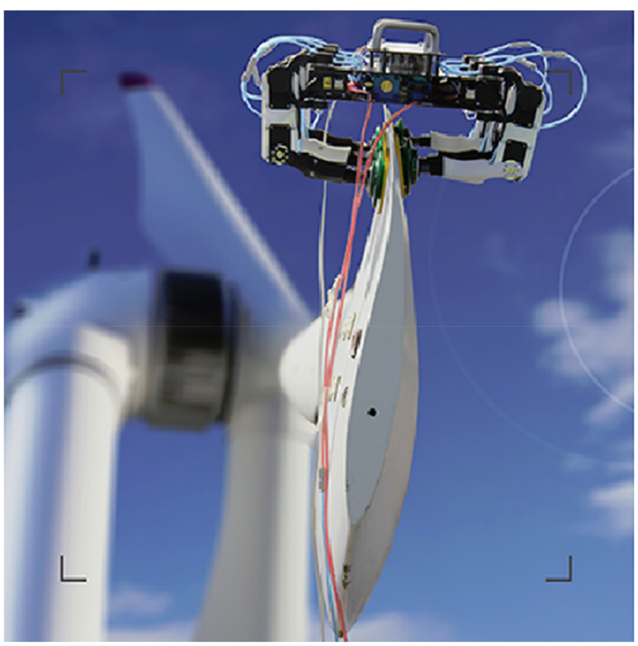


Source: ORE Catapult

curved profile, coupled with the need to travel from one side of a blade to the other. An innovative robotic arm for cleaning and resurfacing the blades is being developed by a team at the Royal College of Art Robotics Laboratory. A system for transporting, deploying and retrieving the robot will be developed at Manchester University, while an artificial intelligence system designed to coordinate missions and allow onshore personnel to analyse is being developed at Royal Holloway University. The anticipated strategy is for the vessel to navigate autonomously to the turbines and perform a visual inspection of a blade with a specialised camera while the turbine is still rotating. The drone would then take off from the vessel and conduct a closer visual inspection if needed, before returning to pick up the crawling robot and position it on the turbine blade. The consortium predicts that use of the technology will save an average wind farm £26m over its operating lifetime.

Also in 2019, Danish start-up Rope Robotics announced receipt of funding from the EU's Horizon 2020 programme for its Wind Turbine Repair Robot project. The company has already developed the BR-8, a climbing robot (Figures 10 and 11) that can conduct blade inspection and repair and this project aims to demonstrate that the robot meets the needs of the wind turbine operators and manufacturers and to document its performance, thereby allowing it to be accepted as the industry standard for wind turbine repair. With funding of over €2m from the Danish Energy Technology Development and Demonstration Program (EUDP), Rope Robotics started work on a project with Siemens Gamesa Renewable Energy in 2019 to support the further development and demonstration of its technology. The BR-8 robot can travel the length of a turbine blade using pre-laid ropes and wires to control its movement and is remotely controlled. It can be equipped with

Figure 9 The BladeBug robot



Source: ORE Catapult

Figure 10 The Rope Robotics robot inspecting a turbine blade

Source: Rope Robotics

Figure 11 Close view of the robot inspecting a turbine blade

Source: Rope Robotics

visual sensors and lasers for inspection tasks and with a variety of tools for repairs such as filling, grinding and painting.

In the USA, Sandia National Labs announced in 2019 that, with funding from the Wind Energy Technologies Office, it has developed a robotic blade inspection system (Figure 12). This involved a collaboration with International Climbing Machines, a manufacturer of climbing robots, and Dophitech, a Norwegian ultrasound imaging company. The robot uses vacuum technology for adhesion and can move up and down and from side to side on the surface of a blade and gather high resolution images to detect surface damage and also detect

Figure 12 The climbing robot equipped with a camera and ultrasonic scanner

Source: Photo by Randy Montoya

internal defects through the use of phased array ultrasonic imaging technology.

Concluding comments

Robots that can climb vertical or near-vertical surfaces are the topic of an extensive and technologically innovative research effort and many developments take their inspiration from the capabilities of living creatures. Drones with the ability to adhere to and ascend vertical surfaces are also being developed. Climbing robots are expected to play an increasingly important role in applications such as inspection and maintenance, surveillance and search and rescue and are poised to provide a solution to the need to de-man and reduce the cost of inspecting and maintaining composite wind turbine blades.

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