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"A novel walking robot based system for non-destructive testing in wind turbines"

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A novel walking robot based system for non-destructive testing in wind turbines

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Abstract.

The constant increasing of renewable energy demand is leading wind turbines to become very complex and sophisticated devices. These technological developments imply new methods and tools to ensure the reliability of the systems. For this purpose, non-destructive testing techniques are widely employed in the field of wind turbine maintenance. This work presents the implementation of a walking robot-based system that allows non-destructive testing to be carried out in difficult access areas of wind turbines. The paper is divided as: a brief literature overview is done to identify those limitations of current procedures that could be overcome by using the proposed tool; a detailed explanation of the novel system is given, where the different components and features of the robot are described; several applications of the proposed systems are also shown. These applications can be classified regarding to the type of sensor and the area to inspect: Acoustic emission, visual inspection, guided wave testing, noise analysis or thermographic inspections are some of the non-destructive testing techniques that can be aided by this tool. Moreover, external and internal surfaces of blades, tower, nacelle and other difficult access areas can be reached by the robot. Finally, some advantages of this system are enhanced with respect to the conventional methodologies. The usefulness of the proposed system is demonstrated in terms of safety and efficiency with respect to other procedures.

Keywords: Wind energy, reliability, non-destructive testing, walking robot system.

1. Introduction

Wind energy is a clean, renewable and sustainable resource which is becoming one of the most important sources of energy. The production of electricity by wind turbines (WT) has not stopped growing and progressing. For instance, in 2016 wind energy overtook coal as the second largest form of power generation capacity in the European Union. It was due to the new installed capacity and the reduction in the use of fossil fuels. Figure 1 shows the new installed capacity of different energies since year 2000, being wind energy the first energy in new installed capacity. Nowadays, it covers more than 11% of the European electricity demand [1].

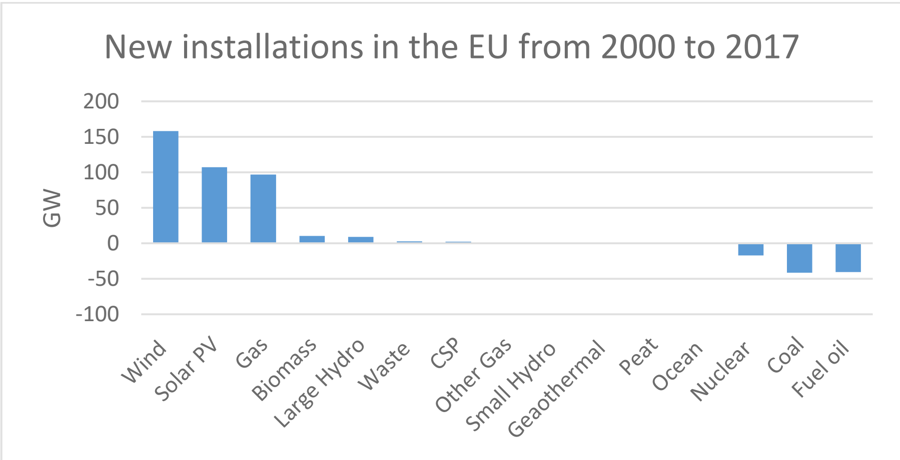

Figure 1. New installations in the EU from 2000 to 2017.

The increasing of wind energy installed capacity is affordable due to the wind energy systems are becoming more and more efficient [2]. The sophistication and complexity of modern systems allows high performance WTs to be developed. However, the improvement of this technology is accompanied by an increase in the operation and maintenance (O&M) investments. They can be from 12% to 23 % according, e.g., the location or the maintenance strategy [3].

Nowadays, one of the most common strategies is condition based maintenance [4]. This maintenance is performed due to the information provided by multitude of sensors that are installed in the WTs and determine if critical components can fail [5,6], or any fault can be done. The maintenance tasks are carried out when any fault is detected. In this field, WT analysis through non-destructive testing (NDT) techniques is done.

This paper presents a new development that can be useful for carrying out a wide range of NDT based analysis. A walking-robot has been equipped with a vacuum system that allows the robot to climb, being able to reach difficult access areas. This robot can be also equipped with numerous sensors and other devices that allows NDT activities to be developed with several benefits.

The paper is divided into four sections. Section 1 presents an introduction, where the wind energy context is analysed briefly and the necessity of new tools for improving the maintenance is highlighted. Section 2 explains the most common NDT techniques applied to WTs. Section 3 details the main components, characteristics and capacities of the developed system. Section 4 describes a set of applications, where the proposed system can be helpful and exposes the advantages and limitations of using the system in each application. Finally, Section 5 presents the main conclusions.

2. Non-destructive testing in wind turbines

The sophistication of WTs implies the implementation of multiple advanced systems for controlling their performance. The development of NDT techniques allows WT to be analysed in laboratory conditions and also in operation. Different NDT techniques are employed in order to determine the state of WT components. Ultrasonic testing, thermography, visual inspection, acoustic emission and radiography are some of the most employed techniques [7]:

- *Ultrasonic testing (UT):* is aimed at identifying defects in the materials [8]. These techniques are based on the acoustic impedance of these materials when ultrasonic waves pass through them. UT techniques are mainly used for WT blades inspection. Several methodologies have been developed in this field, e.g. air-coupled technique using guided waves [9] or contact pulse-echo immersion testing [10]. The main defects that can be detected by employing these techniques are cracks, delamination, manufacturing defects, etc.
- *Visual inspection (VI):* is used for inspecting almost all the WT components, for instance rotor's blades, nacelle, slip rings, yaw drives, bearings, generator, transformers can be object of visual inspections [11]. Some defects that can be identify through VI are defective connections and terminals, leaking and corrosion, worn or broken components, chattering gears or hot bearing housings. VI can be carried out by fixed cameras installed inside the nacelle or by direct visual inspection. The new technologies such as Unmanned Aerial Vehicles (UAV) allows VI to be carried out autonomously [12]. These modern tools are demonstrated to reduce costs and improve the efficiency of the inspections.
- *Acoustic emission:* is the generation and propagation of different type of waves produced by a material when irreversible changes occurs in its structure. These changes are caused by a rapid release of energy inside the material. Different sensors can be installed in several place of the WT in order to record the acoustic emissions [13]. A data processing stage is required to obtain information when the emissions are recorded [14]. There are numerous techniques and methods that can be applied for detecting bearing failures [15], damage in blades through Macro Fiber Composite (MFC) sensors [16], analysis of WT blades during fatigue testing [17], etc.
- *Thermography:* consists on the measurement of the infrared radiation emitted by objects. It is a non-contact method that requires of an IR-camera. The inspection can be active and passive. Active techniques employ an external heat source that generates a heat flow inside the object. On the other side, passive techniques measure directly the radiation emitted by the matter. The most common use of thermography in renewable energies is the inspection of solar plants [18,19]. Thermography can be applied for monitoring and failure detection of gearbox and generator [20], failure detection in electric and electronic components, ice detection [21], detection of superficial defects in WT blades [22], tower or nacelle surfaces.
- *Radiography*: is based on the effects of X-Ray passing through the matter. It is rarely employed for the inspection of WT [23]. However, it has been demonstrated to be efficient in detecting cracks and delamination in WT blades, rotor and tower structures [24].

NDT techniques allows the detection of irregularities in the WTs and, therefore, employedin predictive maintenance. However, all the NDT requires specific data acquisition components, for instance, IR-camera for thermographic inspections, transducers for ultrasonic testing, digital cameras for remotely controlled visual inspections, etc. These devices are usually installed in those places where the NDTs will be developed. In this paper, a mobile system capable of carrying all these devices are proposed.

The literature contains numerous research works about robots that aid the development of NDTs. In some cases, they are designed to support the aforementioned techniques, or even some of them together. These systems are usually designed to reach inaccessible places, such as pipes or structures, and also dangerous places. Figure 2 presents some robots related to NDT techniques. Some of them are only concepts (f, g), and other ones are real images (a, b, c, d, e).

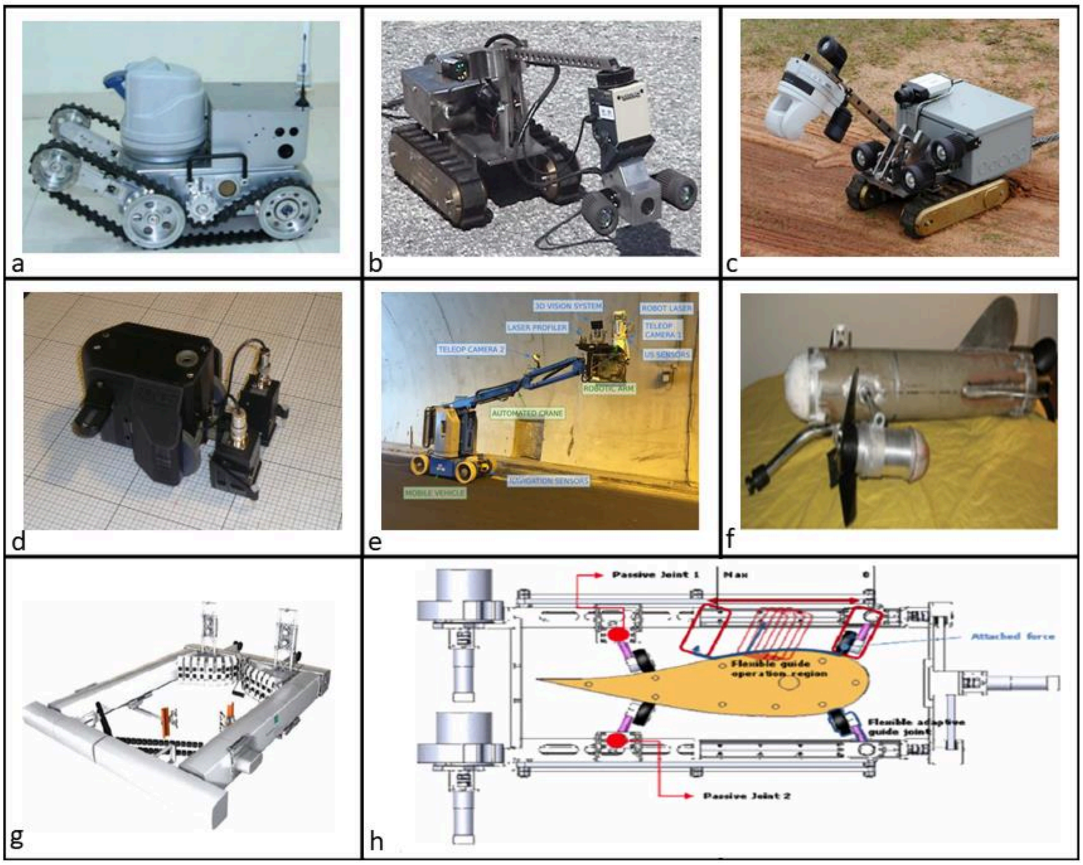

Fig.1 . Presented robots: a [25], b, c [26], d [27], e [28], f [29], g [30] and h [31]

Visual inspection technique is the oldest one of the abovementioned. The emergence of digital charge-coupled device cameras has contributed to perform high quality visual inspection. The reduction in weight and size of modern cameras are crucial factors for being adapted to a robot. For instance, Zhuang et al developed a cable-tunnel inspecting robot for dangerous environment [25]. This system is equipped with a pan, tilt and zoom camera and sensors to measure dangerous gasses. Minichan et al. proposed a crawler robot to inspect tunnels in places with radioactive material [26]. Dobie et al. created a robot for inspecting narrow places [27]. Unlike conventional ultrasonic inspections that need a contact fluid the probe and the structure under test, this robot employs air-coupled ultrasounds.

UT techniques can be also supported by robots, even autonomous. Ravichandran [32] proposed an inspection system that utilizes high frequency sound waves, being able to detect surficial and internal defects. It sends information to the operator in case of defect detection. UTs are also employed by robots that explore large surfaces or tunnels with hundreds of meters and even kilometres [28].

Regarding the acoustic emission, it is not widely extended in robots. However, Hedayati studies to inspect fibre optic under the sea by using a robot. This robot is able to map underwater structures and installations [29].

In opposite, the passive thermography is getting easier to develop due to the quality of IR cameras and the reduction of size and weight. Thermography is employed by robots in disasters [33], or detect air and gas leaks in pipes [34].

There are many prototypes and robots to facilitate the inspections in WT. For instance, Elkmann et al. [30] developed a concept robot for blade inspection. This robot is interesting due to two main reasons: the frame is a structure divided in two parts that can be installed easily in the blade, even offshore, and allows the robot to be in contact with the blade and to move around it; the robot is able to carry a lot of NDT sensors, e.g. thermography, ultrasounds and high resolution cameras. A similar robot is proposed by Lim et al. [31] for maintenance and inspection. This robot adapts to the shape of the blade trough a flexible adaptive mechanism. It is equipped with a camera, UT, an infrared temperature sensor and X-ray tool.

The system proposed in this paper provide some advantages regarding to the literature:

The weigh and the shape of the robot. The proposed robot only weight 4.42 kg and its diameter is 52 cm. These features allows the robot to be installed through and UAV or transported by operators inside the WT.

The movement of the robot. The robot can be remotely piloted and has an omnidirectional move. This capacity makes the robot suitable for accessing to difficult access areas.

Flexibility. The robot is battery powered, doing the machine versatile and flexible, since cables are not necessary. D

NDT variety. Different sensors can be installed easily depending on the requirements.

Labour risk prevention. The robot can be equipped with an emergency parachute, reducing the risks for both humans and devices.

3. Description of the system

The robot is based in an hexapod robot by Trossen Robotics [35]. This robot works by an open source platform, with three degrees of freedom (DOF) legs. A vacuum system has been designed and developed to provide the capacity for climbing. On board, the system is composed of a vacuum pump and other necessary components, such as electro valves, pipes or suction cups. Furthermore, several sensors has been mounted in the robot platform since it is a system designed for inspection, including a camera and macro fibre composite (MFC) sensors. The main components of the robot platform and the vacuum system are shown in Figure 2 and detailed below.

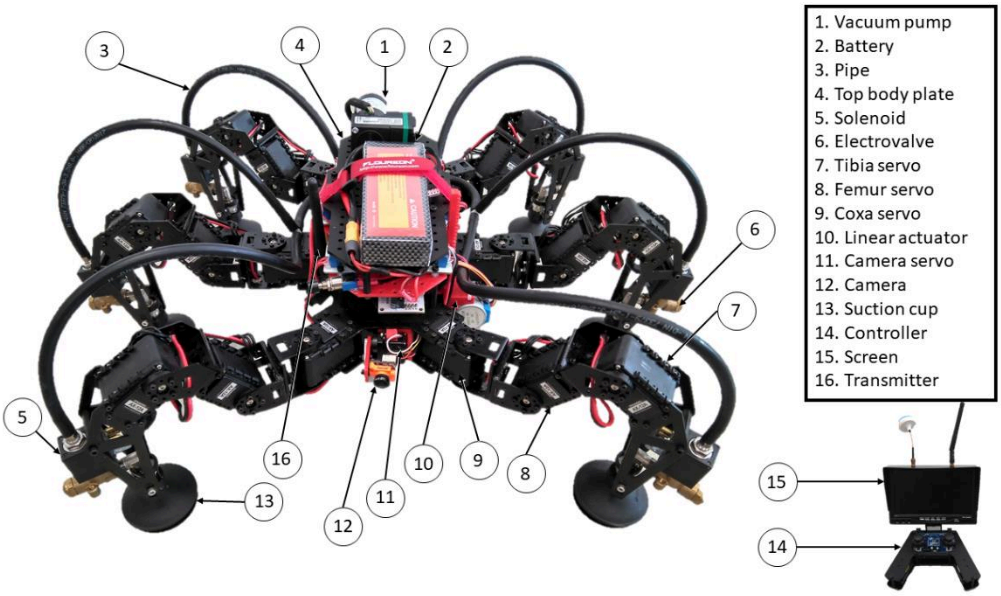

Figure 2. Main components of the proposed system

3.1 Robot platform

The robot platform is a well-known platform in the research field, with continuous improvements to enhance the weigh (made in Plexiglas[36] and aluminium), the battery duration and the software. The main parts that compose this platform are:

- *Body frame:* The main frame, or chassis, is made of Plexiglas plastic. It is a light material with a high resistance. The top and the bottom plates are perforated in order to facilitate the attachment of components and servos. Six servos join the main frame with the legs.
- *Legs:* The robot has a total of 6 legs, two in the front, two in the rear and two in the middle. Each leg is formed by two servos, the tibia and the femur, united to the coxa, with three DOF. In the centre of the leg there are some anchors to fix the electro valves and the pipes. At the end of the leg, the suction cups are in contact with the surface.
- *Servos:* They are one of the most important part in any robotic system. In this case, the robot employs Dinamyxel AX-12A by Robotis [37], with a torque between 12 and 16.5 kfg.cm (depending on the voltage). The resolution of these servos is 0.35º. The servos are equipped with a led alarm and can alert when some parameters to prevent breakages, such as internal temperature, torque, voltage, etc… deviate from user defined ranges. The coxas servos make more effort than the tibia and femur servos in a vertical movement.
- *Battery:* Two 3-cell lithium-ion batteries are mounted in the robot due to the high consumption of energy by the servos. They provide voltage of 12,6 V, the working voltage of the whole system, servos and microcontroller board. The auxiliary battery is used to provide energy to the vacuum system.
- *Software:* The microcontroller board is an ArbotiX-M [38], an Arduino [39] based board. This board has special connectors that are adapted to the servos. The programming is carried out in the Arduino IDE software.
- *Walking modes:* the robot can walk in three different modes:
    - *Ripple:* It is the simplest mode in which only one leg is moving at a time. Each leg is raised and lowered in order. This is the mode utilized to walk vertically. The movement is synchronized with the opening stage of the electro valves.

  - *Amble:* It moves two alternate legs at the same time.
  - *Tripod:* It moves three legs simultaneously.
- *Controller:* The remote control of the robot is based on Arduino with a Xbee module. It works with the protocol Zigbee [40] based on the standard IEE_802.15.4. The communication is developed in the 2.4 GHz frequency. The transfer rate reaches 256kbps, and the distance can be up to100 m.
- *Remote linear actuator:* The aim of this device is to apply and remove a contact sensor (transducer) in any surface of the WT to take measurements. The movement is made by a stepper motor that transmit the motion to a teeth rack, converting the circular movement into a linear one.
- *Tilt movement:* A camera can be installed in a support able to perform the tilt movement in order to provide the camera with a vertical movement. The pans movement is made by rotating the robot.

3.2 <u>Vacuum system</u>

The robot platform is a commercial product, however, the system proposed in this paper includes an own system that provides the capability for climbing. The development consists of the following components:

- *Pump:* It is the main component of the vacuum system since it is in charge of providing the absorption force. The pump is made by Thomas, the model 1410 [41]. It is needed a pump with a high flow (5.5 l/min) and vacuum (75%). This pump has a diaphragm made in ethylene propylene diene monomer. It is equipped with a brushless direct current motor. The pump causes the required vacuum to fix the robot to the surface.
- *Electro valves:* They aree responsible of controlling the air flow in the suction cups. The robot has six Aignep [42] solenoid valves that operates at 12 V. A Mosfet converts the 5V signal of Arduino into a 12 V signal for the electro valves. The operation of these valves is as follows: the default position is opened, i.e. the vacuum is always in the suction cups; when the leg is ready to move up, the valve closes the way that goes to the suction cup. This allows the leg to rise, besides of keeping the vacuum in the rest of the circuit. Each electro valve opening has a duration of 50 ms. If the operation of all the electro valves is not synchronized properly, the robot could fall down.
- *Suction cups:* They are designed in a soft rubber for adapting to different surfaces. The diameter of each suction cup is 50 mm, covering an area of 1963mm^2. Therefore, the total contact surface of the robot is 11.775 mm^2. The suction cups are connected directly to the electro valves.
- *Pipes*: They must be able to support the vacuum, i.e. if the pipe is not thick enough, the vacuum can bend it avoiding the passage of air. It also needs to be flexible to allow the leg movements.

4. System applications

It is important to remark that the paper focuses on WTs, but the proposed system could be also employed for inspecting other devices. It can be equipped with different sensors and subsystems required by NDT techniques. The most important activities that can be carried out by the proposed system are detailed below:

Ultrasonic testing: the traditional UT system requires a couple of transducer, the emitter and the receiver [43]. For instance, MFCs are suitable sensor for the UT inspections on WTs [44,45]. These piezoelectric sensors are made of fibres aligned uniaxially, encircled by a polymeric matrix [46]. The remote linear actuator of the proposed system puts in contact the MFC with the surface to analyse [47].

The emitter can be fixed regarding on the size of the area to scan, being the robot in charge of moving the receiver throughout different points of the surface. In WTs, this configuration is not suitable in large areas, due to ultrasound signals suffer important attenuation passing through the composite materials. There are two possible configurations for scanning little areas:

- To equip the robot with both transducers, being separated by the maximum size of the robot.
- To employ a couple of robots, each one fitted with a transducer. This configuration allows transversal sections of the blades to be analysed by positioning the robots on the internal and external surfaces, respectively.

Since the robot allows horizontal and vertical movement, it is possible to access different places that otherwise are unaffordable to robots or people.

The main advantages of using the proposed system for UT are the capability of carrying out the analysis remotely and the high mobility of the sensors over the surfaces. The main limitation is the necessity of a proper transmitter.

Visual inspection: the proposed system has been equipped with a high definition camera, manufactured by RunCam [48]. It is based in CMOS sensor of 4,6 g. The camera signal is sent in real time by a video transmitter in the frequency of 5,8 GHz [49]. The camera is attached to a servo motor, controlled remotely, that allow to do the tilt movement, i.e. the up-and-down movement. This movement allows the inspected surface to be observed from a proper position. The pan movement can be generated by spinning the robot horizontally. The visual inspection could be even more interesting in case of accessing inside of the blade.

The principal advantage is the real time vision. It has two mainly functions: it allows the robot to be controlled in the WT, and; a visual inspection can be carried anytime.

Acoustic emission: unlike the UT, only a receiver sensor is needed. MFC sensor, or microphones, can be employed in this case. As aforementioned, MFC sensors would require the linear actuator. In this field, the most interesting approach is the use of microphones [50], (either dynamic, condenser, piezoelectric, etc.). An abnormal condition can be detected from the noise generated by the WT. The mobile parts, such as the gearbox, could make noise in case of malfunction [51]. The robot can remain in a stable position while the turbine is rotating. The absence of noise in the robot causes all the noise to come from the environment and the WT.

The robot does not deliver noise into the received signal unlike UAVs, allowing for hearing just the noise generated by the WT.

Thermography: this NDT technique is one of the novelties in the robot system. The robot has been fitted with a IR camera in order to inspect ice or those components susceptible to heating such as the gearbox. The proposed camera is a Flir Vue Pro R [52], with resolution 336x256, and wide dynamic range. The camera can be controlled remotely and send the thermographic images in real time. The robot allows high quality thermographic images to be obtained. Since the equipment is designed to take temperature data, it can be combined with a radiometric sensor [53].

This application presents the possibility of monitoring the contribution of the temperature to the correct operation of different components the WT.

Figure 4 shows the proposed robot with the equipment and devices described above. Figure 4(a) details the MFC sensor installed at the bottom of the linear actuator; Figure 4(b) presents the visual camera together the servo that moves it; Figure 4(c) shows the thermographic camera mounted at the front side, and Figure 4(d) presents the radiometric sensor is attached to the top body plate.

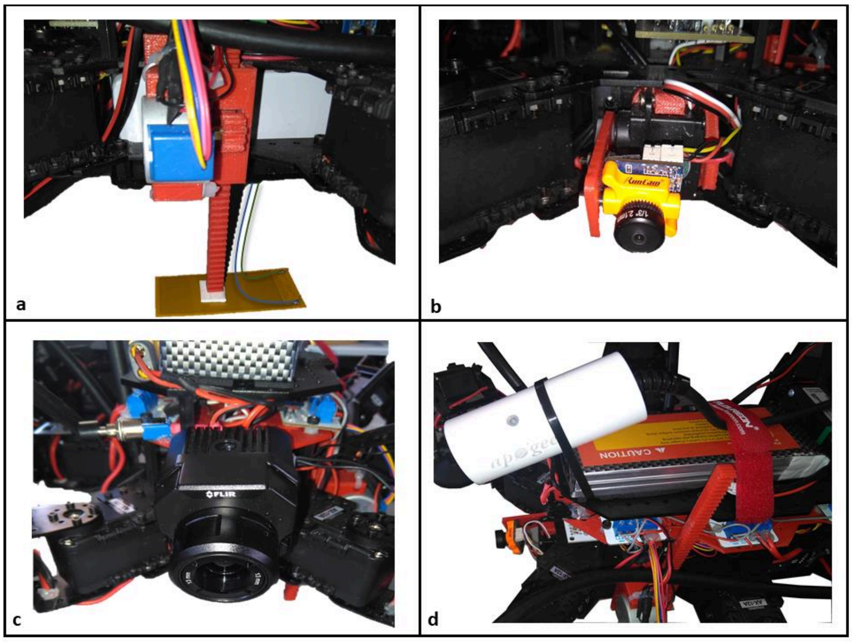

Fig. 3. Different sensors installed in the proposed system

Finally, Table I shows a summary of the different applications of the proposed system for WT analysis.

Table I. Overview of applications of the proposed system in WTs.

NDT	Sensor	Location	Advantages
Ultrasonic testing (UT)	MFC	Blade, tower, nacelle	Detailed inspection, access to difficult places
Visual inspection (VI)	HD camera	Blade, tower, nacelle	Real time vision
Acoustic emission	MFC, microphones	Blade, tower, nacelle, gearbox	Absence of noise
Thermography	Thermographic camera	Blade, gearbox	Monitor the temperature

5. Conclusions

The importance of non-destructive test for inspection of wind turbines has been remarked in this paper. A brief overview of the main NDT techniques used in WTs have been presented. The necessity of novel methods and tools to ensure a correct operation of the WT has been remarked. For this purpose, a novel walking robot-based system has been developed to improve and facilitate the application of NDT techniques. Several research studies have been considered to enhance the original contributions of this paper. A detailed description of the main components and subsystems that compose the proposed system is given. The use of each component has been justified by considering the requirements and the possible applications of the robot. Moreover, the main applications of the proposed systems in WT have been detailed, highlighting the main advantages in each case. The proposed system has been demonstrated to be useful for facilitating some inspection activities, and particularly, for carrying out analysis in difficult access areas.

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