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FOLDABLE MAGNETIC WHEELED CLIMBING ROBOT FOR THE INSPECTION OF GAS TURBINES

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This paper describes the design and prototype implementation of a miniature climbing robot with magnetic adhesion, developed for the inspection of gas turbines. It can be inserted through an entrance hole of only Ø15mm and then unfolds to a magnetic crawler with 2 traction units and an antenna module for holding the camera. This crawler is able to move on vertical and overhanging ferromagnetic surfaces and to carry a camera for the visual inspection of the turbine blades. After a detailed description of the industrial environment where it is supposed to be used (inspection of gas turbines, housing not opened), we describe the basic mechanical concept and show how we solved the most difficult design challenges – torque transmission at this very small size and design of the folding mechanism. The paper concludes with a prototype implementation and some test results; and provides an outlook on future improvements in a final industrial version.

1. Introduction

This paper describes the design and prototype implementation of a miniature climbing robot with magnetic adhesion, developed for the inspection of gas turbines. These turbines are installed in every combined-cycle power plant and their blades have to be checked regularly for failures, to assure that the power plant works safe and reliable. As each day of outage can easily cost up to one million euros, the most important goal for these inspections is to be as fast as possible. Thus, ideally the risky and time-consuming work step of removing the turbine housing should be avoided by using inspection devices of very small size. These devices should to be thin enough to fit through the very narrow entrance holes (down to Ø15mm, originally only designed for borescopes) but still mobile enough to reach every part of the blades (up to 500mm) and to operate in all directions of gravity. Additional difficulties are the small gap between blades and housing (sometimes only 10mm) and the fact that the blades are mostly covered with a thick layer of ceramics for heat protection and thus cannot be used for magnetic adhesion. In contrast to similar applications in tubes and pipes, the curvature of the surface is not a difficulty in this environment, as with normally Ø2000mm or more, it is significantly higher than the robot size.

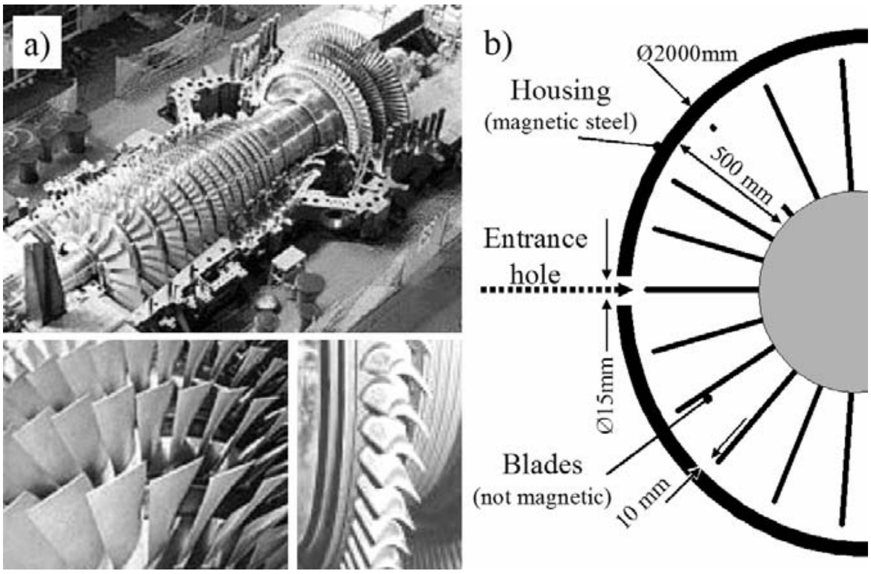

Fig. 1. Typical geometrical constraints in this application
(a) Photo of an opened turbine showing the geometry of the non-magnetic blades to inspect
(b) Sketch of a closed turbine with the most critical geometrical values in the worst case.

Until now, the inspection of blades is done either by borescopes [1] that are inserted through holes of approximately Ø15mm or by opening the turbine housing. Both methods have significant disadvantages: While with the borescopes, not all parts of the turbine can be accessed, removing the upper part of the housing is a very risky and time-consuming task; as such a part weights several tons. For this reason, the goal of this project was to realize a miniature climbing robot that can be inserted through the very thin borescope holes of only Ø15mm and then is able to reach every part of the turbine blades to perform a visual inspection.

The paper is structured as follows:

Section II provides a brief overlook on existing climbing robots in related fields and shows why they cannot be used in this application. Section III explains the basic idea of the foldable structure. In section IV, we provide some more details how we realized the traction modules and the folding mechanism. The paper concludes with some test results in Section V and provides an outlook on future improvements in a final industrial version.

2. State of the art in climbing robots at extremely small size (<15mm)

Among the existing climbing robots at such an extremely small size, basically two adhesion principles are used: Mechanical spreading between two surfaces and magnetic adhesion using NdFeB permanent magnets. Other adhesion principles such as vacuum suction, spines, glue or dry adhesion have not been analyzed in detail, as we did not find any examples of existing robots that are at least close to the required size (Ø15mm) in this application.

Climbing robots that mechanically spread between two surfaces are used for the inspection of pipes [2], tubes [3] or small gaps in generators [4]. Within this group, two subgroups can be distinguished: Passive spreading with springs or active spreading using additional actuators. The first group allows for robots with relatively small and simple mechanisms robots that reach sizes of Ø25mm (= 1 inch) in tubes (Toshiba tube crawler, [3]) or 12.7mm (= 0.5 inch) height in gaps (GE Magic for generator inspection [4]). However, these robots cannot move in complex shaped environments. For such environments, more complex robots that use legs for mechanically spreading, such as the "Moritz" [2], have been developed. However, robots of this type normally result in relatively big sizes that are far away from fitting through the specified entrance holes.

Another principle to realize vertical mobility at extremely small size is the use of magnetic adhesion, mostly combined with locomotion based on wheels. Robots with permanent magnetic wheels have been realized down to heights of only 8mm in the field of generator inspection [5]. Also for tube inspection, the use of magnetic wheels could be imagined, if the tubes are made out of ferromagnetic material. In contrast to robots that spread between two surfaces, there are no needs regarding the shape of the geometry above the main surface (except having enough space). The main constraint for this type is its limitation to ferromagnetic surfaces. In our application field, a magnetic wheeled robot could only move on the surface of the housing, but cannot generate adhesion to the blades.

3. Basic concept

Due to the limitations described in the last section, the idea to realize a robot that directly climbs on the blades was regarded as unfeasible with current technology.

However, a magnetic wheeled robot that moves on the ferromagnetic surface of the housing seemed realistic. For realizing such a robot at very small size, the basic idea was to couple two traction units similar to the ones already used in tube inspection robots [3] (only difference: with magnetic wheels instead of mechanical spreading) with a connector part in between – to realize a robot with 2D-mobility on vertical surfaces. This connector part is mounted at a very low position for avoiding collisions with the blades, as the distance between blade and housing can sometimes be only 10mm. For reaching also the higher parts of the blades, the camera is fixed on an antenna module that stands perpendicular to the magnetic surface (see Fig. 2, a).

To solve the challenge of passing the very narrow entrance holes (Ø15mm), the entire robot can be folded straight using articulated joints between the four modules (traction unit 1 – connector - traction unit 2 - antenna; see Fig. 2, b).

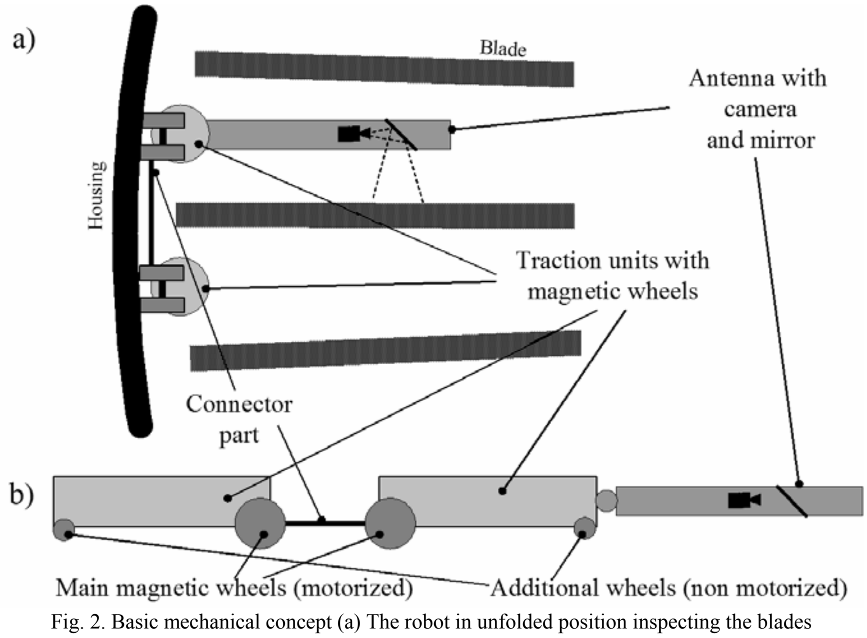

Fig. 2. Basic mechanical concept (a) The robot in unfolded position inspecting the blades (b) The robot folded straight for passing the narrow entrance hole.

4. Detailed mechanical design

Within the mechanical design, two main challenges had to be solved – building strong enough traction units at a size that still fits through 15mm holes and realizing a folding mechanism that is easy to handle, can also be realized at this very small size and guarantees for enough stability during turning.

4.1. *Traction units*

For the design of the traction units, some elements from our previously designed robot for generator air gap inspection [5] could be reused:

- Magnetic wheels of only 6mm diameter that can generate adhesion forces in the range between 5N (ring magnet without rims) and 25N (double magnet with rims) per wheel.
- Motors with planetary gearboxes of only 6mm outer diameter, that can provide an intermittent torque of up to 60mNm
- Experience with relatively complex-shaped plastic structures at very small size, produced with a stereo-lithography rapid-prototyping machine

However, the spur gears for transmitting the torque from motor to wheels could not be reused as in the vehicle for generator air gaps (no limits in width). As in our application the traction unit hat to pass through a narrow hole of only 15mm, the wheel axis should be perpendicular to the motor axis. For this reason, we used a worm gear transmission – similar as it is also implemented in the traction units for tube crawler robots [3]. In our design, we used a worm-wheel with 12 teeth in Mod 0.2 (maximum transmittable torque: 50mNm).

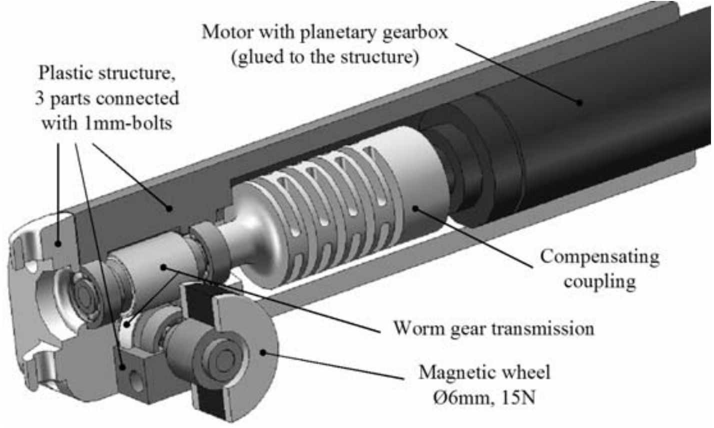

Fig. 3. CAD-model of the traction unit, with motor, worm gear transmission and magnetic wheels.

For the magnetic wheels, we used single magnets with rims on each side, resulting in a total magnetic force of 15N per wheel (30N for both). For the actuator choice, we dimensioned it with the maximum torque in the same range as the limit of slipping between wheels and surface. Assuming a friction coefficient between wheel and surface of approximately $\mu=0.5$ and the gravity force small compared to the magnetic force, the limit torque generated on the wheel shaft resulted to 30N*0.5*3mm=45mNm. With the transmission ratio of the worm-gear being i=12 and its efficiency assumed to 0.5; this leads to 45mNm*0.5/12=7.5mNm. This value could be achieved with a 3-stage-planetary gearbox (i=57) on a Maxon RE6 (nominal torque: 11mNm). With the nominal output speed after the planetary gearbox being 100rpm, we calculated the expected driving speed to (100/12)*pi*6mm=158mm/min. This value seemed fast enough for this application.

For making the entire robot statically stable in all inclinations, also on the back of the traction unit we had to put magnetic wheels. As these wheels do not have to provide traction and even slip sideward when the robot is turning, we chose magnetic wheels of lower adhesion force. With a single ring magnet without rims, the adhesion force there is only 5N instead of 30N.

4.2. *Folding mechanism*

For the folding mechanism, we linked all modules with articulated joints that are mechanically limited at exactly 90° in one direction; and allow for free turning into a straight position and approximately 30° into the other direction. For pulling the modules into the final position for driving, we used a fishing wire that is fixed at the first traction module (gets inserted at first) and can be moved within a screw hole in the antenna-module (gets inserted as the last one).

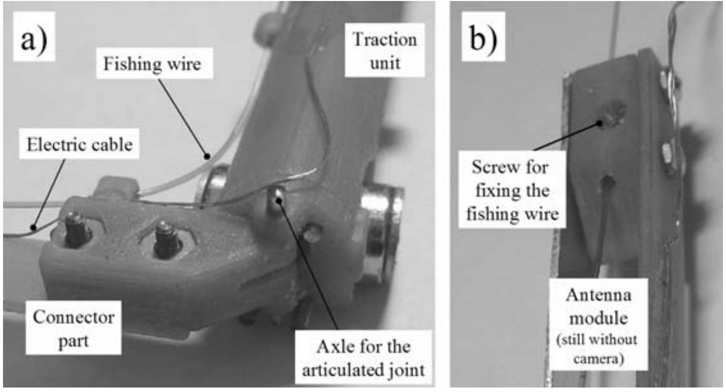

Fig. 4. Folding mechanism (a) Joint with wire transmission (b) Wire fixation in the antenna module.

When the robot is inserted completely, the operator just pulls the fishing wire and afterwards fixes it with the screw. Details of the joint with the wire transmission and the fixation in the antenna-module can be seen in Fig. 4; the entire operation of folding is shown in Fig. 5.

4.3. *Power supply and control*

As a cable is anyway necessary for pulling the robot out of the turbine and for transmitting camera signals, batteries and electronics for wireless signal transmission are not necessary. For the first tests, the prototype was remote-controlled with simple bi-directional switches to change the polarization for forward- and backward movement. For the final industrial version we propose to use motors with encoders, measure the odometry and implement speed control.

5. Test results

Both the folding mechanism and the mobility on vertical and overhanging surfaces were tested. Fig. 5 shows a sequence where the robot is pushed through the entrance hole (a), pulled into its final shape (b), fixed (c) and then lowered down to the surface to drive (d-f). Folding and unfolding (+ removal) were tested several times and it worked without any problems.

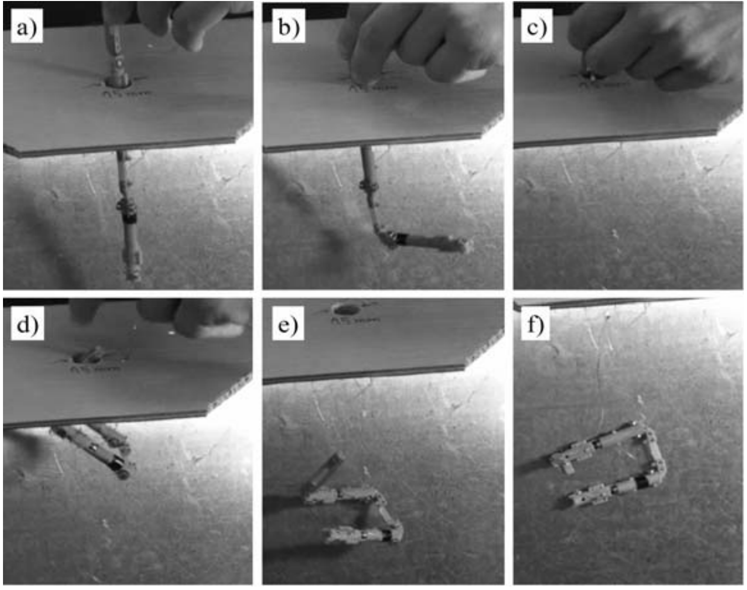

Fig. 5. Sequence of passing the entrance hole and unfolding the robot.

Also driving along ferromagnetic surfaces and turning was tested – on the ground, on vertical walls and in overhanging sections. Also here, the robot performed well and could easily carry the estimated payload of 100g that we assume for a longer antenna module that also includes the camera with mirror and an extra manipulator for turning it.

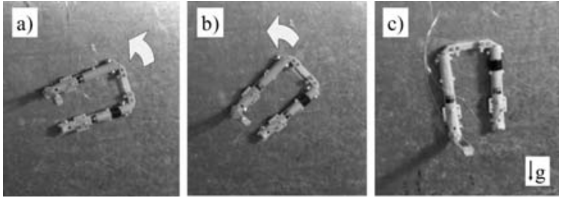

Fig. 6. The robot turning on spot on a vertical wall.

6. Conclusion and outlook

In this paper, a miniature climbing robot on magnetic wheels was presented – with the remarkable additional feature to fold it straight for passing through narrow entrance holes of only 15mm diameter. Both moving on vertical and overhanging magnetic surfaces and folding/unfolding have been tested successfully. Payload tests showed its potential to carry a longer antenna module with a camera and an extra actuator for moving it. Folding mechanism and magnetic wheel units at very compact size elegantly solve the very limiting specifications of the application. The prototype paves the way to a promising alternative to borescopes.

The future development will stress on integrating such a camera with mirror and an actuator; making all parts more robust (Al instead of plastics); and improving and perhaps motorizing the folding mechanism.

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