Tubulo – a train-like miniature inspection climbing robot for ferromagnetic tubes

Patrick Schoeneich, Frédéric Rochat, Olivier Truong-Dat Nguyen, Gilles Caprari, Roland Moser, Hannes Bleuler, Francesco Mondada

***Abstract*—A train-like miniature climbing inspection robot for ferromagnetic tubes is presented in this paper. Using magnetic wheels, it climbs in tubes of 25 mm of diameter and bigger in any orientation, and pass bends with curvatures above 150 mm in some cases. It has embedded electronics and energy, and can transmit images through a cable. Applications are in tubes inspections as found in power plant boilers for example.**

***Index Terms*—mobile robots, inspection, magnetic forces, robot sensing systems**

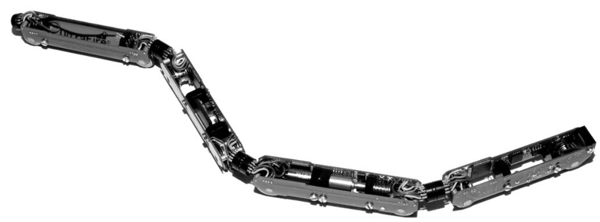

Fig. 1. View of the complete robot *Tubulo*, using magnetic wheels.

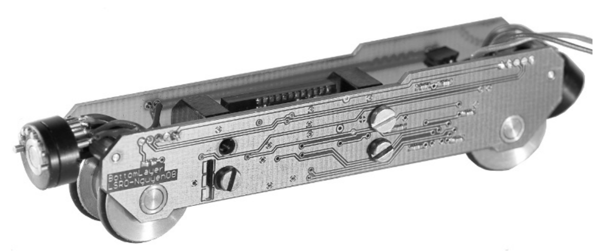

Fig. 2. Close-up of the communication module, measuring 75 mm long.

I. Introduction

INDUSTRY requires new technologies to inspect their factories, especially in the power generation sector. One particular industrial application we are working on is the inspection of coal-fired boilers. They contain kilometers of tubes that need to be inspected to prevent failures during operations. Theses outages can cost millions of dollars if the plant has to be stopped for repair. Tube defaults can be of many kinds, including cracks, wall thinning, holes, weld damages, etc... Theses fails can be due to different reasons like corrosion, stress, creep, overheating, weld attack and others.

Current inspections are first done visually from outside. Non-destructive tests (NDT) can be done from the outer surface using portable sensors like Eddy current testing, ultrasound and others [1], [2]. Finally probes can be pushed inside tubes with different sensors, like cameras and other non-destructive testing devices [3], [4].

Some robots are able to climb the surface of water walls carrying sensing elements. The robot from Park and co. [5] has four caterpillars surrounding magnetic wheels. It carries an EMAT (electro magnetic acoustic transducer) sensor to detect defaults such as wall thinning or pinholes.

Other robots are going inside tubes of different kinds [10]. Li's robots [7] moves in tubes of 200 mm of diameter. Wheels following a helical path make the modules move. Kwon's robot [8] is made of two modules, each having 3 pairs of caterpillars placed around. It can move in 90 mm tubes and steering allows it to chose a destination in T-branch. The Toshiba robot [9] has a diameter of 23 mm. It can move in tubes of this size and has an on-board camera. Tsuruta's robot [11] moves in 10 mm pipes. Energy and communication are done wireless, and it can transmit two images per second.

All the mentioned robots going in tubes are pushing mechanically on the sides to generate a friction force used for propulsion. For boiler tubes of 25 mm of diameter, they are too big, too slow or not enough resistant. By using magnetic wheels, our aim is to improve the capacities of tube inspection robots. We developed *Tubulo*, a train-like climbing robot, able to move in 25 mm of diameter ferromagnetic tubes in any inclination, and able to pass curves of 150 mm curvature in some cases. It is energy autonomous and can transfer images from an embedded camera using a cable.

This work was done in the frame of the Swiss CTI project "Highly compact robots for power plants inspections" referenced as CTI 8435.1 EPRP-IW with Alstom.

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II. Robot

The robot — which is shown in Fig. 1 — is composed of different modules having specific functions. Each module has a frame composed of two PCBs. They embed the electronics and are also used as mechanical structure. They have two magnetic wheels that keep them attached to the tube.

Four main modules are used for the robot: the locomotion module, the energy module, the control and communication module and the visual inspection module. They communicate with each other through a CAN bus. The control and communication module sends commands to the others (Fig. 2). The locomotion module has one motor driving a magnetic wheel, and is able to push or pull the entire robot. The energy module supplies energy to the other modules using a battery.

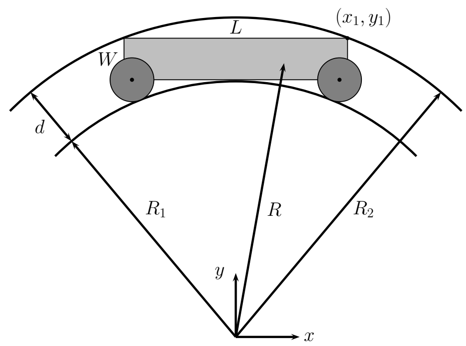


Fig. 3. Module length L and width W constraint.

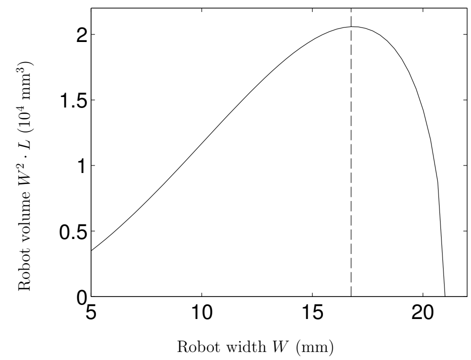


Fig. 4. Volume of one module depending on its width, the length being dependent on the width so that the module can pass bendings (Fig. 3).

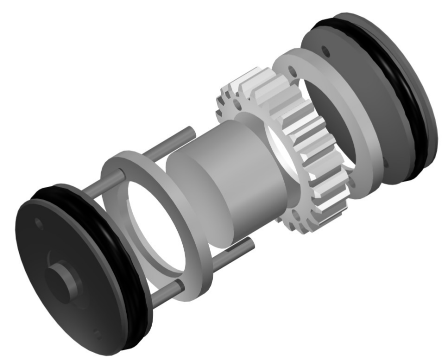


Fig. 5. Magnetic wheel construction without central axis to increase the holding force. The wheel has a diameter of 12 mm and a width of 10 mm. It holds 2.5 N with the rubber seals.

The visual inspection module has a camera, LEDs and an accelerometer on board.

Using these four modules, the robot has a total length of 350 mm and a weight of 100 g. More details are presented in the next chapters.

A. Modules design

Moving in small curved tubes sets some geometrical constraints. The robot must be able to pass curvatures in the tube, and pass possible tube defaults. Typical boiler tubes are in ferromagnetic steel of 25 mm in diameter, with 150 mm radius bends and weld joints up to 2 mm of thickness (which can reduce locally the diameter to 21 mm).

We chose to make the full robot by attaching several modules together like a train. It has the advantage of being flexible, so that it can pass curvatures, and it is more versatile, as modules can be added or changed easily.

For a module to pass bending, its maximum length is related to its width. The optimal size is the one that optimizes its volume and allows room for crucial components as motors, battery and electronics.

Fig. 3 shows a module in a bending. The maximum length L it can have depending on its width W is when its corners touch the external circle, i.e. position (x_1, y_1). The coordinates of this point are related with the circle equation:

$$x_1 = \sqrt{R_2^2 - y_1^2} \tag{1}$$

with $L = 2 \cdot x_1$, $y_1 = R_1 + W$, the bending radius $R = 150$ mm, tube diameter $d = 21$ mm, $R1 = R - d/2$ and $R2 = R + d/2$. A diameter of 21 mm has been chosen because of the possible diameter reductions due to weldings. The volume of the module, $W^2 \cdot L$ with respect to its width W is shown in Fig. 4. The optimal width is around 16.7 mm with a length of 73.3 mm.

Similar calculations can be done to compute the wheels diameter so that the body does not touch the tube in down curvatures. We want the wheels to pass possible steps of up to 4 mm. They need to be at least twice this height to be able to pass this kind of obstacles. The final wheels are 12 mm in diameter.

Keeping in mind some constraints such as motor sizes, electronics and a safety margin, the final modules are approximately 75 mm in length with a width of 15 mm.

B. Magnetic wheels

We want our robot to move in tubes in any inclination, we thus need a holding system. As boiler tubes are ferromagnetic one solution is to use magnetic force. One advantage of the magnetic force against mechanical force (i.e. mechanically pushing on the side of the tube) is that the robot can adapt to various tube sizes. Indeed with mechanical solutions, diameter variations are lower than 2 times.

We designed standard magnetic wheels, with a central magnet and two iron flux guides on the sides. One particularity is that they have no central axis, keeping more volume for the magnet. The mechanical stability is ensured by pins (Fig. 5).

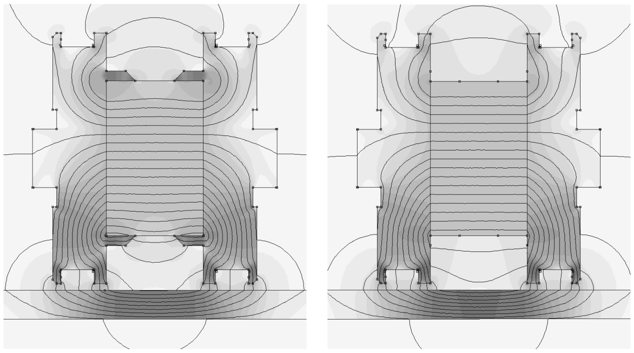
2D simulations done with the software *FEMM* helped us improving the wheel (Fig. 6). It showed that the magnet holders machined directly in the flux guides were generating leakage. We changed them with non ferromagnetic material which improved the force by 12% in simulation.

The final wheel design holds up to 250 g. Hence the robot is always attached on one side of the tube, and can hold in any orientation of gravity.

C. Locomotion results

The achieved mean speed is of 6 mm/s, and the robot can effectively move in tubes of any orientation.

However the traction wheel tends to slip easily. As the friction force F_f is proportional to the friction coefficient μ_f



(a) (b)

Fig. 6. 2D simulation of the version *a* and *b* of the magnetic wheel on a ferromagnetic plate. Changing the small supports for the magnets in non ferromagnetic material increases the force by 12% (from 2.26 to 2.5 N), as they introduced leakage.

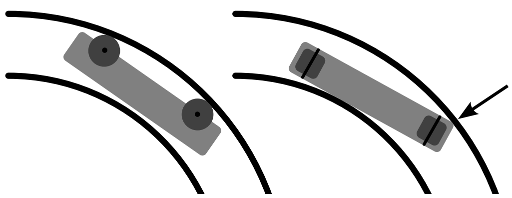


Fig. 7. Up bendings pass easily, but the robot get blocked in lateral and down ones.

and the normal force F_n ($F_f = \mu_f \cdot F_n$), we can increase both values to reduce slippage. Increasing μ_f is difficult as the rubber used has already a good friction coefficient (around 0.55). Reducing the airgap increases the normal force following an inverse-square low. This solution was used and the force could be increased from 250 to 600 g by reducing the airgap from 0.85 to 0.15 mm.

Another problem is that the magnetic wheels tend to gather dirt, and are then difficult to clean.

Furthermore some difficulties arise in curves. The robot can pass tube bendings that are going up (Fig. 7 and 8), but get stuck in lateral and down bends viewed from the robot, because of some friction from the sides of the modules, and because the front wheel comes off the tube on one side which reduces a lot the adhesion force (Fig. 9). Percentages of bend passing success depending on the angle are shown in Fig. 10. $0°$ is the angle corresponding to an incoming up turn, 90, 180 and $270°$ to left, down and right respectively. The graph was obtained by making 35 experiments, letting the locomotion module move in a bending of 150 mm radius with different orientations. We see that the robot can pass only the bendings going up.

Increasing the radius of the bending would give better results, as the robot would less touch the tube with its structure. Better optimizing the wheels would increase the magnetic force, and thus the friction force. This would also increase the bending passing capabilities. Adding sliders or small wheels on the sides would reduce friction force. Adding an active or passive degree of freedom to the wheels, allowing them to turn left and right, could also increase the overall performances.

Fig. 8. Robot passing a curve going up.

Fig. 9. Robot stuck in a lateral curve.

Finally adding traction wheels — on the locomotion module, or by adding another module — would also allow better locomotion results.

D. Attaching system

Special connectors have been designed to ease the manual reconfiguration of the robot, by attaching and detaching the different modules (Fig. 11). The connectors have two degrees of freedom, allowing bending between the modules, and thus passing tube curvatures. Integrating a magnetic circuit, they attach automatically when placed less than around 5 mm apart. Electrical connection is done with contacts mounted on springs (Fig. 12).

These connectors showed good overall performance and were easy to use. However some false contacts arose, which could block the robot. As this is really not possible in industrial case, some commercial robust connectors will need to be used.

E. Embedded electronics

All modules can communicate between each other through a CAN bus. They embed a dsPic microcontroller to control the communication, motors, energy or camera.

The locomotion module receives command information such as *forward*, *backward* or *stop*. This module keeps track of the traveled distance by odometry, counting the gear turns with

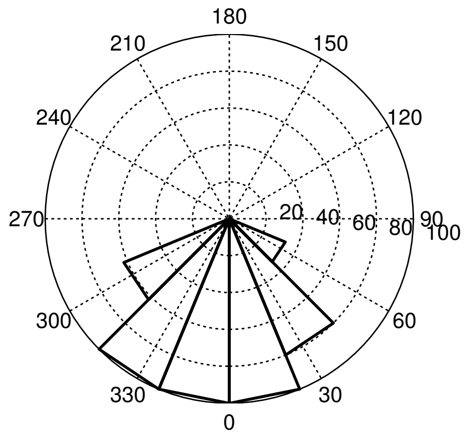


Fig. 10. Success of bend passing in %. 0, 90, 180 and 270° correspond to respectively up, left, down and right bends respectively. The bending has a 150 mm radius. Only upward bends are passing well, the robot is easily blocked in the other ones.

Fig. 11. Spring loaded magnetic contact connectors.

a self made optical encoder, as commercial ones are too big. Unfortunately it is not fully reliable, and using a commercial one would give better results. Measuring the traveled distance on a free wheel would also be better, as there would be less problems due to slippage.

A microcontroller in the camera module is used to control the lightning LEDs, and interface a 3D accelerometer. It receives commands and sends the orientations values through the CAN bus. The camera is independent of the electronics, it just takes its energy from the modules. An image taken by the camera can be seen in Fig. 13.

The battery module includes a protection chip that allows a safe use, avoiding overcharge, over-current or complete discharge of the lithium-ion battery. One battery allows the robot to run for 45 minutes. Several of these modules can be plugged in parallel on the robot, increasing its autonomy. Ideal diodes chips prevent batteries to charge from other batteries when their voltages are different.

The control and communication module has a bluetooth link to a computer. It allows receiving commands from the user, and sending the state of the robot like its orientation, traveled distance or battery state. It works well in the small test tubes we have (less than 1 m), but will not work in longer ones. Indeed, the theoretical required frequency should be over 8 GHz with the correct waveform to have a low attenuation of the signal [12].

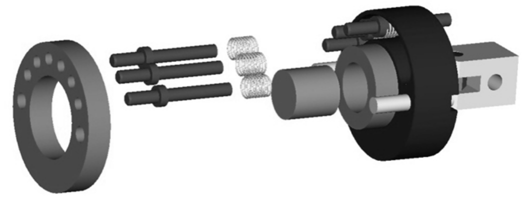


Fig. 12. Exploded view of the spring loaded magnetic contact connectors.

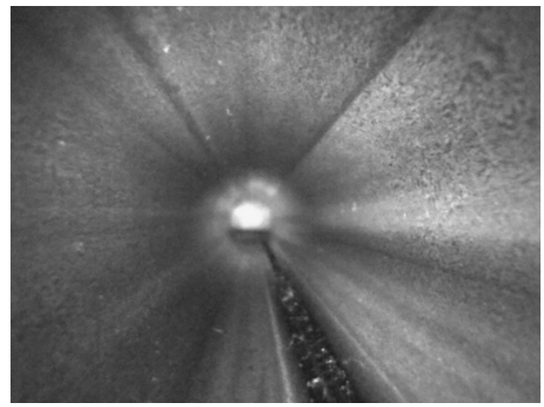


Fig. 13. View of the camera inside a clean 22 mm of diameter tube.

III. Conclusion

We achieved building a modular miniature tube crawler. It can move in 25 mm diameter ferromagnetic tubes in any orientation of gravity and transmit images. Due to its modular construction, changes or other modules can be easily developed and added. For example, more specific inspections modules could be added. If the weight of such a module would be too high, adding a locomotion module would be easy.

Future developments will focus on enhancing the robustness of the system, improving its resistance to real unclean environments, and passing better the tube bendings.

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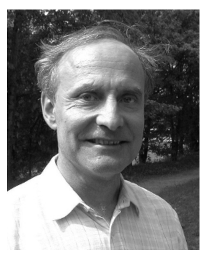
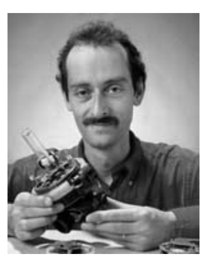
Roland Moser received a M.Sc. in Precision Engineering, micro technologies in ETHZ, and his PhD at EPFL in 2002. He has been Manager of the Electronic Department of SSM AG (2003-2005), and Director of R&D Inspection Technologies at ALSTOM Power (2005-2010). He is now the Department Head of R&D Inspection Methods and Robotics/Automation at Alstom Power.



Hannes Bleuler received his M.Sc. in Electrical engineering in 1978 and his PhD in 1984 at ETHZ. He has been a research engineer at Hitachi Ltd, Japan and at the Tokyo Institute of Technology (1985-1987). He was then Senior Assistant at ETHZ (1988-1991), and regular Associate Professor at The University of Tokyo (1991-1995). He is now Full Professor at EPFL on micro-robotics and biomedical robotics. He is co-founder of MECOS-Traxler AG and Xitact SA (robotic surgery instrumentation & simulators). He has been President Conference of Professors and Lecturers of EPFL, member of Assemblée de l'Ecole (2002-2006). He was Chairman of ISMB10 (10th International Symposium on Magnetic Bearings, Martigny, Switzerland, 2006). He was nominated as member of the Swiss Academy of Technical Sciences (SATW) in 2006.



Francesco Mondada received his M.Sc. in microengineering in 1991 and his Doctoral degree in 1997 at EPFL. During his thesis he co-founded the company K-Team, being both CEO and president of the company for about 5 years. He is one of the three main developers of the Khepera robot, considered as a standard in bio-inspired robotics and used by more than 1,000 universities and research centers worldwide. He participated to the SWARM-BOTS project as the main developer of the s-bot robot platform. In November 2005 he received the EPFL Latsis University prize for his contributions to bio-inspired robotics. His interests include the development of innovative mechatronic solutions for mobile and modular robots, the creation of know-how for future embedded applications, and making robot platforms more accessible for education, research, and industrial development.