Compact Magnetic Wheeled Robot With High Mobility for Inspecting Complex Shaped Pipe Structures

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Abstract— This paper describes a compact robot with two magnetic wheels in a bicycle arrangement, which is intended for inspecting the inner casing of pipes with complex shaped structures. The locomotion concept is based on an adapted magnetic wheel unit integrating two lateral lever arms. These arms allow for slightly lifting off the wheel in order to locally decrease the magnetic force, as well as laterally stabilizing the wheel unit. The robot has the main advantage to be compact and mechanically simple. It features 5 active degrees of freedom: 2 driven wheels each equipped with an active lifter-stabilizer and 1 steering unit. This paper also presents the design and implementation of a prototype robot and its high mobility is shown. It is able to pass 90° convex and concave obstacles with any inclination regarding the gravity. Finally, it only requires limited space to maneuver, since turning on spot around the rear wheel is possible.

I. INTRODUCTION

Using mobile robots carrying sensing tools for internal pipe inspection is an attractive alternative to conventional inspection methods. By avoiding disassembling complex structures or excavating deep pipe constructions, inspection and then outage time can be saved. Furthermore, these systems allow for inspecting locations that are not reachable using conventional tools.

As mentioned in [1], [2] and [3], many locomotion systems were developed for maneuvering about in different kinds of pipe environments. When climbing ability is required, the most common solution is to use spreading systems [3], which are not suitable for environment with high abrupt diameter changes. In these cases, the locomotion concept is combined with an attachment system such as grasps, suction cups [4], adhesive polymers [5] or (electro) magnetic elements.

The in-pipe environment considered in this paper requires a compact locomotion system with climbing ability, as well as a high degree of mobility for negotiating obstacles. The environment is a complex structure with narrow sections, high abrupt diameter changes and inclined elements. Since the first attachment concepts listed above usually imply complex mechanics and since the environment is ferromagnetic, magnetic wheels were selected [6] for this application.

The following state of the art then focuses on mobile robots with magnetic elements and describes their limitations. Simple compact systems such as *Magnebots* [7], *Tripod* [8], Osaka Gas inspection robot [9] and *Nanomag* [10] have a limited mobility. They are not designed for passing obstacles: they can at most travel on slightly curved surfaces (e.g. on the outside of tanks) or go over small size steps (smaller than the wheel radius).

In comparison, Fischer [11], Yukawa [12] and Kawaguchi [13] robots implemented special mechanisms to negotiate specific complex obstacles. The first two are designed for vertical walls and the outer surfaces of pipes. They aim to pass difficult obstacles such as sharp ridges which do not provide magnetic attraction force, but these robots require a lot of space and many DoF. The last one is more related to this work, since it is designed for inspecting the inner casing of pipes, but can only pass over a single step obstacle thanks to a passive wheel mechanism.
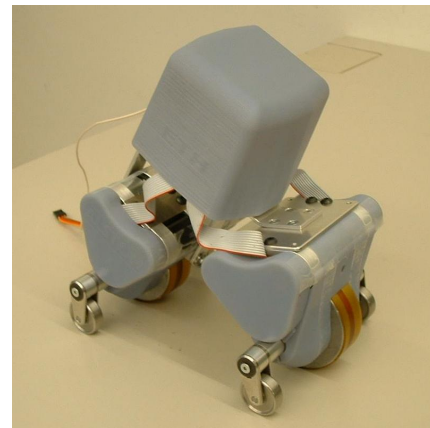

Fig. 1. Compact robot with two magnetic wheels in bicycle arrangement

A previous paper [6] describes in details why the existing locomotion systems cannot be used in this very restrictive environment and proposes a novel adapted magnetic wheel

unit allowing for negotiating complex obstacles. This paper then presents the design and implementation of a compact two wheels robot with bicycle wheel configuration (Fig. 1) based on this concept. The prototype proves the feasibility of the concept and tests show the high mobility of the robot which can negotiate complex obstacles.

The paper is organized as follows. After having presented the characteristics of the challenging environment in Section II, Section III reminds the concept of the adapted magnetic wheel unit and its advantages towards mobility and miniaturization. Design considerations are then explained in Section IV. While the robot implementation is described in Section V, preliminary results obtained with the first prototype are presented in Section VI. After having described the current prototype limitations, improvements and future work are proposed.

II. REQUIREMENTS: APPLICATION AND ROBOT NECESSARY MOBILITY

This section gives an overview of a specific ferromagnetic environment for which non-destructive testing (NDT) is desired and the challenges it addresses to the necessary locomotion system.
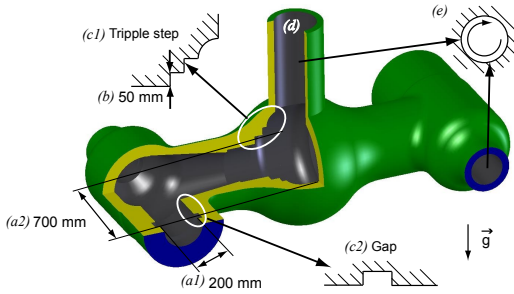

Fig. 2. 3D CAD model of a typical environment

An efficient inspection robot allows for bringing the inspection sensor to any location in the environment. Here is the list of the application requirements, as depicted on the 3D CAD model (Fig. 2):

a) the wide range of inner diameters encountered. The diameter varies from 200mm (this defines the maximum robot space envelope) up to 700mm.

b) the local abrupt inner diameter changes, up to 50mm on Figure 2. These can be seen as 90° convex or concave obstacles.

c) the complex arrangement and sequence of these obstacles such as triple steps or gap.

d) the environment is composed of horizontal pipe elements, as well as vertical elements. Generally any inclination can be encountered. Climbing ability is then required.

e) The locomotion system has to be able to maneuver (turn on spot) in narrow locations and to be able to travel on circumferential paths, which can also have any orientation regarding gravity.

Furthermore, since the system is intended for inspection, it has to embed NDT sensors. Thus the robot should be able to carry its own mass plus some extra payload (estimated to 500g) corresponding to the mass of the sensors and their manipulation tools. Finally, the inspection system must not damage the environment. Every part which is in direct contact with it has to be equipped with a protecting material, typically rubber.

III. 2 + 4 WHEELS LOCOMOTION CONCEPT

As analyzed in [6], it is a complex task to design a universal system able to face any combination of 90° surface transitions. In this previous paper, it is also shown that an adapted wheel (Fig. 3) is necessary to get rid of the unwanted magnetic force (F_{mag2}), when one or several wheels are in contact with 2 different surfaces (e.g. a 90° concave edge).
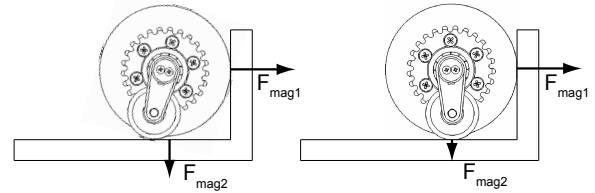

Fig. 3. The lever arm mechanism is applied, in order to slightly lift off the wheel and locally decrease the unwanted magnetic force F_{mag2} [6]

Among the potential wheels configurations illustrated in Figure 4, arrangements ②, ③ and ④ have a major problem: there is a magnetic force decrease, when the wheels are not standing perpendicularly to the pipe surface (Fig. 5, bottom). The best solution to avoid this problem would be to implement complex passive mechanics with virtual center of rotation on the wheel-to-surface contact point as illustrated in Figure 5 (right). This solution allows for ensuring a maximal magnetic adhesion (Fig. 5, top), but unfortunately uses too much space, is complex and heavy. On the other hand, the 2 aligned wheels (bicycle wheel configuration) arrangement ① in Fig. 4, which is not dependant on the pipe diameter, has the main drawback to be laterally unstable.
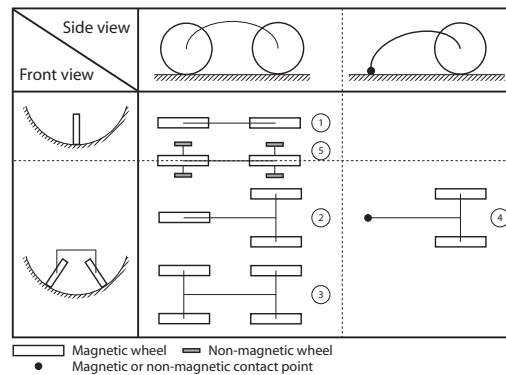

Fig. 4. 2 to 4 wheels arrangements: matrix of top view regarding side and front views [6]

The chosen locomotion concept consists in assembling two adapted magnetic wheels unit integrating an active rotary lifter mechanism (Fig.3), which can also be used as wheel stabilizer. Indeed, this compromise including 2 + 4 wheels (configuration ⑤ in Fig. 4) has the advantages of the 2 aligned wheels robots: it is mechanically much simpler and consequently smaller than other wheel configurations. Moreover, it can be laterally stabilized thanks to the 4 lateral non-magnetic wheels.
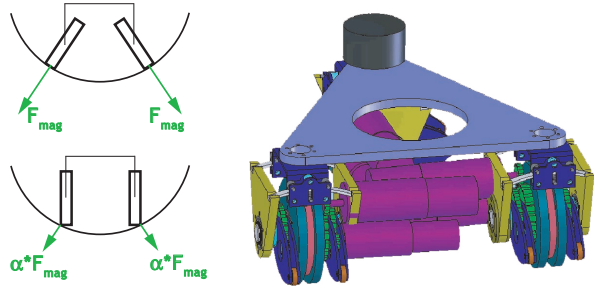

Fig. 5. Left: magnetic wheel without and with ground adaptation. Right: example of a 3 magnetic wheels robot with cumbersome passive mechanics and actuators

This paper then presents the design and implementation of a robot (Fig. 1) with 2 aligned magnetic wheels integrating the lifter-stabilizer function. Steering is ensured thanks to an active DoF on the front wheel and surface adaptation is ensured thanks to the free joint in the fork (Fig. 6). This system has then the main advantages to have high mobility while being mechanically simple and compact. It only has 5 active DoF (2 driven wheels, 1 active steering and 2 lifter-stabilizer arms pairs) and 1 free joint.
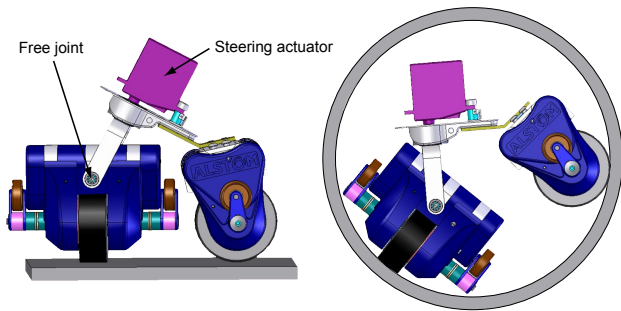

Fig. 6. The free joint on the fork allows for adapting to different environments: flat or curved surface

IV. ROBOT DESIGN

A robot which can drive on surfaces with any orientation regarding gravity requires special design attention. In order to avoid the robot to fall, to ensure stability, to allow climbing and obstacle passing ability, a good compromise between the magnetic force of the wheels, the robot mass and the power of the actuators has to be found.

This section then presents the robot model, the main assumptions, the worst cases and their consequences on the design.

A. Magnetic wheels tests

Since data about magnetic wheel performance (relation between the magnetic force F_{mag}, its mass and size) are necessary for the calculation, some tests were performed.
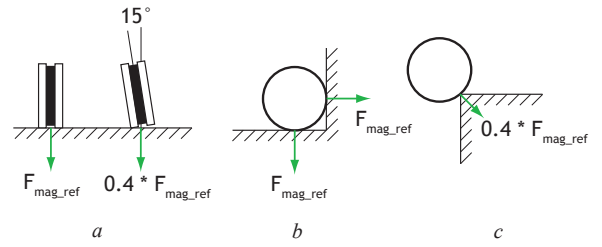

Fig. 7. Main results of the magnetic wheel tests

The most critical results are illustrated in Figure 7:
a) the magnetic force of a tilted wheel decreases to 75% at 3°, 55% at 10° and even 40% at only 15°.
b) the same reference magnetic force (F_{mag_ref}) is measured on both contact points for a wheel positioned on a 90° concave edge.
c) the magnetic force decreases fast on sharp edges: 40% of the reference force when the wheel is positioned on a 90° convex edge.

B. Robot model: forces and torques

The following forces and torques are considered in the robot model (Fig. 8): the magnetic forces (F_{mag_ix}), the robot weight which includes the payload (mg), the actuator torques T_i, the traction forces (T_{r_ix}) and the reaction forces (R_{ix}) which define the necessary friction coefficient ($\mu_{ix} = T_{r\_ix}/R_{ix}$). The main mechanical dimensions used are the robot length L, the wheel diameter r and the position of the center of mass (x_{CM}, z_{CM}).
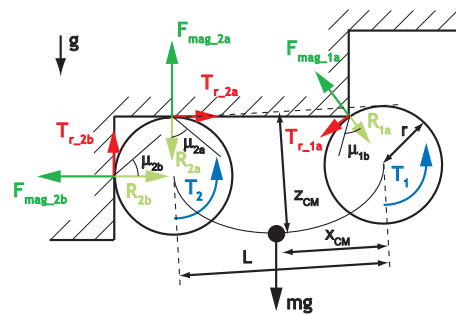

Fig. 8. Forces model of the robot

The static equilibrium force and torque equations were calculated for all robot positions on various obstacles and the results analyzed, in order to extract the worst cases, which are described afterwards.

C. Necessary magnetic force

The magnetic force aims to ensure that the wheel does not lose contact (Fig. 9a), but also provides enough traction force

to move. Assuming a minimum friction coefficient μ of 0.5 (measured), the absolute worst case is to ensure that the robot is able to provide enough traction when climbing a double step, on the ceiling, when one wheel is on a sharp edge and the other needs to get detached from a double contact point as depicted on Figure 9b. This case sets the minimum magnetic force. The force should however not be over-dimensioned to minimize the load on the lifting mechanism.
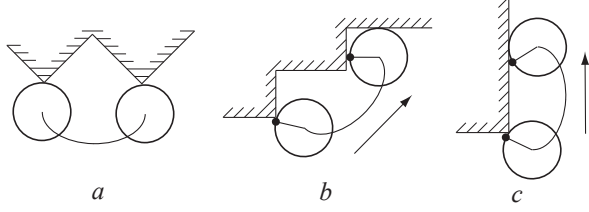

Fig. 9. Worst cases. *(a)*: not loosing contact, *(b)*: not slipping, *(c)*: maximal wheel actuator torque

D. Necessary wheel actuator torque

The wheels actuators have to be strong enough to drive the robot in any situations. For the wheels actuators, two worst cases can be distinguished. The absolute worst case happens when the robot is climbing vertically and 1 wheel cannot provide much traction (Fig. 9c). This calculation determines the absolute maximum intermittent load on the wheel motor. The worst case, determining the maximum continuous load on the wheels actuators, happens when the robot climbs a vertical wall for a long time.

E. Necessary lifter actuator torque

Concerning the lifters actuators, the worst case happens when a wheel has to be lifted in the narrowest tube (respectively 200mm of diameter). Indeed, in this situation the lifter lever arm (x_{lift}) is the longest and the lifter force $F_{lift} = (F_{mag} + mg/2) \times L/(L - x_{lift})$ is the highest. The required torque $T_{lift} = F_{lift} \times x_{lift}$ is then maximum. Since the lifter only works in intermittent mode, there is no continuous load worst case.
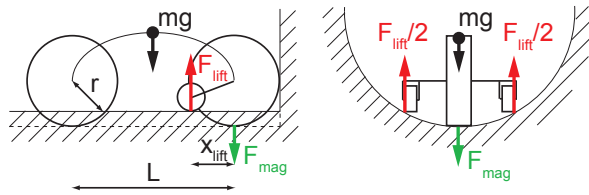

Fig. 10. Worst case regarding lifter-stabilizer actuator torque: lifting the wheel in the narrowest tube

F. Necessary steering actuator torque

The steering torque (T_s) necessary to turn the front wheel can be deduced from the wheel geometry and the friction forces (F_{fr_i}) between the wheel and the surface: $T_s = \mu \times$

$(F_{mag} + mg/2) \times b/2$. The steering torque is high for a robot equipped with magnetic wheels, due to the magnetic forces which are several times higher than the robot weight.
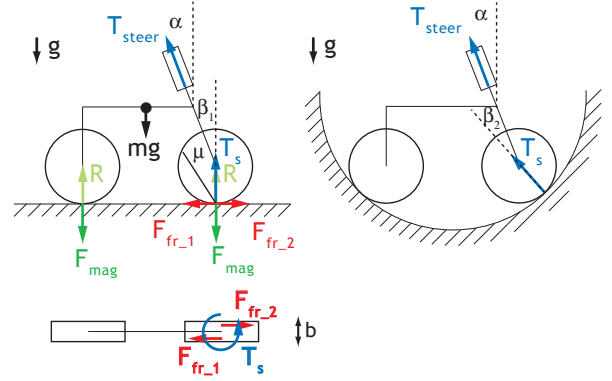

Fig. 11. Necessary steering torque

The effective torque (T_{steer}) of the steering actuator depends on the robot geometry and its location in the environment as depicted in Figure 11. The steering axis is inclined from an angle α to satisfy the ground clearance constraint on sharp obstacles (Fig. 13c). This inclination is also set, so that the angle β between the steering axis and the surface normal vector remains small for extreme positions of the robot: on a flat surface (Fig. 11, left) and on a curved surface (Fig. 11, right).

V. IMPLEMENTATION

Now that the main design issues have been presented, the feasibility of the concept is demonstrated by a prototype implementation. This section explains the main constraints in the implementation process of the magnetic wheel bicycle, composed of 2 adapted wheel units, of which one can be steered.

A. Wheel unit

The main challenge is to implement a compact wheel unit integrating the coaxial wheel and lifter mechanisms and their actuators. As illustrated in schematic 12, the following choices have been made:

- Both actuators (wheel and lifter) have been positioned on top of the wheel for compactness.
- The power transmission (wheel and lifter) is ensured by 2 stages of spur gears, one on each side of the wheel.
- Collision with obstacle in front of the wheel unit must also be avoided (Fig. 12, right).

B. Steering unit and assembly

The robot is then the assembly of two similar wheel units and a steering unit that is added to the front wheel. The following constraints require special attention:

- There must be no mechanical collisions, when the front wheel is steered at 90° in the narrowest space as shown in Figure 6 (right).
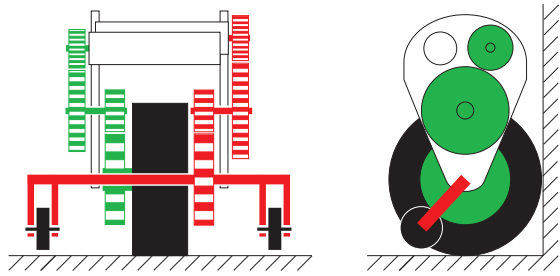
Fig. 12. Sketch of the wheel unit with coaxial lifter and wheel shafts. Shafts are independently actuated through two different gear trains: one on each side of the wheel

Fig. 13. Robot negotiating a 90° convex edge, followed by a 90° concave edge on the ceiling

- There must be enough ground clearance between the 2 wheel units, so that the robot can pass on 90° convex edges (Fig. 13*c*).

C. Robot characteristics

Based on all these design considerations, a prototype (Fig. 1) was built. Table I summarizes its main characteristics and further explanations are given.

TABLE I
ROBOT CHARACTERISTICS

Mass :	3.3 kg
Mass repartition:	Wheels: 23%, actuators: 18%, gears: 17%
Size :	$170{\times}130{\times}220\text{mm}^3$ (L×W×H)
Wheel distance :	115mm
Wheel diameter :	60mm
Magnetic wheel force :	250N (NdFeB magnets)
Maximum speed :	2.7m/min
Operating voltage :	24V
Consumption (max. speed):	0.19A (hor.), 0.28A (vert.)
Communication :	RS232 @ 115'200baud
Control mode:	Remote control

The wheels are equipped with synthetic rubber tires (PU), in order to increase the friction coefficient and protect the environment. The robot is not power-autonomous, since it does not embed any battery. It is tethered with a cable that is used for communication, power and security. Power autonomy is not yet an objective, since a cable is in any case required, because wireless communication might cause problems in thick metallic pipes.

VI. RESULTS OF TESTS AND DISCUSSION

In this section, the functionality of the concept is proven by presenting the results of preliminary tests in different reference environments.

A. Experiment 1: overhanging step

Figure 13 shows the robot negotiating a 90° convex edge, followed by a 90° concave edge on the ceiling.

This experiment shows that:

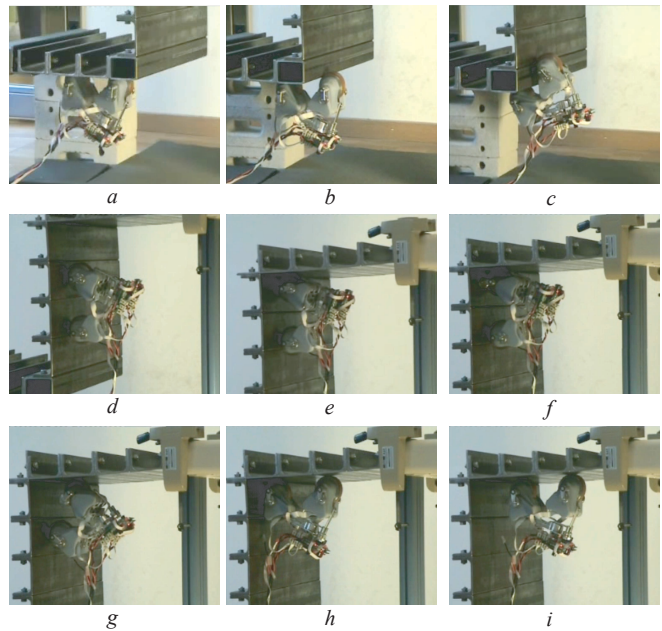- the magnetic force is strong enough, even on sharp edges (*b*).

- the ground clearance is sufficient (*c*).
- the robot can climb vertical walls (*d*).
- the lifter torque is strong enough to lift off the wheel (*f,h*). Additional tests were done to prove that it is strong enough even in the worst case (smallest pipe diameter).

B. Experiment 2: turning on spot and circumferential path

Further experiments were performed, in order to confirm the functionality of the concept. For instance, Figure 14 shows that the robot is able to turn on spot and to follow a circumferential path in the real environment.

In this experiment, the robot running along the pipe *(a)* stops, so that it can turn its front wheel from 90° *(b)*. The robot then turns 90° on spot around its rear wheel *(c)*, before starting a circumferential path *(d-f)*. The robot then turns again on spot *(g,h)*, in order to continue its way in the pipe *(i)*.

Further tests confirmed the high mobility of the system: the robot can drive sideways by using the lifter arms as stabilizers (the robot is not self-stable laterally). However passing a step with this orientation remains difficult in remote control mode. For that purpose, an automatic stabilizer controller function is under development.

C. Limitations and discussions

The experiments results presented above showed the expected performance of the bicycle robot. However, testing revealed a few limitations which mainly affect the robot control strategy. First, the robot needs to face the obstacles perpendicularly, so that the magnetic force does not decrease due to the tilt angle regarding the obstacle (as illustrated in Fig. 15, left). This remark is nevertheless valid for any magnetic wheel system.
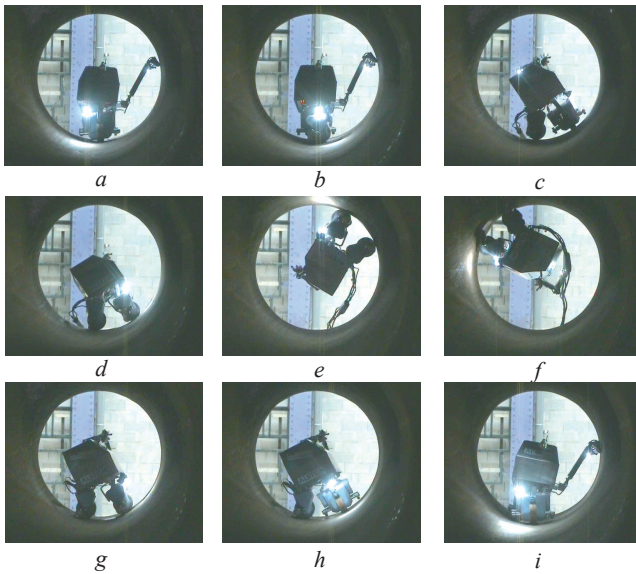
Fig. 14. Robot turning on spot and then following a circumferential path (real environment)

Another limitation comes from the two aligned driven wheels structure and the irreversibility of their power transmission trains. This wheel configuration implies a good control strategy: powering one wheel does not allow for forcing the movement of the other one, moreover a bad speed (or torque) repartition between them implies the robot deformation or slippage (which should be avoided on a robot which is intended to climb).
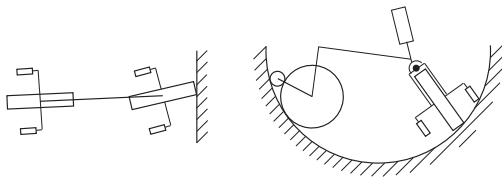

Fig. 15. Necessity to maintain ground contact. Left: correctly approaching the obstacle. Right: reducing wheel distance when turning

The same remark implies when the robot steers its front wheel to 90° position. Indeed, the wheel distance has to be controlled, in order to avoid the front wheel tilt and a magnetic force decrease as depicted on Figure 15 (right). Next developments address these issues.

VII. CONCLUSION AND FUTURE WORK

In this paper, an in-pipe environment, for which a mobile robot brings attractive advantages over conventional inspection methods is presented. Its complex shaped structure requires a locomotion system with a high degree of mobility, in order to negotiate complex combinations of step obstacles with several inclinations regarding gravity. Based on the concept of an adapted magnetic wheel unit already proposed in [6], a two-wheeled robot with bicycle wheel configuration is proposed, implemented and tested.

This robot has the advantage to be compact and mechanically simple. It only has 5 active DoF and 1 free joint, moreover the aligned wheel arrangement makes it almost independent of the pipe radius. The preliminary experiments showed that the robot mobility fulfills the application requirements and that the concept is feasible.

At the moment, the robot can be remote controlled by a trained user that has a good overview on the scene. However, since this will not be the case in the real closed environment, an automatic control is required. Ongoing work first consists in integrating sensors that help ensuring a correct distance between the wheels, in order to avoid the robot deformation (or slippage) and to ensure front wheel contact when steering. Moreover, an automatic stabilizer arms positioning system is necessary. Later on, higher level control functionalities will be implemented, in order to decrease the user interaction with the active system.

VIII. ACKNOWLEDGEMENTS

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