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Very Compact Climbing Robot rolling on Magnetic Hexagonal Cam-Discs, with High Mobility on Obstacles but Minimal Mechanical Complexity

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Summary / Abstract

In this paper, we present the mechanical design of a very compact climbing robot with outstanding mobility in environments that allow for ferromagnetic adhesion. It is planned to be used for the inspection of complex shaped environments in power plant components, as they can be found in the housings of large generators, steam chests or pipe systems. After a detailed discussion of previous designs and their main limitations, we present a new vehicle concept that rolls on magnetic hexagonal cam-discs. In preliminary experiments we show that inner and outer transition can be passed with such magnetic cam-discs very easily. Where a normal magnetic wheel would get stuck, this new design just passes. This observation and its impact on robot design are analyzed more detailed by using a 2D mechanical calculation model. This analysis leads to the finding that a robot rolling on such cam-discs instead of classic magnetic wheels can be realized much simpler than previous designs – using traction on only the front shafts, no rubber cover on the cam-discs (higher robustness on rusty surfaces) and no additional mechanisms such as additional wheels in the structure, dual magnetic-wheels or even additional actuators for actively reducing the unwanted adhesion force in inner transitions. After successful tests with a preliminary prototype with only one traction unit, the paper concludes with the realization and tests of the final prototype (also including a second unit for steering and a camera mock-up), a comparison towards our previous design and an outlook to future improvements and enhancements.

1 Introduction

Compact robots rolling on permanent magnetic wheels combine the continuous motion and the simple control of wheeled robots with the high mobility of climbing robots. For this reason, they are frequently used for the inspection of complex shaped structures out of ferromagnetic steel, as they can be found in huge ships, pipelines, power plant components or similar environments. For dealing with inner transitions (corners), several mechanisms have been proposed, with all of them showing specific limitations or disadvantages.

In order to avoid these limitations, other robots do not roll on wheels but use other roll-legged locomotion principles - caterpillars or whegs. By using these principles, they are able to pass inner transitions without the need of specific mechanisms - but mostly still need a relatively high mechanical complexity and/or show limitations on outer transitions.

In this paper, we present a compact climbing robot that can be seen in between these approaches by using wheels that are not round but shaped hexagonal; like screw-nuts. With these special discs, the advantages of normal magnetic wheels and whegs can be combined – simple mechanical design but high mobility in inner and outer transitions.

Preliminary experiments, calculations for estimating the required friction coefficient and the motor torque, the design of a preliminary and an advanced prototype, and potential applications are presented.

The paper is structured as follows: Section 2 provides a short overlook on three typical scenarios in power plant inspection that have been investigated by our team and point to the most difficult obstacles and environment challenge that have to be solved there. In section 3, the most recent compact climbing robots for such types of applications are presented. This state-of-the-art-overview is followed by the presentation of the concept to use hexagonal cam-discs instead of wheels and a detailed comparison towards standard magnetic wheels - based on preliminary experiments and calculations (section 4). The paper concludes with the implementation and successful experiments of a prototype with the specified mobility on inner and outer transitions, two symmetric wheel units that allow for steering, and a reasonable payload capability to perform the inspection tasks.
2 Typical challenges for moving in power plant components

As already stated in the introduction, the main motivation behind this paper and also the previous research in our team [3, 5, 6, 7] is to design very compact robots with high mobility that are used for the inspection of power plant components. As already explained in these previous publications and summarized in Figure 1, the most difficult challenge for a robot’s mobility is to pass inner and outer transitions, which is usually necessary in all possible inclinations in respect to gravity and sometimes with very short distances between the transitions (combined obstacles such as triple steps, see Figure 1-a). In most applications, the available space for the robot is very limited (down to Ø142mm in generator housings, see Figure 1-c and [7]). For this reason, robots with active mechanisms for passing inner transitions (e.g. the rotary lifters in the MagneBike [6]) cannot be used for the narrowest environments, as the necessary mechanics and control electronics would not fit any more. Furthermore, some environments such as boiler walls (Figure 1-b and [13]) are extremely dirty and abrasive. Such a structure does not allow for using wheels with a rubber-cover. As it was already shown in our paper about calculation theory of magnetic wheels [3], such a rubber-cover on the wheels – which increases the friction coefficient between wheel and surface – is crucial for rolling passively through inner transition with a magnetic wheeled robot that does not use any additional mechanisms.

Figure 1 Typical challenges for moving in power plant components (a) Steam chest with combinations of inner- and outer transitions at short distance [6], (b) Boiler walls with abrasive surface that does not allow for using wheels with a rubber-cover on the rims, (c) Generator housings with the most difficult size limitation [7].

To sum up – the goal of this project was set to find a solution that allows for passively rolling through inner and outer transitions without using a rubber-cover on the steel rims (µ=0.3-0.4) and by keeping the mechanical complexity as low as possible for allowing for minimal size and complexity.

3 Overview on compact climbing robots

Several types of climbing robots have been developed during the last years – not only for the inspection of power plants, but also for similar applications such as search-and-rescue or anti-terrorism-duty. The following chapter provides a brief overlook on the most recent ones that are highly relevant for the here presented applications.

3.1 Simple Robots on magnetic wheels

If the environment to inspect is made out of steel that allows for ferromagnetic adhesion and does not contain difficult obstacles such as inner and outer transitions, magnetic wheeled robots with two motorized wheels for differential steering and a castor wheel as the third contact point are the principle of choice. They are already state of the art since many years and commercially available by several companies. Examples of this type are the Tripod [1] by Jireh Industries or the MRS 200 [2] by ALSTOM Inspection Robotics. If also inner and outer transitions have to be passed, traction on all wheels and a rubber-cover on the wheels is necessary. An example for such a robot is the preliminary test prototype which was developed in our team [3]. This publication also shows the basic 2D calculation model for magnetic wheeled robots.

3.2 Magnetic wheeled robots with mechanisms for passing inner transitions

If the required mobility is not only limited to simple inner transitions but to more difficult obstacles such as thin ridges, holes or triple steps, the most intuitive approach is to use active mechanisms for passing these obstacles – with their necessary size and complexity strongly depending on the difficulty of the worst-case obstacles they have been developed. Examples for robots with very high obstacle-passing capability (even thin ridges), but relatively big size and mechanical complexity are the PIR [4] or the ETH-concept for gas-tank-inspection [5]. A simpler robot with still very high mobility (no thin ridges, but difficult combinations of inner- and outer transitions such as triple steps) was also developed in our team at ETH – the MagneBike [6]. Even if this robot is already significantly simpler than the above mentioned prototypes (need for only 5 motors), its control complexity was still regarded as too high for downsizing it to a size that would fit through the entrance gaps in generator housings (Ø142mm). For this application, we then developed a concept with additional non-motorized wheels in the robot structure [7].
With this design, the required friction coefficient between wheels and surface in inner transitions can be decreased significantly in comparison to simpler robot structures [3]. This allows for passing these obstacles even without rubber cover on the wheels. Even if already being much simpler than previous robots, the robot with additional non-motorized wheels still needs 8 wheels in total and traction on 4 of them. Also on rusty surfaces, this robot does not perform well, as the small wheels can get stuck in little holes formed by the corrosion process.

Another approach for facilitating inner transitions is to use a dual-magnetic wheel – as proposed in a robot for sewage-pipe-inspection [8]. However, this approach shows its limitations when passing inner transitions on the ceiling, as there is a high risk that the robot falls down. A detailed explanation of this limitation is provided in the introduction of the publication about the MagneBike-Robot [6].

3.3 Robots with magnetic adhesion but alternative locomotion principles

Concerning non-wheeled locomotion principles, the most intuitive approach in the field of climbing robot with magnetic adhesion is to use legs instead of wheels. Examples are the ROBINSPEC by Catania University [9] or the Inchworm-robot by Dartmouth College [10]. Note that legged climbing robots with only two legs are often also called Inchworms, Arms or Bipedes. All these robots achieve a very high mobility, but are usually even bigger and more complex to control than wheeled robots with active mechanisms. For this reason, they cannot be considered as simple and compact enough for the here analyzed applications in power plant inspection.

Partially inspired by these robots on legs, also combinations of wheels and legs have been realized in the field of climbing robots with magnetic adhesion – under-actuated legged locomotion, or also called “whegs”. One example for such a robot is the one developed by Berenguieres et al. [11]. It uses the peeling-effect for reducing the motor-torque for climbing, but the paper does not provide a comparison to wheeled robots or a report about the obstacle-passing-capability of this design. Another robot that uses a locomotion principle somewhere between wheels and legs is the “Gecko” by Ben-Gurion University [12]. By placing several small magnets that can move in radial spring-loaded slide-bearings on a wheel like structure, a compliant-adhesion-effect can be used which allows for passively rolling through inner transitions even without rubber on the magnets. However, the ability to pass outer transitions in all inclinations was not proven with this robot yet, and also the mechanical complexity of these special wheels still seems as high as the design with passive extra wheels in the structure [7]. Some implementations with magnetic caterpillars exist as well. The most recent and to our best knowledge also the most compact one is the TriPillar [13] developed by EPFL. Thanks to a wheel arrangement that is very similar to the one in our previous design with passive extra wheels in the structure, it is able to pass inner transitions but fails on outer transitions as the caterpillars get peeled off there.

3.4 Other compact climbing robots that use roll-legged locomotion principles

In the field of non-magnetic climbing robots, several new designs have been proposed in the last years as well. While legged (e.g. the Roma II [14]) or hybrid solutions (e.g. the City-Climber [15]) usually result in even bigger systems than comparable robots with magnetic adhesion; in the field of robots rolling on caterpillars or whegs, very simple and compact solutions have been realized:

In the field of robots rolling on adhesive caterpillars, the CMU TankBot [16] is not only able to pass inner transitions in all inclinations, but also outer transitions from a wall to the top ground. It only fails (or at least the video does not show it) on outer transitions from ceiling to wall. Concerning robots rolling on whegs, the WaalBot [17] which was developed by the same team is also able to pass inner transitions passively, but fails on outer transitions and cannot go down (assumption, as this is not shown in the video). Another robot on whegs – the gel-type-sticky-mobile-inspector [18] is able to do these types of transitions, but is however also limited to relatively clean surfaces that do not damage the adhesive material. When analyzing the video in more detail, one may also note that the robot is always shown when it moves upwards, while a concept for also moving downwards is not presented.

3.5. Comparison according to the worst challenges in power plant components

An overview on the most recent and/or outstanding robots from each group is provided in Figure 2. As it can be seen there, none of these previous climbing robots at very small size is able to deal both with inner and outer transitions, and to also run on irregular abrasive surfaces with rust. In addition, the ones with advanced mobility also show a relatively high mechanical complexity.

For this reason, the goal of this project was set to realize a new type of climbing robot that can pass all types of inner and outer transitions even on rusty surfaces at minimal mechanical complexity.

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Limitation</th>
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<tbody>
<tr>
<td>a) Even on rusty surfaces</td>
<td>Need for a rubber cover on the wheels</td>
</tr>
<tr>
<td>b) Even on rusty surfaces</td>
<td>Risk to fall down</td>
</tr>
<tr>
<td>c) Need for 5 motors + 5 sensors</td>
<td>High complexity</td>
</tr>
</tbody>
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Figure 2 (a-c), (c-f) is continued on the next page
Figure 2 Overview on recent climbing robots at very small size and their performance on specific obstacles in respect to their overall complexity
(a) First test prototype at ETH [3], (b) Robot for sewage pipe inspection [8], (c) MagneBike [6], (d) Robot with passive extra wheels in the structure [7], (e) Gecko [14], (f) Gel-type-sticky-mobile inspector [18].

4 Basic analysis of the hexagonal magnetic cam-discs

Given the advantages of both magnetic wheeled robots and the most advanced concepts rolling on non-magnetic whegs, our approach was to combine both ideas – by realizing a robot that rolls on magnetic wheels/discs that are not round but shaped hexagonal like screw-nuts. Preliminary tests with such a hexagonal magnetic cam-disc mounted on a flexible shaft already showed the impressive obstacle-passing-capability on inner and outer transitions. This observation was later-on analyzed more detailed with quantitative tests and 2D-calculation models, for proving the feasibility to build a robot based on this concept.

4.1 Preliminary tests

For the first tests, a pair of M4-screw nuts (wrench-size=7mm, b=2mm) and one NdFeB-ring-magnet (Ø6/3, b=3) were glued together and attached to a flexible shaft which allowed for turning the entire unit by hand (Figure 3-a). The necessary torque on the shaft was measured with a wrench and a balance-weight attached to it (Figure 3-b). This measurement was performed both for normal rolling and for rolling through a 90° inner transition. In addition, the same experiment was also performed with a normal magnetic wheel of similar size (round discs with Ø=7mm, b=2mm, same ring-magnet) in order to see the difference. What could be observed from this preliminary experiment is the following:
- In contrast to a standard magnetic wheel, the hexagonal magnetic cam-disc is able to passively roll through an inner transition – even without a rubber cover on it for increasing the friction coefficient between disc and surface.
- The necessary torque for turning such a hexagonal magnetic cam-disc (measured: 15mNm for normal rolling, 40mNm for passing an inner transition) is significantly higher than for a wheel of similar size (almost zero), but still at a reasonable value that can be achieved with gear motors at a similar size than the screw-nut. For example, a Maxon RE6, with a 221:1 planetary gearbox achieves approx. 50mNm stall torque, at a size of Ø6mm x 40mm.

4.2 Mechanical calculation model

For better understanding these observations and for finding the best values for the core-parameters in the robot design, a 2D-mechanical calculation model was established.

4.2.1 Motion sequence for passing a corner

In order to find the worst cases for the required friction coefficient and the necessary motor torque on the shaft of the magnetic cam-disc, the motion sequence for passing an inner transition (corner) had to be analyzed. Note that in this model, the gravity force coming from the robot can be neglected, as it is approximately 10 times smaller than the magnetic forces.

As represented in Figure 4, the adhesion force between disc and surface changes between two values – the maximum adhesion force \( F_{mag-max} \) (flat surface of the screw-nut) and the minimum force \( F_{mag-min} \) (edge of the screw-nut), which is approximately 3-4 times smaller. When the robot rolls into a corner, the disc usually starts slipping, until it

Figure 3 Preliminary tests with a flexible shaft, for comparing the hexagonal magnetic cam-disc towards a normal magnetic wheel (a) Ability to passively roll through inner transitions, (b) Estimation of the necessary torque for turning the hexagonal magnetic cam-disc

Figure 4 Motion sequence when passing a corner with a robot rolling on a hexagonal magnetic screw-nut, with the worst-cases for calculating the necessary friction coefficient and the required motor torque.

As represented in Figure 4, the adhesion force between disc and surface changes between two values – the maximum adhesion force \( F_{mag-max} \) (flat surface of the screw-nut) and the minimum force \( F_{mag-min} \) (edge of the screw-nut), which is approximately 3-4 times smaller. When the robot rolls into a corner, the disc usually starts slipping, until it
reaches a favourable position where the maximum adhesion force is on the new surface and the minimum adhesion force is on the old one (Figure 4-2c). Thanks to the inhomogeneous distribution of the adhesion force, it becomes much easier for the robot to enter the new surface than it would be for a robot rolling on a normal magnetic wheel.

For quantifying this effect and also the negative effect of the increased motor torque in comparison towards normal magnetic wheeled robots, the worst cases for the required stall torque (Figure 4-2a) and the worst-case for the minimum required friction coefficient (Figure 4-2c) are modelled (Figures 6 and 8). In order to deal with realistic values for the force distribution, the magnetic forces for both the hexagonal cam-disc and for a magnetic wheel at similar size have been measured (see Figure 5).

For calculating this minimum required friction coefficient between disc and surface, the worst case when the disc is just about to leave the old surface, but the old force is still actuating in the wrong direction – similar as already seen in our previous papers about the calculation models for magnetic wheeled vehicles [3, 7]. The mechanical model and the derivation of the formulas for this case are represented in Figure 6. Note that the effect of gravity can be neglected, because it is approximately 10 times smaller than the magnetic forces.

4.2.2 Required friction coefficient for passing an inner transition (corner)

With these values and reasonable assumptions for the wheel axis distance in the robot (L), the required friction coefficient for passing inner transitions can be calculated – both for a hexagonal magnetic cam-disc and for a normal magnetic wheel at similar size.

For calculating this minimum required friction coefficient between disc and surface, the worst case when the disc is just about to leave the old surface, but the old force is still actuating in the wrong direction – similar as already seen in our previous papers about the calculation models for magnetic wheeled vehicles [3, 7]. The mechanical model and the derivation of the formulas for this case are represented in Figure 6. Note that the effect of gravity can be neglected, because it is approximately 10 times smaller than the magnetic forces.

With the values of the hexagonal magnetic cam disc which is used in our robot (F_{mag-min}=4N; F_{mag-max}=15N; r=3.5mm) and values for L up to 30mm, the required friction coefficient is calculated and represented in Figure 7 – both for the cam-disc and a standard magnetic wheel of similar size for comparison.

In this graph, it can be observed that for vehicles with a long wheel axis distance (L>r), the design with hexagonal magnetic cam-discs shows significantly lower values for \( \mu_{req} \) than the standard magnetic wheel. These values even stay below 0.4 – which allows for passing inner transitions without a rubber cover on the discs.

4.2.3 Required motor torque

For calculating the maximum required motor torque, a similar 2D-calculation model was established (Figure 8), and calculated for the case of normal rolling and the worst case when slipping in a concave corner; both for the hexagonal magnetic cam-disc and a normal magnetic wheel. For the friction coefficient between disc and surface, in this case the maximum value was assumed (\( \mu=0.5 \) in case of steel rolling on steel). The influence of the back wheel was neglected (L>>x \( \rightarrow \) \( F_{mag-max}=F_{nc} \)) for simplification.
Figure 8 Mechanical 2-D-calculation model for estimating the maximum motor torque at the worst case in inner transitions and for normal rolling – both for hexagonal magnetic cam-discs and for normal magnetic wheels. When comparing the results calculated with the measured values for force and geometry (Figure 5), the required motor torque for the hexagonal magnetic cam-disc is of course higher than for a standard wheel – with the values corresponding to the ones measured in the preliminary experiments with the flexible shaft (section 4.1). However, the torque is still low enough for being transmitted with a gear-motors at similar size than the screw nut – especially as the continuous torque which is necessary during normal rolling is only a third of the maximum-value which occurs during corner-passing.

4.3 Preliminary test-prototype
Given these positive results from the calculation, a preliminary test-prototype with one hexagonal magnetic cam-disc and a non-magnetic tail at the back was built and tested. It performed well in all types of inner- and outer transitions, and also on rusty surfaces. The test in inner transitions (concave corners) is represented in Figure 9.

Figure 9 The preliminary prototype with only one unit rolling through a test-environment with concave corners in all inclinations in respect to gravity.

5 Advanced prototype with camera and two wheel units
In the advanced prototype, two of such wheel units are connected together in the same structure. For the third contact point, a magnetic wheel with lower force (2.5N) is placed on the back of the robot. By magnetizing this castor wheel, a better stability for the camera image during normal rolling can be assured, while for outer transitions the non-magnetic zone around the castor wheel (“tail”) is designed in a geometry that does not disturb.

A CAD-model of the final prototype and photos of the tests are represented in Figure 10 and 11. During these tests, also the advanced prototype performed well on all specified obstacles.

Figure 10 CAD-model of the final prototype.

Figure 11 Tests with the advanced prototype (a) Normal inner and outer transitions and turning on spot, (b) Double-edges (ridges) with only 8mm thickness.

6 Conclusion and outlook
In this paper, the concept of using hexagonal magnetic cam-discs instead of magnetic wheels; and the advantages for improving the mobility of compact climbing robots for inspection purposes has been discussed, analyzed and proven in a prototype. This analysis was done based on 2D-calculation models and successful tests with a real prototype. This prototype was able to pass both inner and outer transitions independent from the direction of gravity – with traction on only the front shafts and without a rub-
ber cover on the discs. This combination of high mobility at minimal mechanical complexity had not been achieved with any previous climbing robot before. Given the outstanding performance, this design concept allows for realizing climbing robots for inspection purposes smaller, simpler and more robust – and thus allow for an enhanced application scope.

Future work will focus on further improvements of the current prototype regarding its control electronics, the integration of a good camera with light, and advanced software for localization based on vision-based odometry.

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8 Literature