An App to Design Flux Focusing Adhesion Systems for Climbing Robots

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Introduction

Mobile robotics is a rapidly advancing research area, thanks to a variety of technological developments in hardware and sensors. The operating environment and the task to be carried out are the main factors influencing the design of a climbing robot for industrial applications. Systems tend to employ either energy intensive suction cups or dynamic vortex adhesion methods for climbing on non-ferrous surfaces but when it comes to ferrous surfaces, the preferred choice is electromagnetic adhesion or permanent magnets. While electromagnets offer the ability to control the magnetic field on demand, they require constant energy consumption to maintain their magnetic field. Previous research on wall-climbing robots has focused on the payload capacity, mobility adhesion safety and energy consumption.
In this paper, we present an application built on top of COMSOL Multiphysics to assist the design of adhesion systems for climbing robots. It takes into consideration the use of permanent magnets (rare earth neodymium magnets) as the adhesion material and uses a flux focusing technique based on [1]. We describe in more detail the theoretical foundations and goals of the application in the next section.

COMSOL simulation set-up

Mobile robots need a locomotion mechanism in order to move around. Additionally, climbing robots have the ability to move on the vertical plane (fig.1), which requires a special adhesion mechanism to carry its payload along a vertical surface.

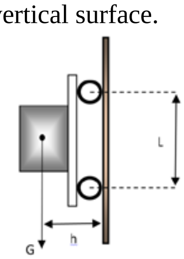


Figure 1. Free body diagram of a climbing robot on the vertical plane (for analysis refer to [5]).

Thus, the most important considerations while designing a wall-climbing robot are its mechanical design, locomotion and adhesion system. While these systems are intertwined, in this paper we focus on the design of the adhesion system.
We are interested in designing an adhesion system to enable a robot to climb on reinforced concrete structures to inspect for defects and corrosion on internal steel rebars. This scenario remains a challenge, as it is necessary to balance the adhesion force with the payload of the robot. The greater the payload/weight of the robot, the more adhesion force is needed. In order to enable the robot to move under such forces, the drive motors require significant torque, which in turn requires larger motors, increasing the overall payload. To tackle the analysis of this problem we used COMSOL Multiphysics.

The proposed adhesion module uses several permanent magnets and a flux concentrator or "yoke". The aim is to achieve the maximum adhesion force while keeping the module weight at the minimum.

Simulation of adhesion force under ideal conditions

In order to ensure the reliability of modelling, an initial simulation was created to set up a model to compute the adhesion force of the magnets under ideal conditions. This means that the obtained results will match with the manufacturer's datasheet. We decided to use N52 50x50mm magnets with 25mm of thickness.

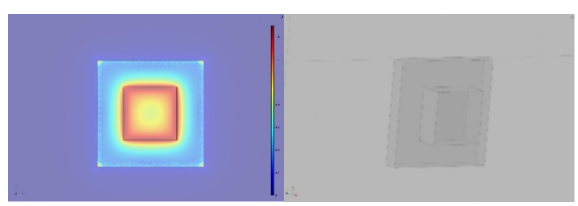


Figure 2. Force analysis of N52 Neodymium magnet under ideal conditions.

As per technical specifications, these magnets can support a steel weight of up to 116kg vertically from the magnetic face when in flush contact with a mild steel surface. This is one of the highest available grades in the market; nevertheless, their weight is 626 grams. The model uses the Magnetic Fields, no Currents interface from the AC/DC module.

While we did not use any models of the application libraries, the permanent magnet model was an inspiration. In the model builder we use only component 1 to define the geometry and materials.

The model comprises one N52 magnet, one steel plate (100x100x15mm) and one iron yoke of the same size as the plate. Geometry is shown in figure 2 and the material properties used for COMSOL simulations are listed in table 1. The air box is sufficiently large for the boundary condition on its remaining exterior to have little influence on the field in the vicinity of the magnet.

Table 1: Material properties for COMSOL simulations.

Properties	Value
Magnetic induction intensity mag **B_r(T)**	1.47
Magnetic Coercive force **H_{cb} (KA/m)**	796
Intrinsic Coercive force **H_{ci} (KA/m)**	876
Magnetic energy product **HB (KJ/m^3)**	398
Relative permeability of magnets **(μ_r)**	1.05
Relative permeability of steel plate	1000
Relative permeability of iron yoke	4500

The study computes the electromagnetic force of the magnet on *x* (mfnc, Forcex_plate), which is towards the steel plate. Thus, it is necessary to leave a small spacing of 0.1mm between the magnet and the plate to achieve reliable results. The mesh is set as extremely fine to avoid warnings due to this small gap. The computed force was 1156.8N (~117kg), which is in line with what is specified by the magnet technical specifications, thus validating the model.

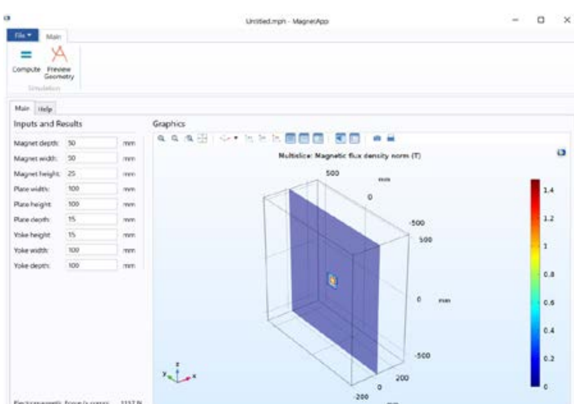


Figure 3. Early stages of the App.

It has been proven in [3] that by adding a yoke, the adhesion force increases significantly. The yoke will focus the magnetic flux on the side that attached the magnet and the yoke together, thus allowing more magnetic flux lines to flow through the opposite side. The results achieved when adding an iron yoke the same size of the steel place increase to 1663.3N (170kg). This model was used as a base model to construct the App shown in figure 3.

The Flux Focusing Adhesion System App

Based on the previous model we have designed an application using the COMSOL Application Builder. The objective of this application is to simplify the study of flux focusing adhesion forces. As shown in [2], two key parameters affect adhesion force: a) the distance between the magnets and b) the effect of yoke thickness.

From the application, it is possible to choose different (global) parameters such as the size and relative permeability of the magnet as well as the structure it will be attracted to (e.g. ferrous plate, single rebar or a mesh of rebars) to easily build and modify the model. The application includes a “preview geometry” button and from the user interface, it is possible to visualize and switch between different results such as (e.g. Magnetic Flux density norm) Multi-slice, contour or streamlines. Additionally, the help menu provides additional explanation on the application usage.

The air gap or distance between the ferrous surface and the magnet is an important parameter when designing and adhesion system for reinforce concrete structures. In [2] it has been analysed and tested that the best configuration to achieve the maximum adhesion force is using three magnets arranged with N-S-N orientation on an iron yoke. Their test was performed on a concrete wall with a rebar distance of 30mm using a small mobile robot (weighting 1.68kg) that claims to attain a maximum adhesion force of 61.8N and thus a payload capacity of 6.3kg.

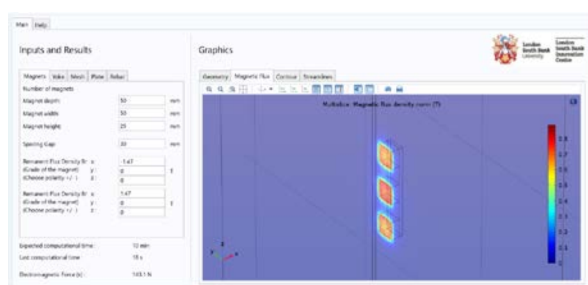


Figure 4. Three N52 magnets arranged N-S-N.

This configuration was used to modify the previous model and started to give shape to the application as shown in figure 4.

The model is composed of an iron yoke (250x50x10mm, approximately 960g net weight), three N52 rare earth neodymium magnets were arranged on top of the yoke in a N-S-N configuration and with 50mm spacing from each other. The magnetic adhesion system (yoke + magnets) was simulated over 12mm steel rebar with 30mm of concrete cover (air gap). The resulting adhesion force computed was 143.1N (14.6kg), thus more than double the one obtained by Howlader et al.

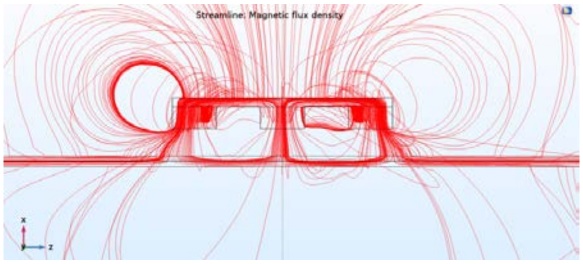


Figure 5. Magnetic flux line behavior.

In figure 5, we can observe the behaviour of the magnetic lines obtained with COMSOL streamlines plot. The flux is clearly concentrated on the iron yoke and flowing uniformly distributed through the air gap towards the steel rebar. This effect is also called *shielding* and allows to safety mount electronics devices on top of the system.

In order to validate the simulation results we have recreated the simulation with an *in-house* test rig. Setup and results are explained in next section.

Experimental results: in-house test rig

As it can be seen on figure 6, special care was taken while measuring and positioning the magnets on the yoke to construct the adhesion system as per the previous simulation. The weight of the adhesion system measured with an industrial scale was 2.83Kg.

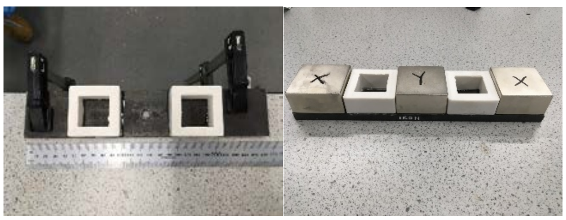


Figure 6. Construction of the magnetic adhesion system.

We have added an attachment on the iron yoke to be able to fix it on the *load cell machine* that performed the force/tension test. The Instron 5567A B723 machine used is capable of measuring forces up to 2kN. Calibration and assessment of the test machine was conducted in accordance with ISO 7500-1:2015 and using Instron procedure N001.

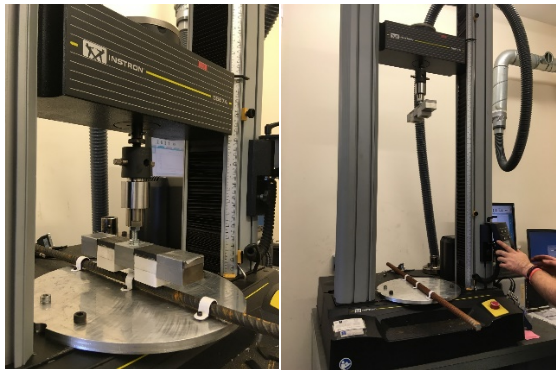


Figure 7. In house test rig using an Instron machine (2kN tension/compression load cell).

The adhesion system on the load cell was set to a distance of 200mm from the rebar (see figure 7). We recorded data (6 values per second), while slowly approaching the system to the 12mm rebar until a 20mm spacing gap was left in between the magnets and the rebar. The experiment was repeated for a 16mm and 20mm rebar diameter. For the sake of illustration, in the following sections we show the results using a 12mm rebar.

In real life, most of reinforced concrete structures have the rebars within a distance of 30-35mm. Nevertheless, the maximum concrete cover can reach 50mm. Hence, we computed the simulation analysis for a 50mm concrete cover obtaining a magnetic force of 31.39N. As expected, the gap between the magnet surface and the climbing surface is critical, as a small gap increases the adhesion force significantly.

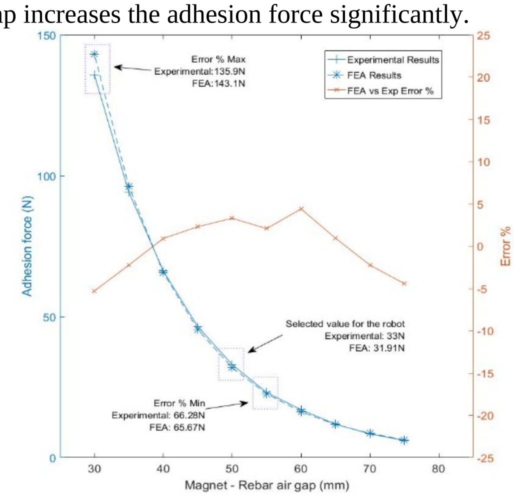


Figure 8. Comparison between experimental results and FEA from COMSOL.

We plot the data obtained from our *in-house* test rig against the FEA COMSOL simulation results to validate the modelling procedure. Considering the graph on figure 8, experimental results and the COMSOL results demonstrates a good agreement.
However, a ~5% error was recorded when the air gap is 30mm and the min error was recorded when the air gap is 40mm (*i.e.* min error of 0.91%). Systematic errors can be the reason for the ~±5 error percentage (*i.e.* when considering the air gap vs forces, ±1mm can influence the adhesion force significantly). These results provide evidence and confidence to validate the COMSOL Model, and thus the application.

Climbing robot adhesion system: case study

Potential workspace

In the previous section, we have shown that the gap in between the magnets and the climbing surface is critical. Nevertheless, other parameters influence the adhesion force such as the diameter and the configuration of rebars (e.g. a mesh of rebars), which can be translated as the amount of ferrous surface available. The standard in the UK that determines the minimum concrete cover is BS 850 and Eurocode [4]. Most reinforced concrete structures are made of a mesh of rebars as shown in figure 9.

Figure 9. Potential workspace for the climbing robot.

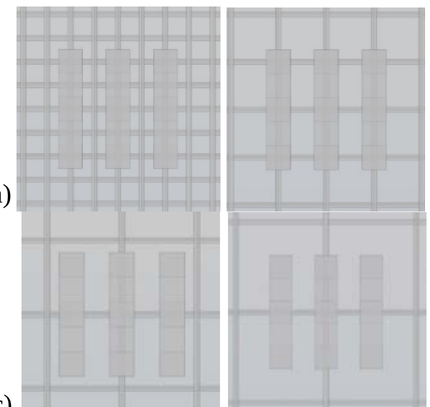
We have improved the application by adding the possibility to choose from a set of rebars (mesh) as the ferrous surface. The distance between the rebars and the concrete cover (gap) can be changed directly from the application.
For this experiment, we tested four different sizes of mesh (see fig.10) with three different concrete covers. In order to cover the most of the ferrous surface and achieve the maximum adhesion force, we decided on an arrangement of three yokes plus magnets (same as in the previous section) systems in parallel with a space of 50mm in between. The results are listed in table 2.

Table 2: COMSOL simulations on different mesh sizes and concrete covers.

Mesh space 12mm rebar	Force at 40mm	Force at 35mm	Force at 30mm
200x200mm	116.7N	159N	225.9N
150x150mm	145.0N	192.6N	265.3N
100x100mm	252.2N	352.6N	506.3N
50x50mm	287.9	391.4N	546.8N

As expected, the closer the ferrous surface is to the magnets, the greater is the adhesion force achieved.

a) b)



c) d)

Figure 10. Rebar mesh spacing in 4 configurations: a)50x50mm, b)100x100mm, c)150x150mm, d)200x200mm

The aim of this experiment is to determine the type of workspace where the robot will be able to climb as well as its payload capacity.

Construction of the test rig

In order to validate the new simulation results, a magnetic adhesion system consisting on 3 yokes systems was built and attached to an aluminum bar as shown in figure 11. The total weight of this adhesion system was ~10kg.

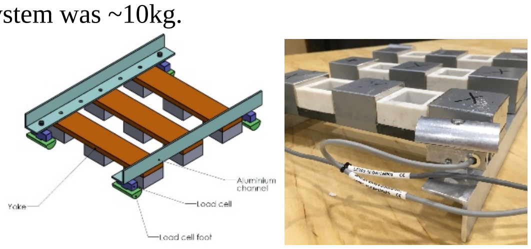


Figure 11. Test rig construction with 4 load cells.

Additionally, we installed four OMEGA mini load cells on each of the corners. Using an OMEGA summing box and a compatible meter, we were able to measure the total force applied by the adhesion system.

Furthermore, we constructed a "dynamic" rebar wall, where it is possible to change the spacing between rebars, with a fixed plywood cover of 30mm. It is important to add, that the relative permeability of dry concrete is practically the same as air and wood, which is why we are confident to use them to simulate concrete. We recorded the load cells results obtained with the constructed test rig over the dynamic wall with 12mm rebar mesh (3 configurations) within a 30mm concrete cover (gap). The comparison between the test rig results and the FEA data from the COMSOL simulation can be found in Table 3.

Table 3: Estimation of the robot's weight with the proposed magnetic adhesion system.

Mesh space with 12mm rebar	COMSOL measured adh. force	Load cells measured adh. force	Max robot weight at 30mm gap
200x200mm	23.03kg	24.14kg	8.82kg
100x100mm	51.62kg	50.91kg	22.20kg
50x50mm	55.75kg	61.82kg	27.66kg

If coefficient of friction is ~0.5 and the total weight of the system ~10kg, an estimation of the robot's weight is proposed in Table 3. See analysis in [5].

Real environment testing: Car park

Results from the above experiment gave us confidence to take our adhesion system to a real-world environment. It is a well-known fact that the columns in multi-story car parks are well reinforced. Since we didn't have a reliable method to determine the size of the rebars or their distance, in the first instance we decided to just try to *stick* our system to the column. Once confirmed that the system was holding we decided to start adding weight, as seen in figure 12, until the system started *sliding*.

Figure 12. Test in a real reinforce concrete structure: car park column.

We have no means to know how much ferrous material is embedded in the car park column we used, but we can be confident that a robot using this adhesion system will be able to carry a payload of 7.6kg.

Conclusions and future work

We intend to extend the application to calculate the minimum torque required for a motor to be able to cope with such magnetic forces and thus the total payload of the robot. This will complete our application to design flux focussing adhesion systems for climbing robots over ferrous surfaces. The results given by the application have not only been validated with a test rig for a single magnet (confirming manufacturer specifications) but also for an arrangement of magnets and iron yoke over a rebar.
We have extended our tests by constructing a multiple yokes adhesion system, thus, increasing the adhesion force of the whole system. Finally, we proved that the proposed system can stick to a car park column of unknown rebar configuration. The proposed system will enable us to safely build a climbing robot for reinforce concrete structures with a payload of 7kg to 10kg, having taking into consideration the weight of the adhesion system.

References

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Acknowledgements

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