TRIPILLAR: MINIATURE MAGNETIC CATERPILLAR CLIMBING ROBOT WITH PLANE TRANSITION ABILITY

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In this paper, we describe a miniature climbing robot, 96 x 46 x 64 [mm^3], able to climb ferromagnetic surfaces and to make inner plane to plane transition using only two degrees of freedom. Our robot, named TRIPILLAR, combines magnetic caterpillars and magnets to climb planar ferromagnetic surfaces. Two triangular tracks are mounted in a differential drive mode, which allows squid steering and on spot turning. Exploiting the particular geometry and magnetic properties of this arrangement, TRIPILLAR is able to transit between intersecting surfaces. The intersection angle ranges from -10° to 90° on the pitch angle of the coordinate system of the robot regardless of the orientation of gravity. A possible path is to move from ground to ceiling and back. This achievement opens new avenues for mobile robotics inspection of ferromagnetic industrial structure with stringent size restriction, like the one encountered in power plants.

1. Introduction

Industry requires robotics solutions to inspect their power plants' complex entrails and save time during overhauls. In many industrial cases, the targeted inspection areas have stringent size limited access, typically with an entrance hole of surface below 0.5 [dm^2]. The particular industrial application we are working on is the inspection of coal-fired boilers. This environment is ferromagnetic and requires 3D mobility. This includes climbing and moving in any orientation of gravity while transiting from plane to plane. Mobile robots technology can definitely be better exploited to access those human unfriendly and inaccessible environments and therefore cut down costs. The availability of miniature and mobile robots will increase the fields of applications for mobile inspection robotics.

Since the targeted industrial environment is ferromagnetic, the choice of magnetic adhesion is straightforward. Even if it suffers from the major drawback of being only suitable for adhesion on ferromagnetic structures, its adhesion force and reliability are superior to other known possibilities, like suction cups [1], pressure sensitive adhesives [2] or electroadhesion [3]. Many existing climbing robots use magnetic adhesion. Implementations exist with wheels [4], feet [5], and caterpillars [6]. Magnetic adhesion can be implemented either with permanent magnets [7], with electromagnetic coils [8], or with a combination of both [9]. We chose to use permanent magnets to reduce energy consumption and increase compactness.

In this paper, we take a closer look on mobility in complex 3D environments and specifically on plane to plane transitions. We will then present caterpillars with embedded magnets and their particular features. Finally, we present TRIPILLAR, our miniature robot which is able to climb on ferromagnetic surfaces regardless of the direction of the gravity. This robot can make inner plane to plane transitions between 0° to 90° and very limited outer plane transitions between 0° to -10°. It can pass those transitions whatever the gravitational orientation of the obstacles. We conclude with future improvements.

2. Plane transition

Among the different obstacles that we can encounter in industrial environments, plane transitions represent a frequent component as well as one of the biggest challenges. The difficulty of plan transition is to secure weight by adhesion on the new surface while releasing it on the previous surface. The robot has to be safe and stable at any time of the transition.

Some robots are already capable of achieving plane to plane transitions. The Magnebike [10] is based on magnetic wheels with the addition of a detaching mechanism, to be activated in plane transitions. Indeed, magnetic wheels suffer from the major disadvantage of simultaneously attaching to both planes. All wheels traction allows to pass both internal and external angles with only 2 dof [11]. Using a bipedal structure [5] allows avoiding the problem of the wheel and being very generic, but adds several degrees of freedom, increasing the size and control complexity. Our system aims at achieving plane transition without additional degrees of freedom than the one required for planar mobility. We chose, in a first step, to focus on inner plan transition, since it is the most common plan transition encountered in closed environment.

3. Magnetic caterpillars

3.1. *Caterpillars and their use*

Among the different locomotion principles, we focus on continuous tracks or caterpillars. In general, they are of advantageous use for mobility of off-road vehicles. Continuous tracks are more adequate than wheels because they distribute both pressure and transmission to the ground, which is ideal for mobility on muddy terrains. But squid steering is less efficient than a differential drive or the Ackermann steering configuration.

Magnetic caterpillars are advantageous for planar ferromagnetic mobility because the magnetic adhesion force is shared by many magnets. Furthermore it allows passing surfaces with small gaps without being blocked in them.

Figure 1: Magnetic caterpillar

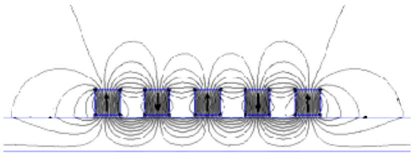

Figure 2: Simulation of magnets with a 180° shift at each increment. delta_x is the space between two magnets.

3.2. *Design of magnetic caterpillars*

Many robots use magnetic caterpillars [6], [12], [13], but they are large – above 300 [mm] in one direction. Existing magnetic tracks are built from modular chain links which form a closed chain. The links are joined by hinges which give flexibility to the rigid elements. Mechanical links are difficult to miniaturize and expensive to manufacture.

In order to construct a miniature robot we had to build a continuous track of small size. We developed a caterpillar with 34 integrated magnets (Figure 1), which is made in a single piece of moulded composite and has a shape similar to a T5 belt. A longitudinal cable is wired to ensure the longitudinal rigidity of the continuous track.

The moulded NdFeB magnets are 1 x 1.5 x 5 [mm^3] in size with N52 grade. The orientation of the magnetisation is normal to the 5 x 1.5 [mm^2] plane. The magnets are arranged so that their magnetisation is a 180° shift at each increment (Figure 2). Simulations showed that this configuration had better properties than a Halbach organisation, where magnets would be shifted by 90° [14]. A Halbach configuration is attractive if magnets are adjacent or at least very close. Its advantage is that it directs the major part of the flux on one side of the magnet arrangement but it is not feasible in this case as we need some space between the magnets to ensure the flexibility of the caterpillar.

The adhesion force of each moulded magnet is 1 [N]. Due to their placement in the moulded continuous track the air gap is of 0.1 [mm]. The rubber chosen for the track offers excellent static friction against ferromagnetic iron. Its value is above 0.9 [-]. The caterpillar drawback is its low resistance to peel-off. Indeed, you can detach the whole caterpillar with the same force that is required to detach a single magnet. This inconvenient can be mitigated with the solutions presented in the following section.

4. Robot realisation

4.1. *Design of the robot*

Continuous track vehicles exist in various designs. The simplest one is a track encircling two wheels. Another solution, as in an army tank for example, is a trapezoidal shape. This configuration helps the vehicle to cross different sorts of obstacles. The symmetry allows passing over obstacles in both the forward and backward direction.

For our robot, we chose the caterpillar shape to facilitate plane transitions. Since we limit ourselves to forward motion for realizing plane transitions, we chose a triangular shape with an obtuse angle (Figure 3). The momentum generated by the reaction force at the contact point on the wall helps lift the part of the robot in contact with the ground surface.

Our caterpillars are powered using two DC motors. This configuration allows differential squid steering. The motors have an external diameter of 10 [mm]. They are coupled with a gearbox with a ratio of 256:1. The motor and gearbox combined are 36 [mm] in length. This configuration allows a maximum output torque of around 120 [mNm].

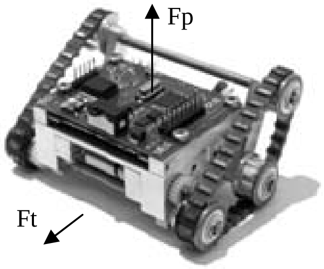

Figure 3: The robot

The built robot is 96 [mm] width, 46 [mm] in height and 64 [mm] in length. The robot is energetically autonomous using a lithium-ion battery, which can last one hour with full motor power. The robot weighs 214 [g] in total. A wireless Bluetooth connection enables remote controlling the robot using a graphical user interface from a computer. Embedded electronics includes a microcontroller which manages the incoming commands, sensors and motors. Two IR sensors can measure the distance of an obstacle in front of the robot up to 25 [cm]. This feature is useful for aligning the robot perpendicularly to an obstacle that we wish to overtake.

4.2. *Preventing peel off*

The major disadvantage of our caterpillar is the low force needed to detach it when peeling it off. This is similar to the peeling effect of an adhesive tape: with a small force you can slowly detach the tape from one end to the other, while the adhesive can resist a higher force when the effort is distributed. In the case of the caterpillar, the force needed to lift one magnet is sufficient to detach the whole caterpillar.

A first way to counter the peeling effect is to tighten the caterpillar. Thus it is no longer possible to detach only one magnet at a time, as the caterpillar reacts similarly to a rigid plate with several magnets on it. However the tension is limited since higher tension increases the driving torque. Thus increasing the tension helps but is still insufficient. An additional mechanism is needed to further prevent peeling; otherwise the robot will not be able to climb vertical walls or ceiling.

An option is to use a tail which can produce a force preventing peeling, consider the geckos for example [15]. This approach, however, has two disadvantages. First, the tail can cause some problems for plane transitions, or will need to be active, which complicates the system. Second, it will not increase the total holding force, which is desirable for increasing the adhesion safety margin and possible payload.

The above reasons explain why another solution was chosen: it consists of fixing magnets on the robot structure. They are placed at the level of the two ground wheels axes to prevent peel off. We chose a hollow cylindrical magnet for the front axis. It is 6 [mm] in height, and has inner diameter 6 [mm] and outer diameter 15 [mm]. This shape is advantageous because the magnetic force can act when the robot is cruising on a plane and helps when the robot transit from plane to plane. We place two rectangular magnets close to the back axis. They are 10 x 5 x 4 [mm^3]. Their position makes them easy to detach with the help of the lever arm when passing from one plane to another.

Tension	Fp [N]
Very loose	5.2
Normal	7.7
Tight	10.2

Table 1: Holding force of the robot depending on the caterpillar tightness

The force needed to detach the robot from the surface is shown in Table 1. The tension used for the operating robot is "Normal". For "very loose" the holding force is only due to the body magnets. With "tight" motors are not able to rotate. Thus we clearly see the influence of the tension, and it confirms the force of 1 [N] by magnet. A better construction using bearings would allow a higher tension, and thus a higher force. The tangential force Ft which corresponds to the friction force is of 15 N. It shows the very good friction properties which can be obtained using caterpillars.

5. Mobility

The robot can cruise on planar ferromagnetic surfaces at any inclination to gravity. We tested our robot on ferromagnetic sheets of 2 [mm] thickness. Its cruising speed was 40 [mm/s] uphill.

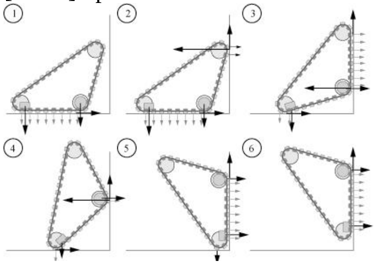

Figure 4: Plan transition stages

Due to its size, the robot can enter a rectangular duct of 100 [mm] x 50 [mm] in forward or backward motion. A diameter of 120 [mm] is needed for a 180° on spot turn. If we place a coordinate system at the center of mass of the robot, the robot can transit intersecting surfaces with angles ranging from -10° to 90° on its pitch axis.

6. Conclusion

We achieved the development of a miniature climbing robot, 96 x 46 x 64 [mm^3], using magnetic caterpillars in a triangle shape, named TRIPILLAR. The adhesion force is provided by a unique combination of small magnets moulded in the caterpillars and by magnets fixed on the robot's frame. Despite its only two degrees of freedom, the robot is able to make inner plan to plan transitions on ferromagnetic structures, and thus move from floor to wall and ceiling and back. The simplicity makes control trivial and the robot compact and robust.

Future work will further develop the miniaturization and mobility. A possibility to achieve external angles passing is to attach two similar robots together with a spring loaded link. We plan to add vision to the system which will allow blind remote control of the robot. The simplicity, the mobility and miniaturization of this robot opens new avenues for industrial robotics inspection of power plants.

7. Acknowledgment

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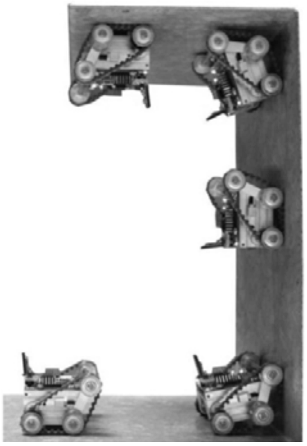

Figure 5: The robot moving from floor to ceiling

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