Klíčové parametry pro polohování magnetických těles v planární rovině

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Key Aspects of Magnetically Guided Actuation on Planar Surfaces

Abstract – **Presented research is focused on key design parameters of the system for magnetically guided actuation of miniature robots on planar surfaces. Attention is paid to field coils and robot design, maximum robot load and robot dynamics. The study based on the numerical analysis and mainly on the experimental measurement on the laboratory prototype of the system.**

Keywords – Contactless Positioning; Dynamic; Load Capacity; Magnetic field

I. Introduction and Motivation

Nowadays, various techniques for miniature robots actuation are being investigated [1][2]. Out of all physical principles that can be used, the interaction of magnetic field with ferromagnetic bodies is one of the most commonly used. Most of the state-of-the-art systems are based on forces generated by a magnetic field on ferromagnetic bodies, frequently on permanent magnets (PM). These systems are different in the coils topology, topology of actuated body and, of course, their operation and locomotion. The system under discussion is based on the mutual interaction of external magnetic field controlled by coplanar coils with a robots composed of permanent magnets. The design and operation of robot motion is described in [3] and [4].

The major goal of the presented research and development is to analyse the key design and operation parameters of the system for magnetically guided actuation of miniature robots on planar surfaces. The paper summarizes our experiences with the discussed actuation technique and formulates them into the design and operation rules.

II. Analysis of design and robot parameters

The basic aspect of coplanar coil design is the size of permanent magnets. The main criterion is the force acting on a single magnet. Due to the periodicity of the magnetic field on the surface of the arena, the size of the magnet determines the step between the partial wires of the coils. With respect to the orientation of the current in the coil threads, it is clear that the basic rule of the coil design is to eliminate the interference of the partial force effects. Therefore, the basic magnet parameter is its diameter d (magnet is cylindrical) in the case of the discussed system, as shown in Figure I.

Let's assume that the coils are equidistant. Magnet diameter d then determines the ratio between the wire width w and the gap g between the wires. The purpose of the analysis was to determine dependencies of permanent magnet size and wire/gap ratio on the force acting on permanent magnet. The numerical model was solved by the finite element method as linear and the relative quantities are used in the results in Figure I. The ratio between the wire and gap is: d = 2w + 2g. [3][5]

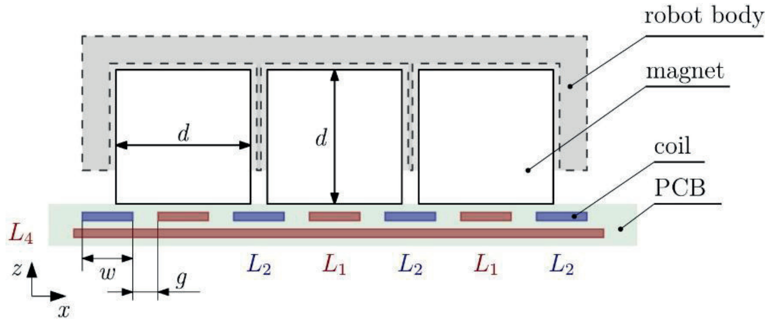

Figure I. **Cross-section view on the discussed system**

Whereas the wire/gap ratio is determined only from one PM diameter, the real robot can combine several magnets. A large number of different combinations of magnets layout is possible. The basic combinations for 3x3 layout are shown in Figure II. After basic measurement of illustrated magnet combinations 5 PM variant was chosen because it has the best parameters from the dynamics point of view (maximum measured speed was 50 mm/s, maximum transported load was 500 %). 4 PM variant has lower maximum load and 8 PM variant has lower total force because magnets are acting in the same field in different directions. So the total sum of forces is much lower than in 5 PM variant. 9 PM variant improves magnetic field distribution from the viewpoint of the total force point of view, but the robot weight is almost 2 times higher then the 5 PM variant (majority of weight of robot is represented by the magnets). From the dynamic viewpoint, 5 PM and 9 PM robots are compared in section III.A from dynamic viewpoint.

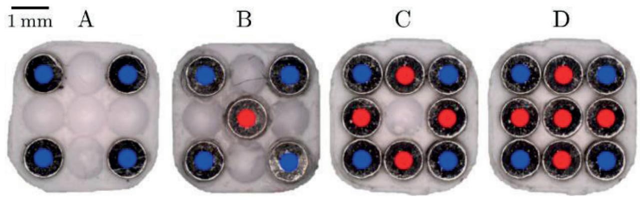

Figure II. **Different robots with indicated permanent magnet (PM) orientation. Blue means south from bottom view and red means north**

III. EXPERIMENTAL INVESTIGATION

All experiments in this paper were realised on the prototype *Scarabeus*. Experiments were performed for 5 PM robot (Figure II B). *Scarabeus* module (shown in Figure III) consists of a microcontroller board, drivers and actuation board with 4 coplanar coils, which was designed as multi-layer printed circuit board (PCB) of dimensions 100 x 100 mm. The characteristic properties of the module are collected in TABLE I.

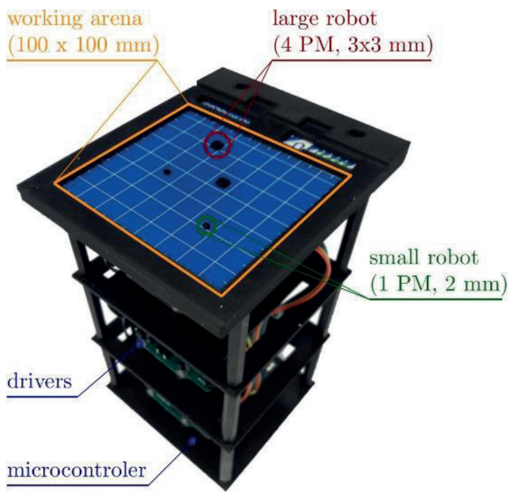

Figure III. **Prototype of *Scarabeus* modul**

A. Identification of dynamic characteristics

Results of robot dynamic measurement are presented in Figure IV, which shows the minimum coil voltage *U* and input power *P* dependent on robot velocity *v* (higher velocity means smaller step time t_s). The higher voltage *U* is applied, faster the robot is. We have discovered that the maximal velocity for specific voltage is dependent on robot design. Higher number of magnets increases the overall weight of the robot but also changes robots magnetic properties. Measurement showed that 5 PM robot was the best one. With the same level of energy the speed could be almost two times higher than in the case of 9 PM robot. The main reason is increased mass of 9 PM robot but improvement of magnetic properties was not increased enough to achieve overall better performance (in comparison with the 5 PM robot). The red area in top-right part of Figure IV represents the area when the actuation force is too high and robot starts to shiver (the robot is kicked back when it reaches this zero-force point).

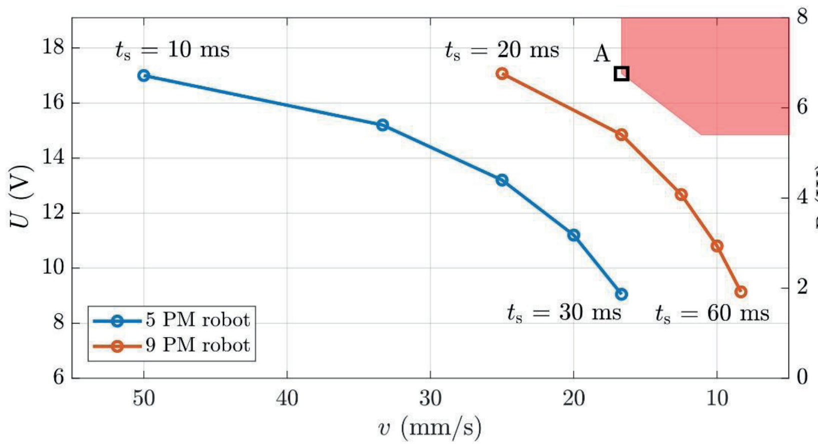

Figure IV. **Dependency coil voltage *U* on velocity of the robot *v***

B. Analysis of transport capabilities

Figure V shows the maximum load of robot and also load mass *m* dependent on time of one step t_s. According to the assumption, the experimental result shows that lower speed of the robot (step time t_s is higher) allow transporting higher load until the breakpoint is reached. The maximum transported load is higher than 500 % in both compared cases and maximum load is almost $m = 200$ mg. For this experiment constant voltage $U = 17$ V was used. The robot load mass *m* was increased for every time step t_s until the robot movement was not accurate any more.

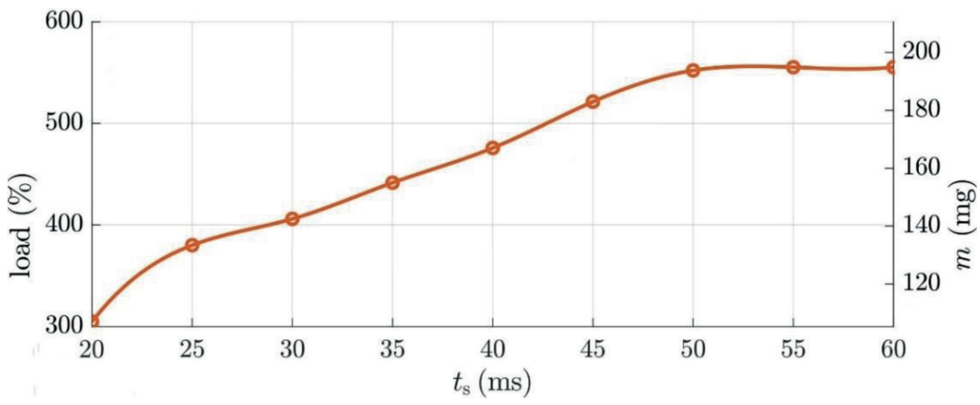

Figure V. **Maximal robot load and load mass *m* dependent on time of one step t_s (step time t_s = 20 ms corresponds to robot velocity 25 mm/s and t_s = 60 ms corresponds to velocity 8.3 mm/s)**

TABLE I. PARAMETERS OF *SCARABEUS* PROTOTYPE

General prototype parameters	Value	Magnets and robot parameters		Value
Wire width	**0.12 mm**	**Magnet weight**		**0.006 g**
Wire gap	**0.38 mm**	**Magnet Dimmensions**		**1 x 1 mm**
Layer gap	**0.1 mm**	**Magnet (BH) max**		**318 – 350 kJ/m²**
Copper height	**35 µm**	**Robot body weight**		**0.0075 g**
Parameter of one coil	**Direction X**		**Direction Y**	
Resistance	**45.29 Ω**		**40.21 Ω**	
Length	**8435 mm**		**8503 mm**	
Inductance	**few**		**few**	

IV. CONCLUSION

The key design and operation parameters of the system for magnetically guided actuation of miniature robots on planar surfaces were discussed. The system was evaluated by numerical analysis and experimental measurements on a laboratory prototype. The key aspect of the coplanar coils design is the wire/gap ratio. The robot design have to balance magnetic field distribution and total weight of the robot for best dynamics and load capabilities.

ACKNOWLEDGEMENT

This research has been supported by the Ministry of Education, Youth and Sports of the Czech Republic under the RICE - New Technologies and Concepts for Smart Industrial Systems, project No. LO1607 and by the University of West Bohemia under project SGS-2018-043 and with the support of an internal project SVK-2018-005.

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