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Magmites – Wireless Resonant Magnetic Microrobots

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Abstract— **Primary challenges in the building of untethered sub-millimeter sized robots include power supply, propulsion methods, and control. We present a novel type of microrobot termed *Magmite* that utilizes a new class of wireless magnetic actuator which accomplishes all three tasks. The device harvests magnetic energy from the environment and effectively transforms it into mechanical propulsion while being fully controllable. This microrobotic agent with dimensions less than 300 µm x 300 µm x 70 µm is capable of maneuvering with 3 degrees of freedom. A specially prepared substrate allows for adjustable speeds exceeding 12.5 mm/s or 42 times the robot's body length per second (see accompanying video). It is powered by oscillating fields in the kHz range and strengths as low as 2 mT – roughly 50 times the average earth magnetic field.**

I. INTRODUCTION

The two principal challenges when building sub-millimeter sized robots are energy storage and actuation. Chemical storage, solar power and inductive coupling work well at the macroscale, but scale poorly to the sub-millimeter range. In addition to the difficulties of transferring energy to wireless devices, the conversion of that energy into mechanical actuation typically requires additional on-board processes and circuitry. This in turn often leads to further inefficiencies, increased robot size, and more complicated fabrication processes. To overcome these challenges new types of wireless actuators are needed for a wide range of untethered applications. By adopting a technology that can transmit energy directly to the mechanical drive system, the size and complexity of the robot can be significantly decreased. Other approaches have been proposed in which microrobots operate in vibration fields [1], with actuators powered by externally applied electrical fields [2], [3], with static magnetic fields and gradients [4] or with focused laser energy [5].

II. ACTUATION PRINCIPLE

The method for wireless microactuation presented here utilizes the build-up of interactive forces between soft-magnetic bodies subjected to an external magnetic field. The magnetic propulsion unit of the microrobot consists of two soft-magnetic nickel bodies connected over a non-magnetic spring. One body is connected to a gold frame that rests on the substrate below. Attached to the frame, but elevated by about 10 µm above the substrate, is a meander spring that supports the second nickel body in its ground position (Figures 1 and 2).

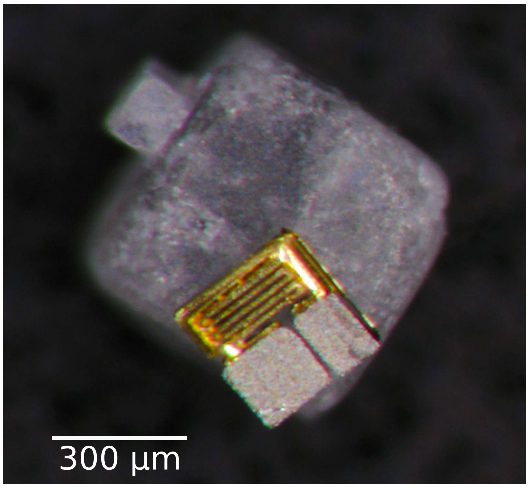

Fig. 1. Microscope image of a *Magmite* on a grain of salt.

In a uniform magnetic field, the soft-magnetic bodies rotate to align their combined long axis with the external field – similar to a compass needle.

The induced magnetization of the bodies leads to opposing magnetic poles across the gap. Attractive forces between the two bodies cause the gap to narrow and finally close as the suspended body deflects. When the field is turned off, the magnetic forces vanish and the spring returns the suspended body to its equilibrium position.

Driving the spring-mass system at resonance leads to larger deflections while keeping the amplitude of the applied field minimal. As impact occurs between the two nickel bodies, the spring-mounted body transfers its momentum to the stationary body attached to the base frame. It then reverses its motion and begins the oscillatory cycle again. The mechanical spring-mass system has to be designed in such a way, that the lowest resonance mode is in the desired actuation direction (Figure 2) while preserving the magnetic properties of the system as discussed above.

III. CONTROL

The *Magmite* can be fully controlled and is capable of driving forward, backwards, stopping, turning in both directions and even turning in place. The orientation of the robot is naturally controlled by the orientation of the external field created by two orthogonal pairs of Helmholtz coils. The *Magmite* can be steered by keyboard at moderate speeds and with the help of a fully automated visual servoing system at higher speeds.

The linear motion of the robot is controlled as follows: Under the correct operating conditions, momentum transfer

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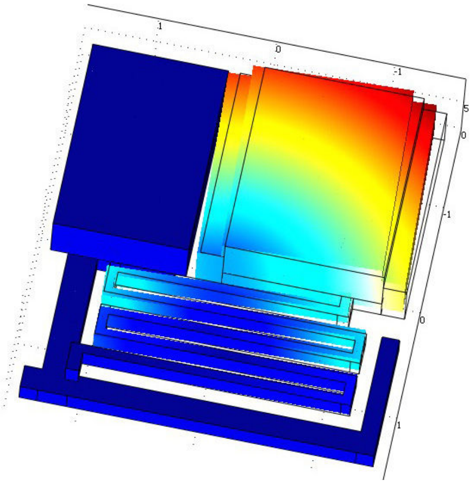

Fig. 2. Example of a FEM simulation (*Comsol Multiphysics*) of the mechanical spring-mass system to determine the order of eigenmodes and the expected resonance frequency in the direction of interest.

between the swinging and stationary body is enough to overcome static friction and each impact causes the robot to slide a small distance on the substrate. To simplify the control of forward and backward motion, the robot can be operated on an engineered substrate with interdigitated insulated electrodes [2]. A phase-locked and phase-shifted electrostatic potential clamps the robot to the substrate during specific parts of the oscillatory cycle, giving the user greater control of frictional forces and allowing the robot to move both forward and backward with the correct phase offsets.

The velocity of the robot is best controlled by a method similar to pulse-width modulation. For a given period of n cycles the ratio of normal motion cycles and cycles during which the robot remains fully clamped is defined, e.g. half-speed is achieved by keeping the robot fully clamped during the first 50 cycles of a 100 cycle period and driving it only during the second half of 50 cycles.

IV. RESULTS

The magnetic field strength required to drive the *Magmites* is as low as 2.1 mT when the applied frequency is within a few Hz of the robot's resonant frequency. This is only approximately 50 times stronger than the average Earth's magnetic field and demonstrates the efficiency and potential scalability of this technology. Velocities as high as 12.5 mm/s or 42 times the robot's body length per second have been observed repeatedly. Assuming a typical driving frequency of 2500 Hz results in a step size of about 5 µm per cycle. Robots have been be driven in environments with relative humidity levels up to 55%. They are also able to push and move objects at the microscale – such as 100 µm gold disks. The robustness of operation in these situations is due to the use of the mass-spring system which stores the absorbed energy over a short period of time before it is released on impact.

The automated system implemented so far is capable of robustly steering the robot through a maze while tracking it at 100 Hz with a microscope-mounted camera. Thin disks of 100-150 µm in diameter have been successfully and repeatedly driven around static obstacles by the visual servoing system.

V. CONCLUSIONS AND FUTURE WORK

We have presented a microrobotic platform called *Magmite*. This platform offers significantly better control and reliability than other systems proposed in literature. A fully automated control system was developed to perform simple tasks such as maze navigation and object manipulation (see accompanying video). The robots produce enough force to push 150 µm x 20 µm gold disks across a planar surface.

Future work aims at the further miniaturization of the *Magmites* while improving their controllability and reliability. Multiple subsequent designs with increased performance have already been implemented and are currently being tested and characterized. Furthermore, strategies for simultaneously controlling multiple agents are being developed.

Related fields of interest include three-dimensional fluidic applications and the integration of the proposed resonant wireless actuators as active components into larger systems – either at chip level or on mobile platforms [4] .

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