Design and control of an embedded mobile microrobotic system for education

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Abstract: This paper introduces a new sub-millimeter microrobotic platform which has been specially-developed for competition and education. The demonstrator consists of a 220µm micro-magnetic core actuated in-plane by magnetic field gradients generated by four external coils. The microrobotic agent is placed in a specially-designed transparent microfluidic chip called "arena" and its trajectory is precisely controlled by using an inverted macro focus camera specially mounted under the arena. Autonomous trajectory control and micro-object manipulation were also successfully demonstrated. The system is fully embedded with a custom-designed circuit board containing the DC-DC power supply, analog-to-digital converters, power amplifiers and coils. The processing unit is based on the popular Raspberry Pi hardware running Python or Matlab/Simulink compiled code. The paper is submitted to the IFAC2017 special feature Automatic Control Demonstrators.

Keywords: Microrobotics, Micromechatronics, Magnetic Actuation, Control, Education

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1. INTRODUCTION

Microrobotics deal with the miniaturization of regular elements all by maintaining or even further increasing the precision, which is highly required in various advanced applications such as micro-component assembly and manufacturing, minimally-invasive or non-invasive surgery, single-cell manipulation and sorting etc. The term of mobile micro- or nano-robot refer to untethered (wireless) actuation of a device less than a millimeter in its largest size.

1.1 The potential of mobile microrobotic applications

Due to potential applications in bio-medicine especially, mobile microrobotic stations have been designed for over two decades by over a dozen research facilities. Starting 1993, the design of a 0.7 by 1.5mm microrobot was achieved by using silicon planar etching process and folding [Yasuda]. The principle used for this very early microrobot was based on vibration induced by a piezoelectric material. In 1999 a related principle of mechanical movement was used, to mimic insects with six legs [Kladitis]. The necessity of integration of these microrobotic systems to a further degree led to the apparition in 2005 of the first microrobot made of SMA (shape memory alloy) [Kim] with remarkable capacity for self assembly without requiring the fulfillment of very drastic conditions. The same mechanical principles are still used nowadays for actuation, in different on microrobot shapes

As we approach the present time, we observe the usefulness of the microrobots in medicine, in particular due to the small size and extraordinary capacity for sampling cells or tissue in a minimally invasive way. For instance a microrobot was used for colonoscopy procedure, a painful procedure normally [Guo]. Placing objects in a human body requires external methods of locomotion that, in this case, were based on magnetic fields.

Noticing the continuous trend of miniaturization and flexibility, predominant in the medical field to this date, the article [Fang] reviewed the four major methods used for assembly: electrostatic, magnetic, inertial and force capillary and analyzed the advantages and disadvantages for each category It has also shown an example in which some of these mechanisms are combined to create a 3D micro-devices from 2D structures. The key is in the combination of several locomotion principles, which can lead to the design of complete systems such as for a wireless cell injection station by using a haptic control interface [Faroque].

For medical applications the main actuation principle employed nowadays still remains magnetic, further papers reporting increased actuation for very low magnetic fields (below 10mT) [Qiu]. Given the high mobility of these microrobots and the extremely small dimensions, combined with micrometer precision and ability to navigate through various liquid interfaces we can clearly see the future of microrobots in the field of medicine such as cell sorting, minimally invasive surgery, cell manipulation, etc.

1.2 The specificities of the designed microrobotic application

The origins of the system reported in this paper came from the participation of our team to the Mobile Micro-Nano Robotics Challenge, which is organized yearly by NIST or Robotics and Automation Society of IEEE . The challenge accepted all types of untethered actuation, the only condition being imposed to the maximal agent size of 1mm or less. The competition has three independent trials: 1) closed loop autonomous trajectory control, 2) microassembly of parts in a narrow channel and 3) advanced showcase and poster session.

We intended to create the most compact and cost-effective demonstrator ever created without compromising the actuation control performance which should be kept in the micrometer range. This device was designed to be capable of various objects insertion and manipulation and ready in the near future for cell sorting.

At the same time, thinking about the actual energy use trends, i.e. green energy, this device was designed to require a very low current consumption and be supplied even from a smartphone battery pack. In compliance with the IoT era (Internet of Things) the device was considered to be operated independently over the Internet, no longer requiring a human user in the equipment proximity (telepathology concept).

The mobile microrobotic station was intended to be presented as an open-source system, with very small dimensions ranging in total 15 x 6.5 x 4.5 cm. This system is composed of a single-board minicomputer (Raspberry Pi), a camera with microscope adaptations for video signal acquisition, a TFT screen for human user interface and a custom shield board that contains the electronic module for the four coils that produce the electromagnetic field gradients for microrobot actuation. For a manual manipulation of the microrobot a joystick can be attached to the system. The system has three degrees of freedom, being controlled in translation along the X and Y axis and in rotation around the vertical direction. Unlike the other existing systems, our station stands out in particular for its integration, all control modules and related coils being supported by a single board which is plug-and-play with the minicomputer.

Introduced in 2015 at Seattle in the robotics competition ICRA MNRA under IEEE MMC, this demonstrator was appreciated as an ideal platform for educational purposes, being awarded with the Showcase and Poster Session Award. In the next year 2016 competition in Stockholm the system was awarded again distinguishing itself for its compact closed-loop control, effective teleoperation capability, robustness and efficiency.

This system proved "multi tasking" features, demonstrating its potential not only for use in various medical procedures such as cell sorting and characterization but also for teaching engineering students in control-loop and mechatronics applications or training future health or microbiology professionals with the specificities and interactions at the microscale.

2. THE SYSTEM STRUCTURE

The microrobotic system consists of a magnetic agent of less than 300µm placed in a microfluidic chamber and actuated by a net of four coils. The system is fully embedded with its additional electronics and processing unit (*Fig.1*). This section will detail especially the system architecture, its mechanical parts and the control loop. The electronics part will be treated in a separate paper. A block diagram of the system structure is represented in (*Fig.2)*, together with the various hardware interfaces. Note that the external PC is only necessary to record the data and the video sequence.

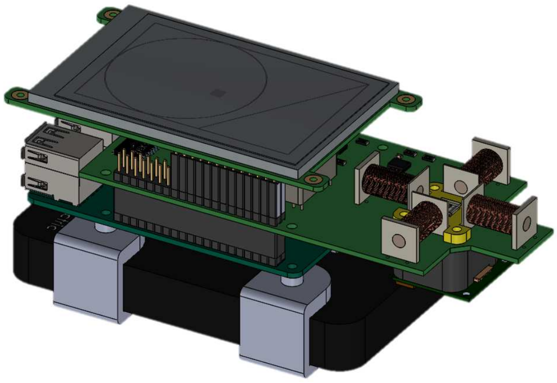


Fig. 1. The CAD model of the embedded microrobotic system

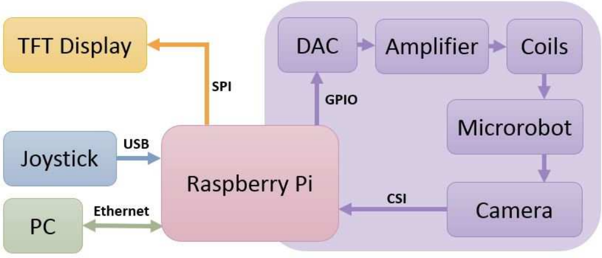


Fig. 2. The microrobotic system connection diagram

2.1 Overview of the system elements

The exploded view may be observed in (Fig.3) The device components may be divided as follows:

- Raspberry Pi, a mini computer running a modified Raspbian Linux operating system that contains the necessary libraries for Python and Matlab;

- Microscopy Raspberry Pi camera assembly, a dedicated camera for the Raspberry hardware that is incorporated into a specially-designed optical assembly with lenses for macro-focus at the size of the arena;

- Display: consists of a serial interface TFT screen with a resolution of 480x320 pixels, used to display the captured video stream;

- Control shield: this part is divided into the following subsystems: an electronic PCB board containing the electronic components (DC-DC converters for supply, DAC converters, current/voltage amps), the four coils for the microrobot control and some mechanical parts for the camera objective.

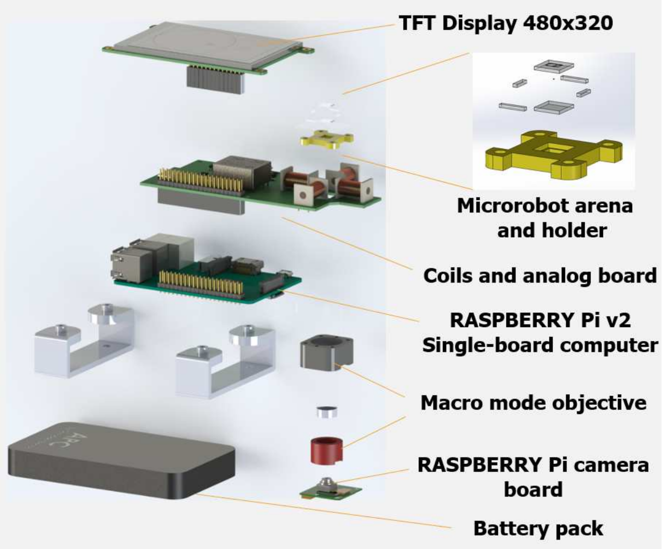


Fig. 3. The CAD exploded view of the microrobotic system

- The microrobot arena and holder, is a replaceable glass microfluidic chip which encapsulates the microrobot into a silicone oil. The holder is a 3D-printed mechanical which protects the arena chip and allows screwing to the control shield.

- Power supply, a battery pack providing autonomy for 2 to 4 hours of continuous operation, depending on battery capacity. The battery packs are easily replaceable.

2.2 The microrobotic arena

The fabrication of the microrobot is straightforward, consisting of precise dicing of a bulk Nd alloy permanent magnet into rectangular parts of less than 300µm. The arenas are made of a glass substrate 700µm thick. The manufacturing of the arena landmarks (squares, triangles, circles etc…) is based on regular clean room photolithographic processes (0.1 µm Cr layer) followed by precision saw dicing into rectangular glass plates of 6 x 6 mm.

The micromagnet and its arena plus optional micro-objects are hermetically packaged into small glass assemblies to avoid any possible physical contamination. The required landmarks are patterned over the top side of the bottom glass layer. The arena surface is 4 x 4 mm.

To demonstrate the manipulation capabilities, a special arena made of a microfluidic channel 750µm wide was required by MMC competition. The objects used to demonstrate the micromanipulation capabilities were triangles of 200 x 350µm which had to be densly-packed at the end of this channel, thus simulating the insertion of objects in a blood vessel. The triangle were manufactured from a laser-cut 110µm thick Al sheet. A number of 28 such triangles cover an area of 1 mm^2. The team achieved the insertion of 8 densly-packed triangles in a time span of 2 minutes.

Fig. 4. Photos of the microrobot glass arena and of the complete system

3. CONTROL OF THE SYSTEM

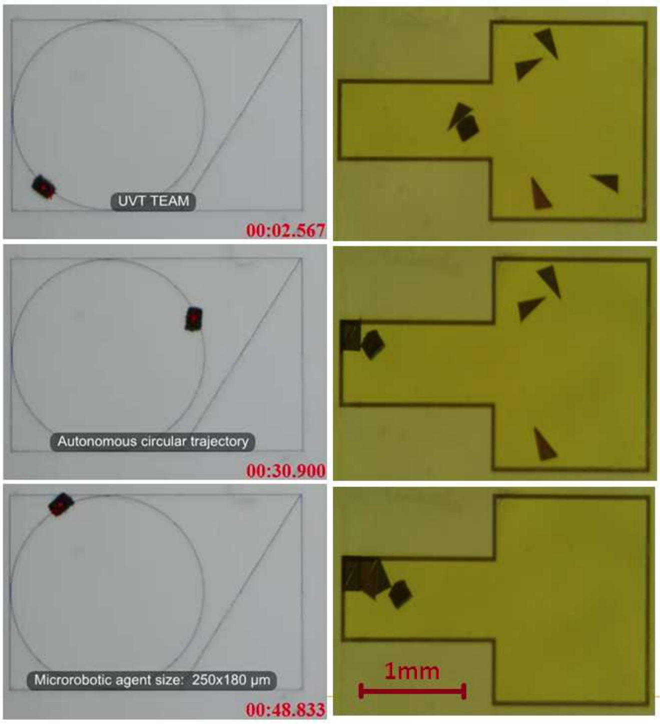
3.1. The operation modes

The microrobotic system has three degrees of freedom, performing movements on the X, Y translation axis and the in-plane θ rotation. It has two operating modes, manual and automatic.

- Manual (open-loop), the user can control the injected current in each coil or in two adjacent coils via a joystick, thus obtaining any movement in the XY plane. Apart those joystick controls which allow for movement along those two axis and some possible rotation, the user also has other three command buttons which can increase or decrease the maximum current range (the microrobot speed), or can reverse the orientation of the magnetic field. The sequence of images below (*Fig.5b*) show manipulation of elements at micro scale with a cube-type micro robot of 200 micrometers. These pictures show the assembly of densely-packed triangles in the narrow channel of 750µm. The control algorithm for the manual mode was developed under Python programming language.

- Automatic (closed-loop) control of trajectory, for this mode the user intervention is only necessary to configure the required trajectory and to start or stop the process. In the sequence (*Fig.5a*) is presented the same type of microrobot performing the circular trajectory in a predetermined time and in an autonomous manner. The position of the microrobotic agent in the image is calculated by image thresholding and centroid calculation at a rate of 30 frames per second. Two types of controllers have been proposed, a proportional controller and a lead compensator. The latter allows for a much faster control and will be detailed in the following section. The positioning accuracy of the controller is around 50µm.

The microrobotic platform has been used in control system lab classes at the University of Lyon and the University of Targoviste. A simplified Matlab/Simulink model of the system is provided to the students who are required to draw the frequency charts and then provide the adequate controller values. Then, the controller is implemented on the real microrobotic platform and conclusions are drawn.



a) *b)*

Fig. 5. a) Closed-loop control of the microrobot trajectory, and b) Manual (open-loop) operation of the movile microrobotic platform.

3.2 Synthesis of the lead compensator

The system accepts the magnetic field gradient d*B*/d*y* as the input signal which is proportional to the magnetic force *F*(*t*) and outputs its position y(t). A very simple linear model of the system consists of a delayed mass-damper second order transfer. This models the system inertia (mass *M*) and the viscous friction of the robot with the liquid (friction coeff. *f*):

$$M\frac{d^2y}{dt^2}+f\frac{dy}{dt}=F(t) \qquad (1)$$

A time delay block should be added, which takes into account the camera delay of 50ms. Following an experimental identification the following open-loop transfer function is found:

$$FTBO(p)=\frac{1}{p}\cdot\frac{25}{0.8p+1}\cdot e^{-0.05p} \qquad (2)$$

The Black-Nichols chart traced in (*Fig. 6*) show that the system is naturally unstable in a closed loop (the blue curve). A proportional gain of -24.6dB (0.06) is therefore necessary to insure the phase margin (see the red curve), but the cutoff frequency is of only 1.21 rd/s.

In order to increase the closed-loop system dynamics a lead compensator is proposed. The lead-lag compensator is a fundamental component in a control system theory [Bakashi] that may locally improve the frequency response by providing a better phase and/or gain margin. In this particular case a phase advance of 40° around the cutoff frequency could improve the dynamics by a ratio of 3 to 4 times.

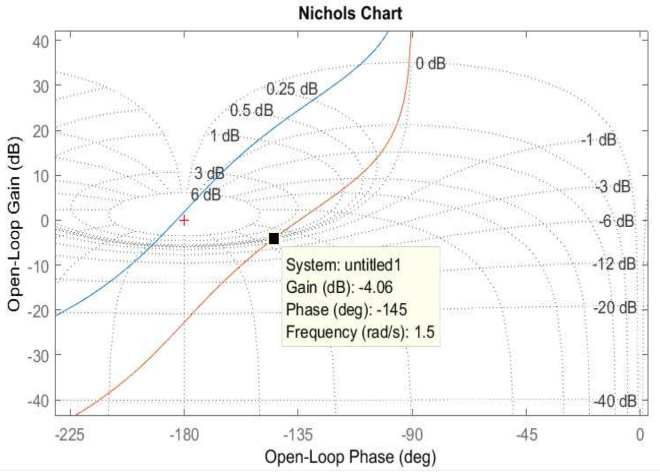


Fig. 6. Black-Nichols plot of the microrobot system (blue) and with a related proportional controller (red) of -24.6 dB Translating the blue curve downwards by -24.6 dB insures the stability margins w.r.t. the critical point.

The synthesized lead compensator in this case is:

$$A_{\varphi}(p)=\frac{1+a\tau p}{1+\tau p}=\frac{1+0.85p}{1+0.17p} \qquad (3)$$

The related proportional gain can be thus increased to 0.184 without compromising the margins (*Fig. 7*). The related Simulink implementation is presented in (Fig. 8).

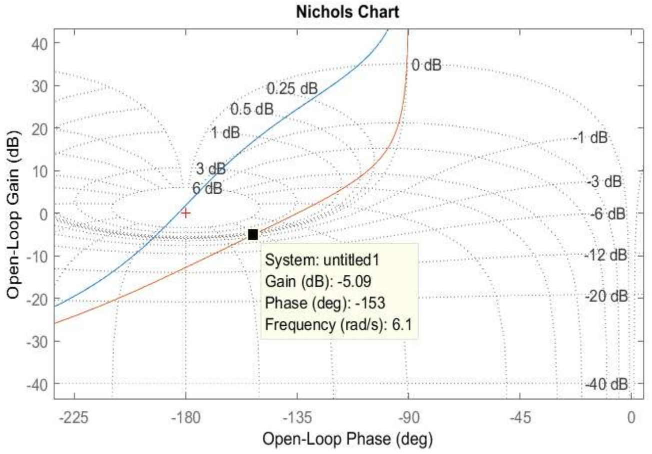


Fig. 7. Black-Nichols plot of the initial system (blue) and of the lead compensation (red) showing the increase of cutoff frequency w.r.t the proportional controller in Fig.6.

The two models were tested using various step and ramp signals. The step response time is improved by a factor of 4 for the lead compensator. As for the ramp reference signals , (*Fig. 9*), which are depicted as more difficult to achieve than the step signals, we may notice that the tracking errors are reduced by a factor of 3. The practical implementation confirmed the gain in terms of system dynamics. This was a simple yet still effective controller implementation. Adding an integral term could theoretically improve the accuracy although in practice we noticed that the nonlinear stick-slip friction with the surface rapidly brings the system unstable. More sophisticated control alternatives should be further considered.

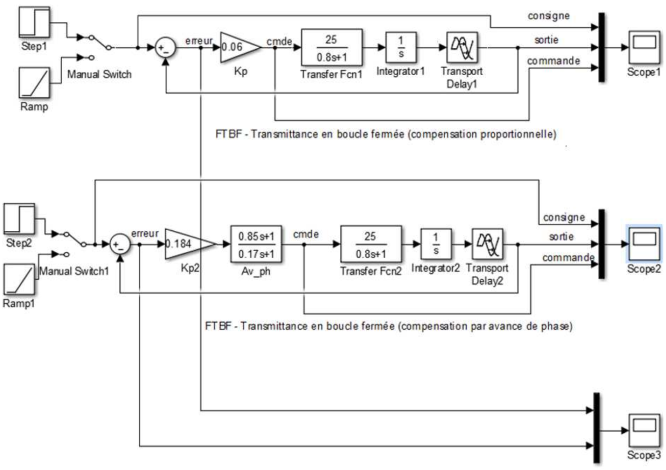


Fig. 8. Simulink model of proportional and lead compensators.

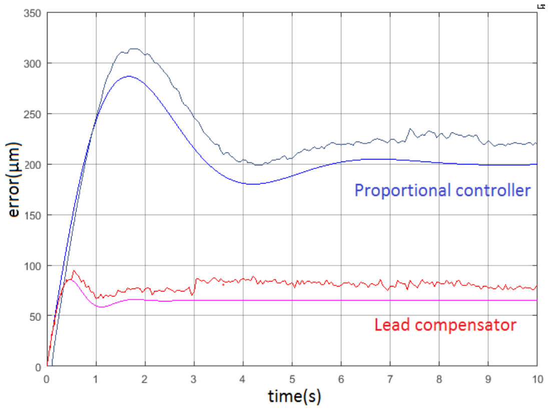


Fig. 9. Plot of the closed-loop errors for a reference ramp of 300µm/s. Combined experimental and modelling results.

4. CONCLUSION

This paper has shown the design, development and control of a new mobile microrobotic system suitable for education and research.

This magnetically-actuated mobile microrobotic system is based on a sub-millimeter size Neodymium magnet and four orthogonal coils. The micromagnetic agent and its arena are packaged into a small microfluidic glass assembly patterned by using photolithography. Some laser-cut triangular micro-objects were also inserted into a special arena designed for microassembly in a narrow channel which simulates the blood vessels.

The novelty of the systems consists into its integration, cost-effectiveness and suitability for the education purpose. This system has shown the feasibility of a complete stand-alone solution: magnetic actuation, optics, control, processing unit, power supply, LCD display in a single device measuring only 15 x 6.5 x 4.5 cm. Being based on the popular Raspberry Pi hardware, an easy and precise control strategy is possible, by combining the advantages of low power consumption and cost effectiveness.

Besides the compact portable design, the educational usefulness is straightforward. The kit contains the tutorial for a complete control systems lab session, including the required code for modelling, simulation and controller implementation under Matlab/Simulink®. The system in itself is highly multidisciplinary, combining aspects from various fields, from mechanics and micromechanics to electronics and programming.

Due to its level of integration, the application received the award of the Mobile Micro/Nanaorobotics Challenge, which was organized within the ICRA 2015 conference in Seattle, WA, which has been based on live demonstration and poster session. This paper is the first one which details more thoroughly the structure of this demonstrator.

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