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Control and Analysis of Low Inertia Miniature Synchronous Motors

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Abstract

Miniature motors are available in sizes as small as 1.9mm in diameter by 10mm in length. Position sensors have not yet been implemented in these small synchronous motors below 8mm in diameter. Open-loop control is optimal with sine-wave driving electronics, but in this case the electronic box is far from being as small as the motor. Open-loop control, like for stepping motors is usually performed, and works well at high speed. This paper presents a pulse frequency modulation (PFM) technique that can be implemented with small microcontrollers and can significantly reduce the irregularities of movement at any speed.

Analysing and measuring the rotation of these small motors is an interesting and difficult problem per se. Adequate test equipment is a requirement to evaluate both open-loop and future closed-loop control algorithms

1. Introduction

DC motors are easy to use (one voltage source) and to control (pulse width modulation), but due to their brushes, which brings the current to the rotor, they cannot be made smaller than 6mm and the life expectancy is quite short, sometimes less than 1000 hours.

Stepping and synchronous (brushless) motors are well known and widely used in industry. Brushless motors frequently include Hall sensors for providing the rotor position to the driving electronic. This permits excellent performance, but is for the moment neither cheap nor miniaturized. Stepping and synchronous motors are not so different. Synchronous motors are designed to spin smoothly in a rotating field defined by the excitation of 3 coils, but they can also be used as stepping motors, and this is the case with miniature motors such as the smoovy from RMB (Roulements Miniatures Bienne) [smoovy].

When extreme motor miniaturization is concerned, the first problem is to build small coils and allow the user to connect their ultra thin wires. Building a rotating magnet is easier, but the bearings must withstand both high rotation speed and billions of turns within their life span. Adding a sensor in order to be able to perform some close-loop control is quite difficult and is still in the research phase for 5mm motors and below.

Open-loop control is the cheapest solution for a very small motor. This paper concentrates on how to do it as simply and efficiently as possible, using a low cost miniature microcontroller. One difficulty is verifying the results. A stroboscope provides qualitative information. We built a special laser system for obtaining quantitative information.

2. Miniature Synchronous motors

Synchronous motors controlled by optimal sine wave supply have a torque/speed characteristic shown in figure 1a). Torque is maximal at low speed and decreases with speed due to inductance and friction effects.

With open-loop control, current is defined by the torque. Above the limit, the motor lose its synchronization. Below the limit, too much power is used. Closed-loop control can be autoswitched (i.e. for a given angle, e.g. sensed by a on/off hall sensor, the motor excitation will switch to the next phase). This provides a DC motor behavior: at any speed the torque is maximum (fig. 1b). The best is of course to precisely measure the position, directly with an analog position sensor, or indirectly by measuring the current on the coils in order to determine the phase shift. When the full torque is not needed, the power provided to the motor is automatically decreased (fig. 1c). The corresponding electronics are not yet available in a one-chip integrated form, This means that the control board is very large compared to the motor.

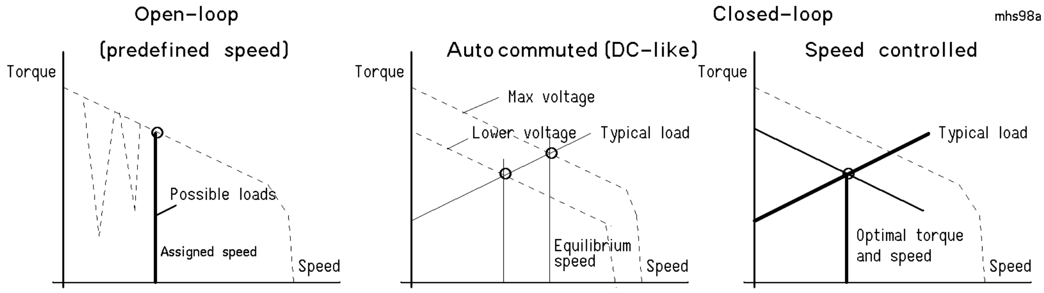

Fig 1. Synchronous motor characteristics

When synchronous motors are controlled by digital signals, and it is our objective to use a simple microcontroller without any special analog power controller, the problem is that the torque varies with the angular position of the rotor. With a low inertia of the rotor, irregular rotation speed occurs, and a significant decrease of the average torque is noticeable at a given speed, meaning that steps can be missed. Closed-loop control avoids this, but it is not yet clear if a low resolution encoder will provide precise enough control of miniature synchronous motors.

3. Control

Synchronous motors, when the back EMF has also a sinusoidal shape, have the best performance with sinusoidal excitation (fig 2b). Conversion to unipolar digital signals is easy (fig 2c), and one gets the usual sequence for a 3-phase stepping motor. At high speed the synchronous motor will not see the difference between a square wave and a sine wave excitation, due to the inertia of the rotor.

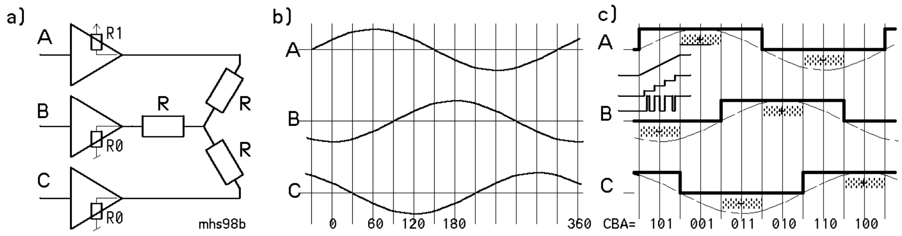

Fig 2. Synchronous motor excitation

With a microcontroller, the generation of successive steps (fig. 3a) is easy if one defines a table pointed to by a circular index (fig. 3b). A next excitation state table (fig. 3c) avoids the need for circular incrementation, which requires a special operation every 6 steps.

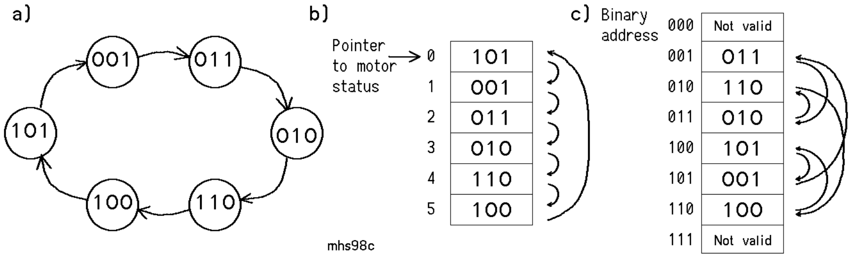

Fig 3. Excitation tables for synchronous motors

In order to smoothen the transition between phases, as indicated in figure 3c), one has many options depending on the use of analog electronics (D/A converter), programmable logic (FPGA), DSP processor, or fast microcontroller. We have taken the option that a 3mm motor must be controlled by an 8-pin processor in an SMD package. The Microchip PIC 12C5xx family matches this requirement, and there will be more powerful processors coming in such small packages.

4. PWM and PFM

Pulse width modulation (PWM) is well known to generate signals for proportional control (fig. 4a). Unfortunately, continuously updating a PWM output is time-consuming for small microcontrollers which do not implement it with dedicated hardware. The "refresh frequency", the microcontroller must keep up with, directly depends on the desired resolution and the maximum pulse length (at 50% duty cycle) the supplied device is ready to accept.

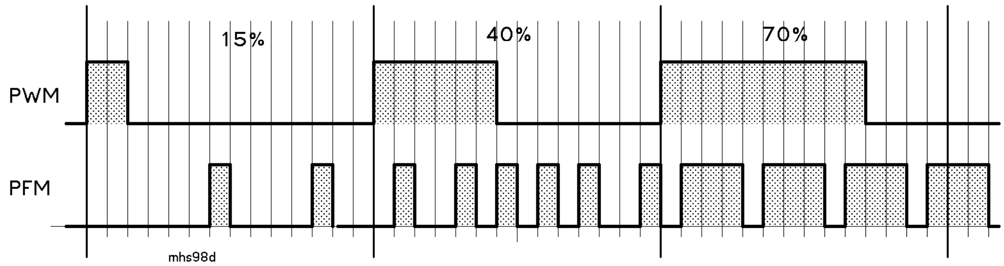

Fig 4. PWM versus PFM

For instance, a 3 mm smoovy motor will exhibit excessive vibration if driven with 2 kHz, 50 % duty cycle signal. If a 8-bit PWM resolution is aimed at, the microcontroller will have to decide whether to change the state of its PWM output every 500 microseconds divided by 256 = 2 microseconds. Lowering the resolution to 4 bits allows for a lower "decision frequency" (~ 30 microseconds between each), compatible with the processing power of a sub-1 dollar microcontroller.

Implementing PFM (Pulse Frequency Modulation) instead of PWM seems more complicated at a first look, but it is not, and offers a significant advantage: in a PFM signal, regardless of its resolution and duty cycle, the so called minority pulses never loose longer that the time it takes between 2 updates. A PFM signal updated every 500 microseconds could therefore fulfill the condition dictated by our previous example, that is it is quite suitable if the rotor inertia is low, as is the case with miniature motors.

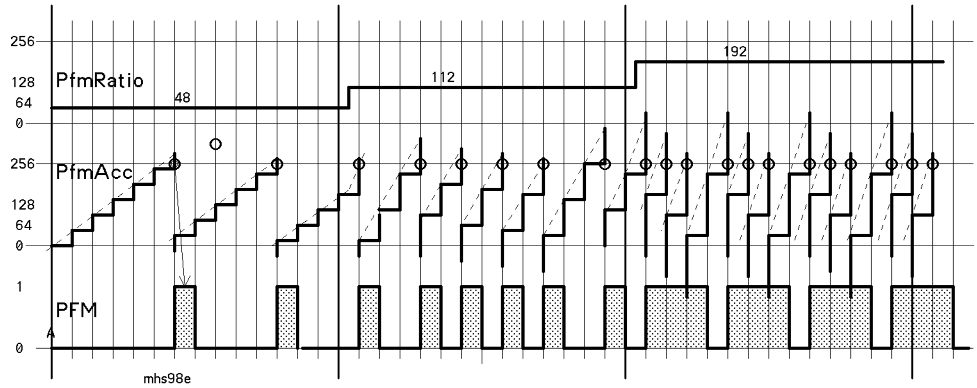

Fig 5. PFM generation

A very efficient way to compute the next state of a PFM signal is to add a value representing the desired duty cycle to an accumulator, for example a 8-bit register, then use the overflow flag as the data to output (see fig. 5). Performing this single operation at a fixed frequency insures that the output duty cycle equals the ratio between the input value and the capacity of the accumulator.

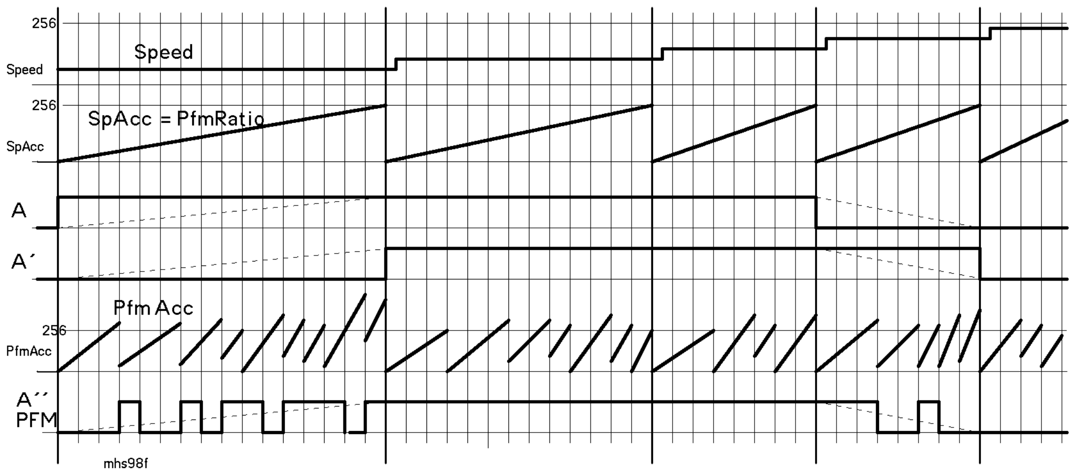

Fig 6. PFM interpolation between phases

Programming the smooth transition between two steps is especially easy now (fig 7). The excitation table includes both the present step output state and the future state. Each value is 3-bits, and the program is easier if the motor is wired so as not to cross the 4-bit nibble boundary (i.e. on port bits 0,1,2 or 1,2,3).

A typical program is listed in fig 7. A table define the future state. Present state in repeated on bits 4,5, and 6. A Swap instruction allows to assign the present state in place of the future one. Hence, when the carry is set after adding PFM ratio, a conditional swap assigns to the motor the future value. PFM ratio depends on the "counter" which increments from 0 to overflow, and is based on the same mechanism. The listing for a PIC processor is given below. Detailed explanation and other examples are given in [Nicoud98].

Angular velocity measurement

In order to precisely measure the effect of this software, one needs equipment to monitor the angular position of the rotor with a resolution better than 50 steps per turn.

The simplest now would be to use the Hall effect sensor and electronics developed by F.Burger [Burger98]: a 1.5 mm in diameter magnet must, however, be installed on the motor axis; for a 3mm smoovy with a $2x10^{-11}kgm^2$ inertia, this means 10% of the load, but indeed it is equivalent to the inertia of the gear that will be fixed on the axis in most cases.

Microchip assembler

```
     ; Initialization
     MOVLW    5
     MOVWF    SPEED
     CLRF     SPACC
     CLRF     PFACC
     CLRF     EXCIT
     INCF     EXCIT
LOOP
; next PFM microstep
     MOVF     SPACC,W
     ADDWF    PFACC
     MOVF     EXCIT,W
     BTFSS    3,0
     SWAPF    EXCIT,W

     ANDLW    B'1111'
     MOVWF    6
; next motor step?
     MOVF     SPEED,W
     ADDWF    SPACC
     BTFSS    3,
     GOTO     NOSTEP
     MOVF     EXCIT,W
     CALL     TAFORWARD
     MOVWF    EXCIT
NOSTEP
; ... Other tasks

TAFORWARD
     ADD      2
     ANDLW    B'111'
     RETLW    0*16+1
     RETLW    1*16+5
     RETLW    2*16+3
     RETLW    3*16+1
     RETLW    4*16+6
     RETLW    5*16+4
     RETLW    6*16+2
```

CALM assembly language and SmileNG editor

```
Program  Initialization and main loop
     Move      #5,W          ; Initial speed
     Move      W,Speed
     Clr       SpAcc
     Clr       PfAcc
     Clr       Excit
     Inc       Excit
Loop:          ; 17 µs min loop duration
; next PFM microstep
     Move      SpAcc,W
     Add       W,PfAcc
     Move      Excit,W
     Skip,CS
     Swap      Excit,W       ; CC, takes present value
; Superpose other bits to be written on the port
     And       #2'1111,W
     Move      W,PortB
; next motor step?
     Move      Speed,W
     Add       W,SpAcc
     Skip,CS
     Jump      NoStep
     Move      Excit,W
     Call      TaForward
     Move      W,Excit
NoStep:
; ... Other tasks to be performed in the loop
Module  Motor table  (unidirectional)
TaForward:
     And       #2'111,W
     Add       W,PCL
     RetMove   #0*16+1,W
     RetMove   #1*16+5,W     ; "present,next" motor excitation
     RetMove   #2*16+3,W
     RetMove   #3*16+1,W
     RetMove   #4*16+6,W
     RetMove   #5*16+4,W
     RetMove   #6*16+2,W
```

Fig 7. PIC listing for PFM smoovy motor control.

We decided to use an optical system with an axial rotating mirror (fig 8). The extremity of the shaft could be cut at 45° and polished. We preferred to add a 2mm plexiglass cylinder. The laser beam is reflected and touches an array of 60 PIN photodiodes (6° resolution).

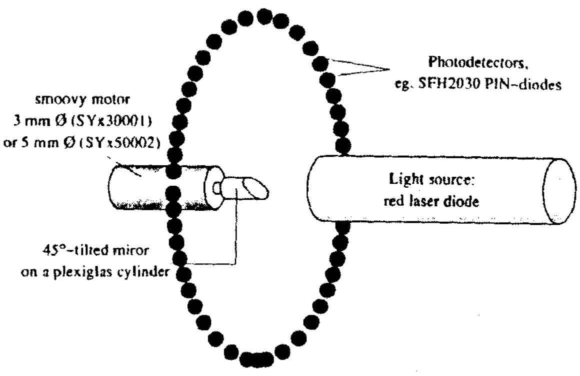

Fig 8. Principle of the equipment

At 120,000 RPM, the pulse duration is about 1 μs, and the time of fly between two diodes is 8.3 μs. The diodes are connected as three groups of 20 bussed-connected diodes to an amplifier-comparator. A fast PIC 16C73 (20 MHz clock) handles the interrupts and maintains a divide-by-240 up/down software counter (steps of 4), connected to an external D/A converter. Direction must be decoded, and some special cases when the motor has small amplitude oscillations must be managed.

Experimental results

The visualization on a digital scope is very convenient. Three cases are shown in figure 9, corresponding to a 3mm smoovy with the small encoder we developed: at 120 RPM, the motor makes its steps with an important overshoot. At 1200 RPM, the motor shows important and relatively stable oscillations (chaotic behavior is observed around 1000 RPM). At 8000 RPM, the rotor inertia makes the motor run smoothly.

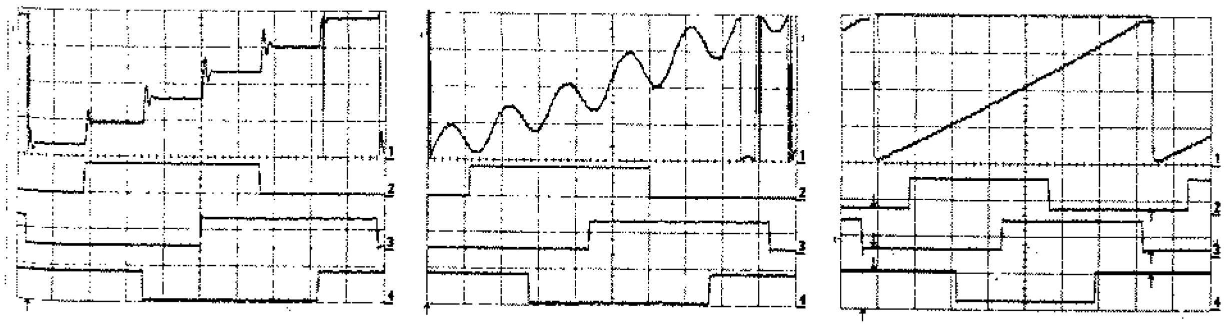

Fig 9. Motor behavior at 120, 1200, and 8000 RPM (square-vave control)

The same three cases are shown with PFM excitation on a linear ramp (figure 10). Surprisingly, the more complex implementation going through a table in order to generate half-sine transitions didn´t work as well. Again around 1200 RPM the linearity is not very good, but still far simpler than with a square wave, at the cost of less than 10 PIC instructions.

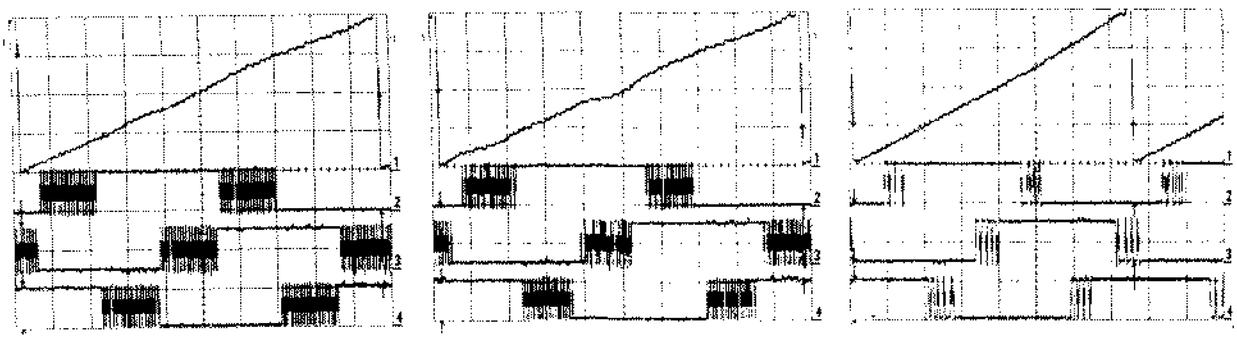

Fig 10. Motor behavior at 120, 1200, and 8000 RPM (PFM control)

Watch motors

Watch motors are unidirectional. Notches in the magnetic circuit allow the motor to have a stable no-power position and step always in the same direction when a bipolar 1 to 10 ms pulse is applied to the coil. Programming such a motor is just a question of generating pulses of the correct polarity, duration and spacing. No such motor is commercially available, but it is easy to dismantle a Swatch or a kitchen clock and play with it. Due to the high resistance of the coil, a microcontroller output can be directly used.

Bidirectional watch motors can be found in pagers or inside the "Swatch phone", the wrist telephone from the Swatch group. These motors look like the 3-phase motors of the previous section, but they have a stable power-saving position. They are very convenient in designing miniature robots [Caprari98].

Large (diameter 30mm, height 9mm) bidirectional motors are now available as the miniature stepper (M-S) motor from Switec, a division of ETA SA, a company of the Swatch Group. The M-S X15.xxx is a pseudo three-phase synchronous motor controlled in a similar way as the smoovy (figure 11), and includes a 180:1 reduction gear. The dynamic torque on the shaft is typically 1.3 mNm at 200°/s (33 RPM), at 5V, 25 mA on the coils. Power must be maintained in order to keep the same position.

The Analog Car Clock ACC M-S X16.xxx uses the same motor structure, but includes an additional gear stage for the hour hand with a divide by 12 reduction factor. Notches in the stator allow for for a currentless holding torque, maintaining the rotor in one of two positions when there is no excitation on the coils [switec].

The routine for making a complete turn and stop is easy to write. PFM is of limited interest on these motors having a high reduction ratio. The detent torque responsible of the stable states of the Lavet motor imply a tricky closed-loop control in order to improve the performance.

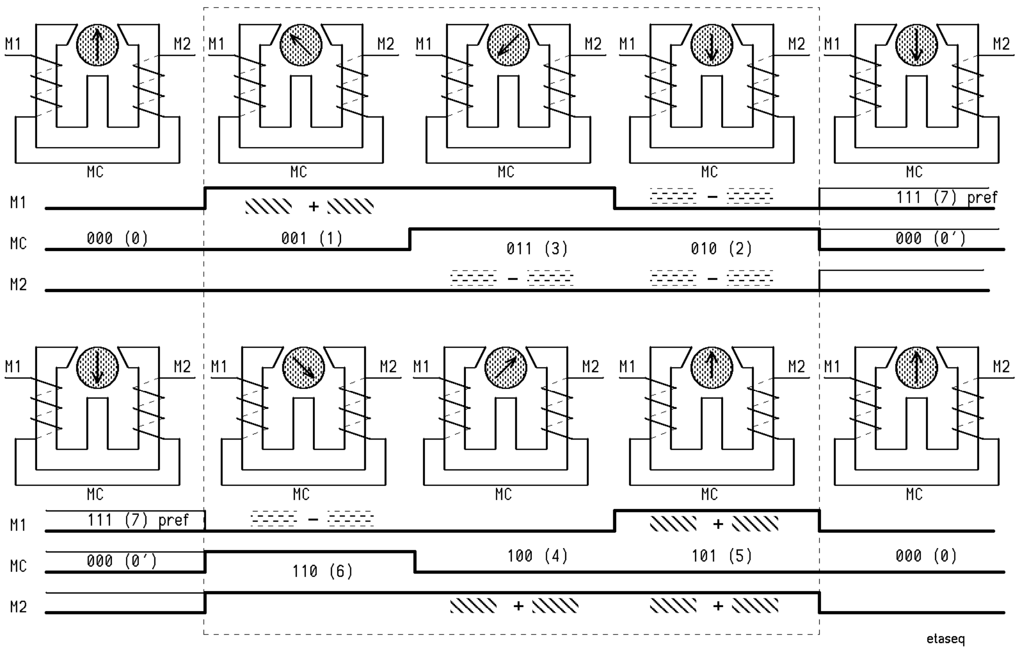

Fig 11. Control of a bidirectional watch motor module or Switec motor (half-steps with optional no-power mode for ACC M-S)

6.Conclusion

PIC microcontrollers, and future competing processors, bring a new dimension to the control of miniature motors, thanks to their small dimensions and low cost. They are quite suitable for open-loop control of miniature motors; in a few years, sensors will be available and it is hoped they will interface easily with these small processors and permit many new applications for miniature smart motors.

This project has been made with the support of the EPFL, RMB and the CTI (Commission for Technological Inoovation). André Guignard has built the mechanics and PC boards with his usual competence.

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