A Programmable Controller/Driver for Electrostatic MEMS Micromotors

E. C. Wood and M. G. Guvench
University of Southern Maine, Gorham, ME 04038

Abstract

This paper describes the design, operation, and use of a PC controlled drive circuit designed to be used to experiment with different drive waveforms on electrostatic MEMS (Micro-Electro-Mechanical-Systems) micromotors. The system designed features a selectible excitation pattern, a programmable frequency generator, and an adjustable high voltage source. The system features excitation patterns for wobble and rotary side drive micromotors. The excitation pattern generator was designed primarily to control wobble and rotary side drive micromotors, however, the system can easily be adapted to produce drive waveforms for almost any MEMS micromotor. Specifically, anyone possessing a universal programmer and the Xilinx Foundation Series Software can easily modify the excitation pattern generator to suit their needs. The excitation pattern generator offers maximum flexibility by allowing the pulse width applied to each stator to be varied from one to eight clock cycles. The system designed offers an adjustable high voltage source that only requires an input of 5V DC with a maximum supply current of 333 mA. In addition, the excitation frequency can be varied from 1Hz to 1 MHz. The operation of the controller is easy due to user friendly software that runs on a PC with the Windows95 or the Windows 98 operating system. The system designed is ideal for anyone doing research with MEMS micromotors.

1. Introduction

This paper describes the design, operation, and use of a PC controlled drive circuit designed to be used to experiment with different drive waveforms on electrostatic MEMS (Micro Electro Mechanical Systems) micromotors. The controller has been designed to drive different MEMS motors, namely, the wobble motor and the rotary side drive. Figure 1 displays a micrograph of a wobble motor with 12 stator electrodes while Figure 2 displays a micrograph of a rotary side drive motor with 8 rotor gears and 12 stator electrodes. These micromotors were designed along with some experimental sensor structures by one of the authors (Guvench) and fabricated at the Microelectronics Center of North Carolina through their "MUMPS" services. MEMS micromotors employ electrostatic attraction, rather than magnetic forces, and take advantage of relatively slow scaling of electrostatic forces at micrometer scales compared to the magnetic forces. Rotary motion is achieved by applying periodic pulses (20V - 200V peak) to a set of stators (typically 12) in a sequential manner from one stator to its neighbor so that the rotor experiences a net torque to spin at a rate proportional to the frequency of the waveform applied.[5,7].

Since optimal waveforms are not known, it is useful to have a drive waveform generator that can easily be adapted to control almost any micromotor. Currently, driver circuits for MEMS micromotors are not available on the market. Literature on MEMS does not supply information on a circuit or setup that can be reproduced either. In other words, one has to build the driver from scratch. One can observe that in some of the highly regarded and well referenced work[5] the investigation of the behavior of the motor designed was done with only two different pattern options available to the investigators, and worse, with waveform patterns having only six phases while half of the twelve poles needed to be driven.

Need for a versatile driver for experimental MEMS micromotors is obvious. The work presented here describes an electrostatic MEMS micromotor driver circuit design which offers an all in one solution to researchers experimenting with MEMS micromotors. Our design is PC controlled, delivers full twelve phases for twelve stators, contains its own variable frequency reference oscillator, allows for slow start-up from zero speed with a hardware determined time constant, generates its own high voltage, amplifies the drive waveforms to a manually adjusted high voltage level of 20 to 200 volts peak, and relies on a programmed chip to deliver 12-phase waveforms with adjustable widths and with a selection between two options, wobble or rotary side drive motor. Use of a programmable chip gives the system the versatility to experiment with unconventional drive patterns.

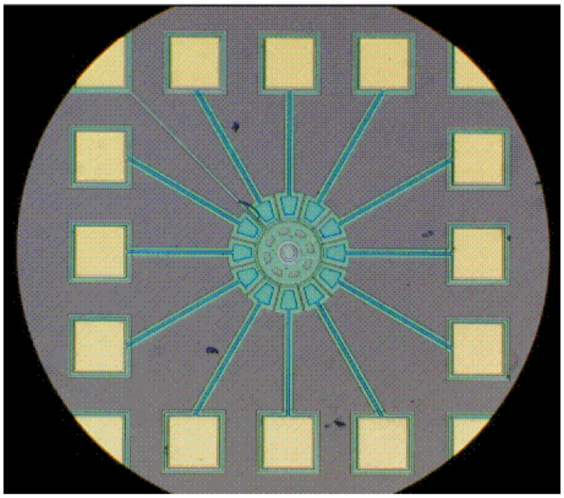


Figure 1. Micrograph of a Surface Micromachined MEMS Wobble Micromotor (Rotor diameter = 100 um)

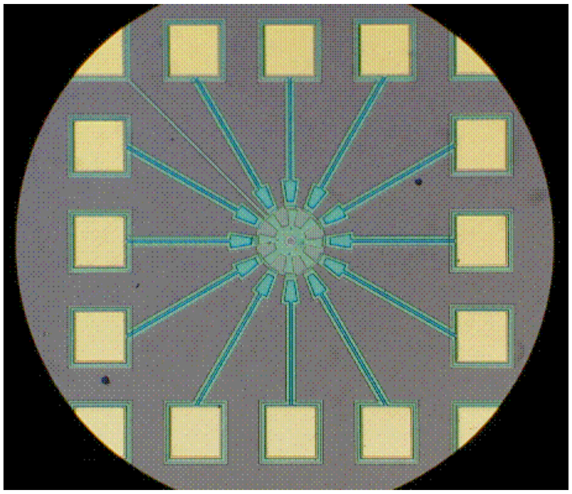


Figure 2. Micrograph of a Surface Micromachined MEMS Rotary Side Drive Micromotor (Rotor diameter = 100 um)

2. Description of The Controller/Driver System for Electrostatic MEMS Micromotors

Figure 3 gives a schematic description of the electrostatic micromotor controller/driver system designed. It comprises of an excitation pattern generator, a set of amplifiers, a programmable frequency generator, an adjustable high voltage source, and an IEEE 1284 Type A parallel port interface for computer control.

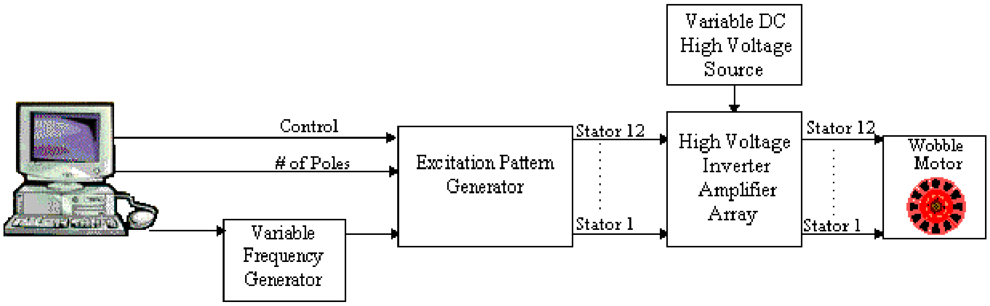
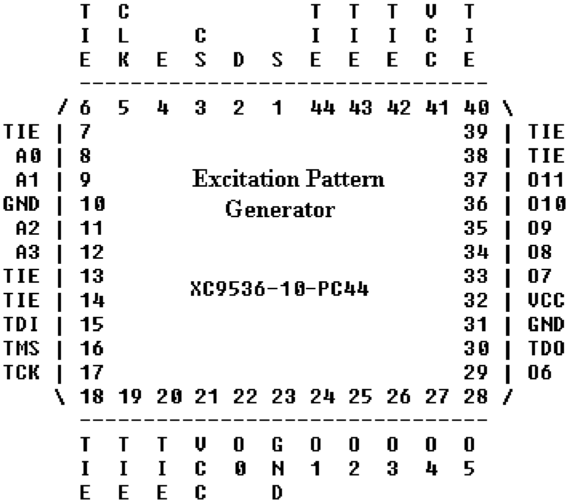


Figure 3. Controller/Driver System Designed to Drive MEMS Electrostatic Micromotors

The excitation pattern generator is essentially a digital logic circuit that produces patterns of ones and zeroes required to drive the micromotors. With twelve phases each pole waveform has 212=4096 possible combinations, but only a small number of these make sense to generate a rotating torque. Figures 10 and 11 show typical twelve-phase waveforms needed to be generated to drive the poles of a 12-pole stator wobble motor and a 12-pole stator 8-geared rotor rotary side drive motor, respectively. Rather than using discrete components, the excitation pattern generator was built using a programmable logic device (PLD). Using a PLD allowed the excitation pattern generator to be designed and tested rather quickly. As a result, more time could be spent on system design rather than wasting time troubleshooting a potentially flawed design. For the PLD, a Xilinx 9536 in a Plastic Leaded Chip Carrier (PLCC) 44 pin package was chosen. Figure 4 gives a pin diagram of the excitation pattern generator. The excitation pattern generator was characterized using a combination of Hardware Description Language (HDL) and schematic entry using the Xilinx Foundation Series design and synthesis software [2]. In Figure 5, the architecture of the excitation pattern generator circuit is presented.



```
        T  C              T  T  T  V  T
        I  L     C        I  I  I  C  I
        E  K  E  S  D  S  E  E  E  C  E
        --------------------------------
      / 6  5  4  3  2  1  44 43 42 41 40 \
  TIE | 7                             39 | TIE
   A0 | 8                             38 | TIE
   A1 | 9      Excitation Pattern     37 | O11
  GND | 10         Generator          36 | O10
   A2 | 11                            35 | O9
   A3 | 12                            34 | O8
  TIE | 13                            33 | O7
  TIE | 14       XC9536-10-PC44       32 | VCC
  TDI | 15                            31 | GND
  TMS | 16                            30 | TDO
  TCK | 17                            29 | O6
      \ 18 19 20 21 22 23 24 25 26 27 28 /
        --------------------------------
        T  T  T  V  O  G  O  O  O  O  O
        I  I  I  C  0  N  1  2  3  4  5
        E  E  E  C     D
```

Figure 4. Pin Diagram of the Excitation Pattern Generator

As depicted in Figure 5, the excitation pattern generator uses a variable frequency external clock to generate the required variable frequency waveforms. In its design, multiplexers and demultiplexers are used to control and select an excitation pattern. The inputs to the demultiplexer consist of control inputs, an enable input, and a chip selection input. The control inputs consist of a pulse width selection input, an input to control the direction of rotation of the micromotor, and an input to start the micromotor. As its name implies, the chip select input is an input to select between the two excitation pattern generator circuits. The enable input serves to enable the multiplexer or disable the multiplexer. Finally, the multiplexor selects the outputs from either the wobble micromotor excitation pattern generator or the rotary side drive excitation pattern generator.

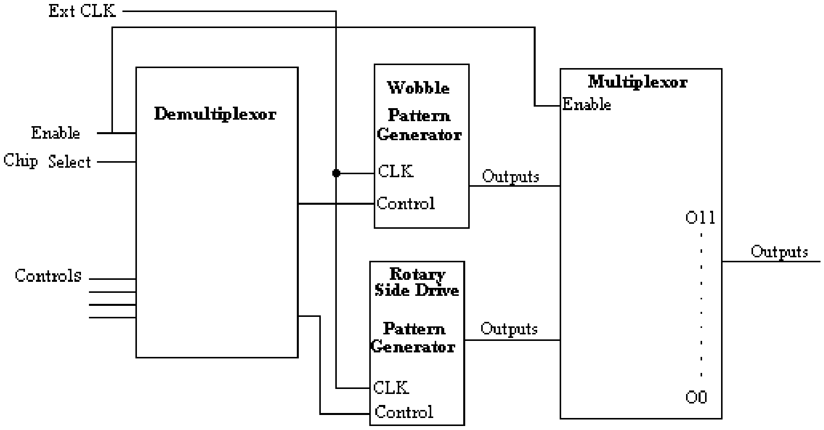


Figure 5. Architecture of Excitation Pattern Generator

Since the output of the excitation generator is limited to +5V, a set of amplifiers had to be used to increase the amplitude level of the excitation pattern to 20-200volt range. Instead of actually using a conventional multistage analog amplifier, an array of high voltage transistor inverters were used to obtain pulses constituting the negative of the excitation pattern by switching the potentiometer varied DC voltage from the 250V high voltage source. The array of transistors consisted of twelve NPN bipolar junction transistors (BJTs) operated as inverting switches. Figure 6 gives a schematic description of the BJT inverter array and its components. Note that the electrostatic micromotor's stator has less than a pF capacitance, therefore, 200V/600K=1/3 mA minute current is sufficient to charge it within a microsecond from 0 to 200Vpeak.

The high voltage source was achieved with a DC-DC converter from Pico Electronics model 5A250S. The DC-DC converter accepts an input voltage of +5V and an input current of 333mA and can output +250V while delivering a load current up to 5 mA. As depicted in Figure 6, a potentiometer was used to vary the +250V supply voltage.

A programmable frequency generator was used in order to vary the frequency of the excitation voltage, and as a result, vary the speed of the micromotor. The programmable frequency generator consists of a CMOS 4046 Phase Locked Loop (PLL) where the voltage controlled oscillator (VCO) on the PLL is used as the frequency generator. The maximum frequency range is selected by selecting from a range of capacitors. The maximum frequency ranges from 1 Hz to 1 MHz logarithmically. In addition, a 12-bit serially loaded digital to analog converter (DAC) from Linear Technology is used to linearly select the minimum frequency to the maximum frequency in each range. Figure 7 gives a schematic description of the programmable frequency generator. Also, the input of the 4046 uses an RC circuit on the input to offer a time delay so the motor doesn't instantaneously see the maximum applied frequency.

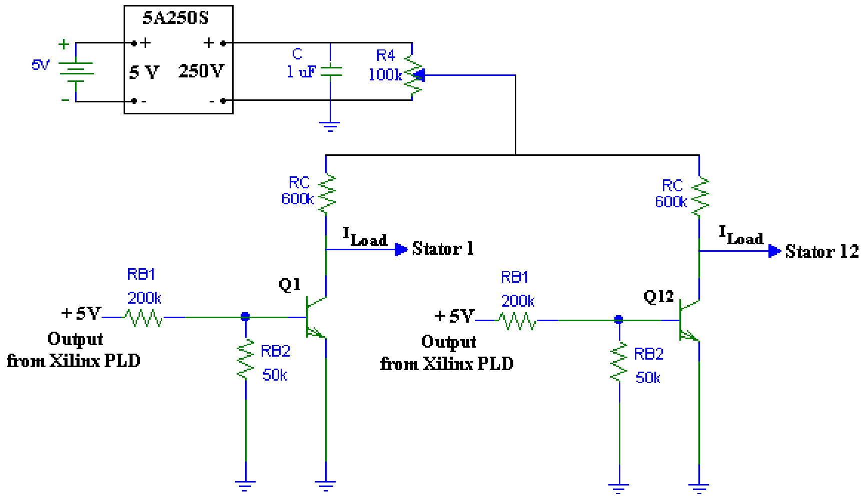


Figure 6. High Voltage BJT Inverter Amplifier Array

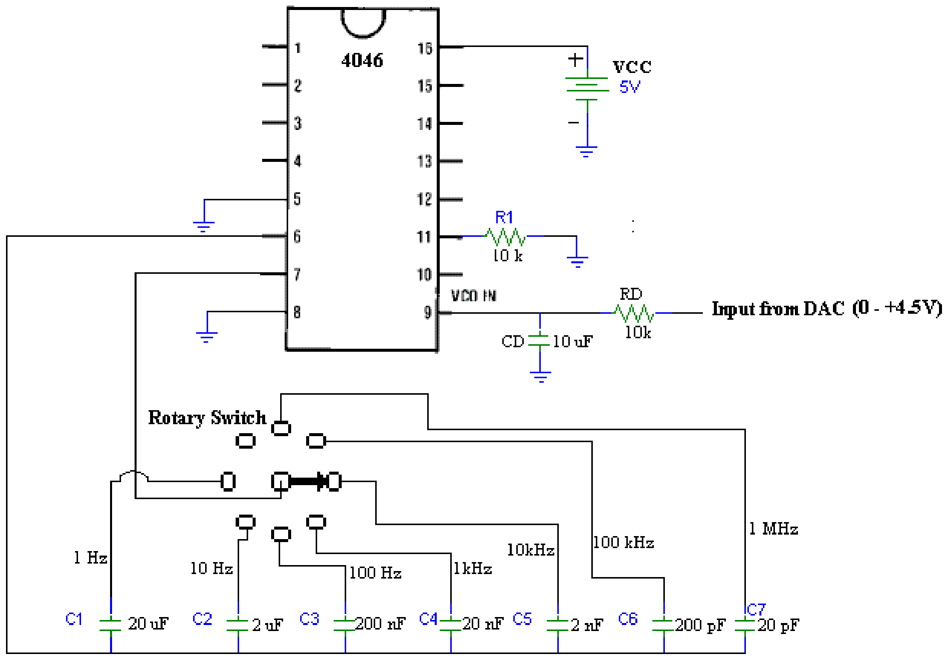


Figure 7. Programmable Frequency Generator

Finally, in order to make the controller user friendly, an IEEE 1284 Type A parallel port was used to interface the controller to a PC running the Windows95 or Windows98 operating system. In order to prevent the excitation pattern generator from loading the parallel port, a 74HC244 buffer was inserted between the excitation pattern generator and the parallel port. Software was developed for the controller using Microsoft's Visual C++ Version 6 compiler. From the software, a user can select the excitation frequency, the excitation pattern direction, and most importantly the excitation pattern. The algorithm implemented is graphically represented in Figure 8 with a flow chart.

As depicted in the flowchart, the software first determines the base address of the parallel port from the Window's registry. Next, the data register and the control register are initialized by setting all bits of both registers low. The user then selects the motor to drive, the pulse width, the excitation frequency, and the motor direction. Next, the appropriate bits of the data and control registers are set. The user then has the choice to stop the motor and enter new settings or quit the program. When the user quits the program, the data and control registers are cleared. Consequently, even if the user forgets to stop the motor before existing the program, the motor will automatically be stopped when the user quits the program. Figure 9 gives a screen shot of the control software. The interface consists of a dialog based application. Certainly, there is room for improvement. Specifically, there could be visual feedback concerning the waveform selected. At the moment, the user must use the help file included to learn about the waveforms generated for the wobble and rotary side drive micromotors.

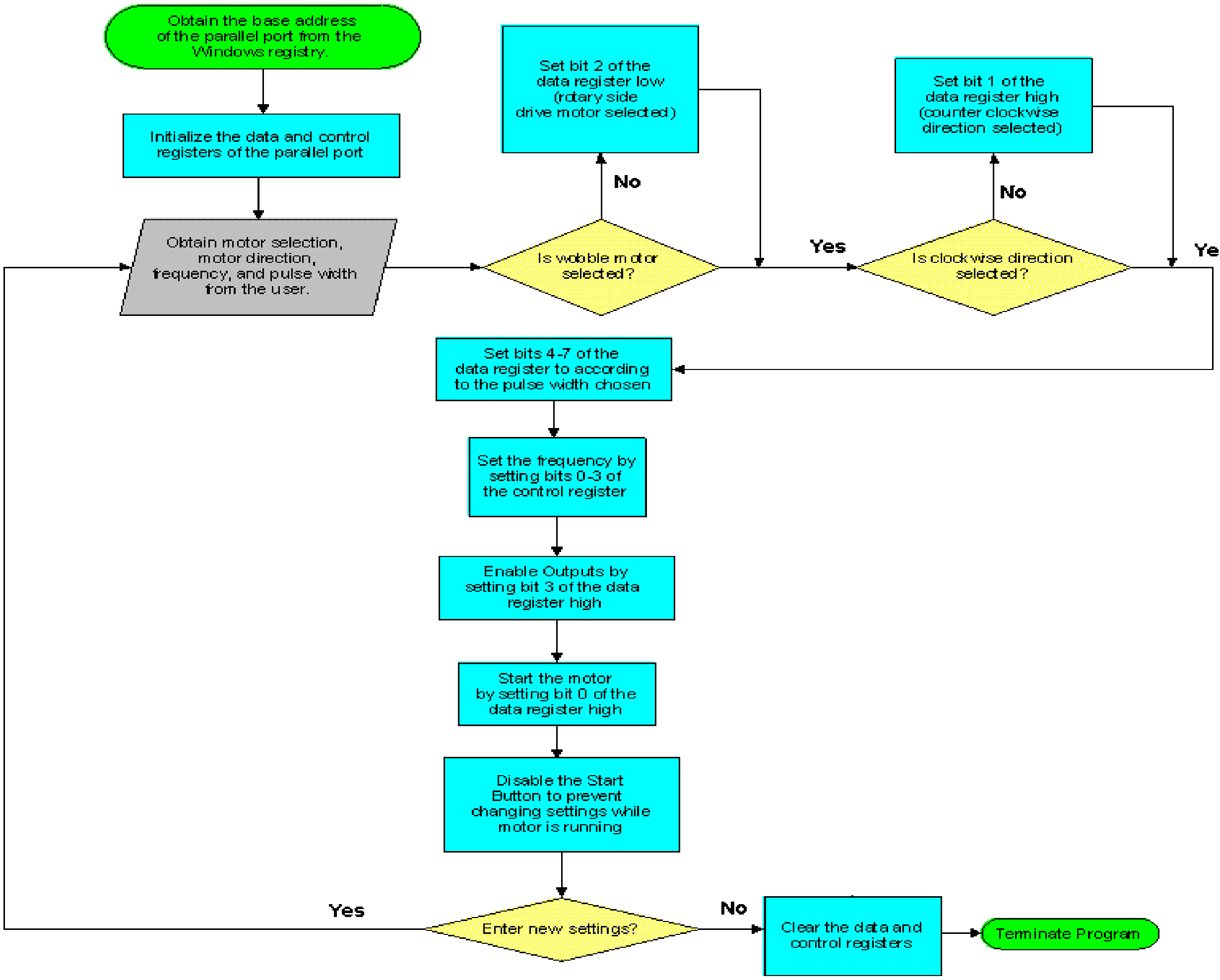
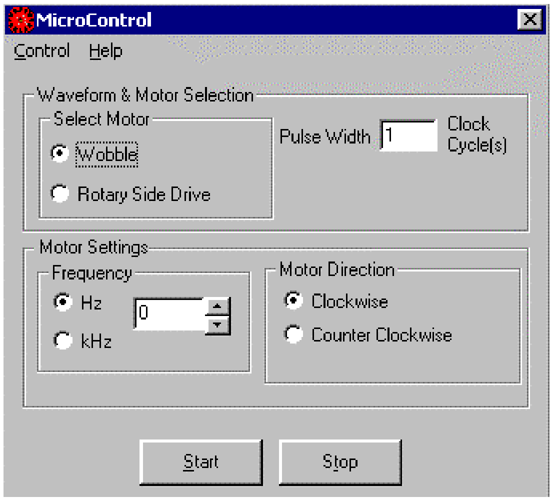


Figure 8. Motor Control Algorithm



Select Motor
● Wobble
○ Rotary Side Drive

Pulse Width 1 Clock Cycle(s)

Frequency
● Hz
○ kHz
0

Motor Direction
● Clockwise
○ Counter Clockwise

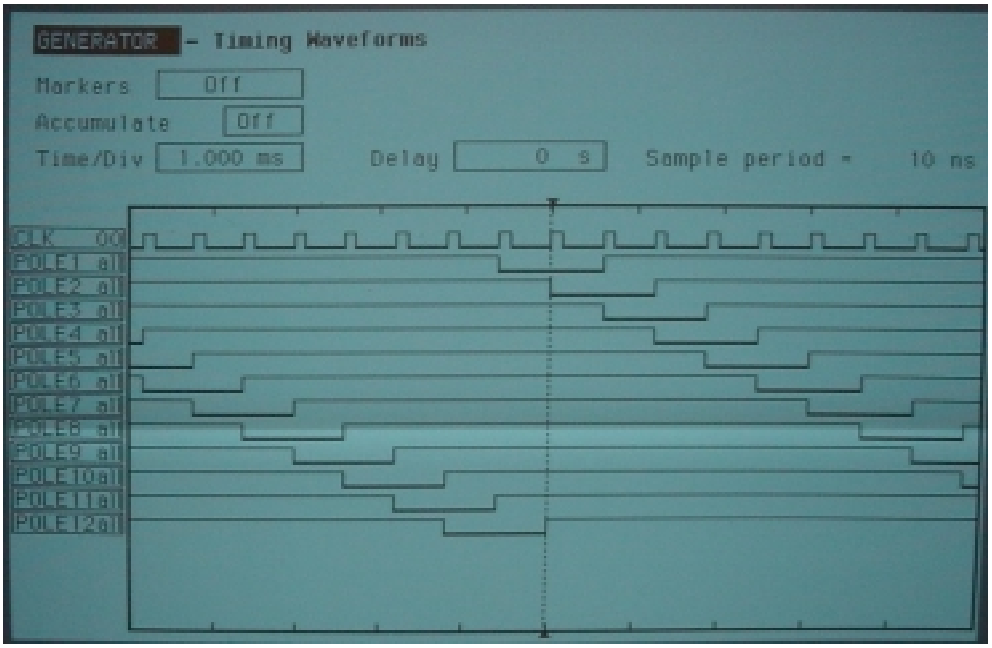
Figure 9. Interface of Motor Control Software

3. Results, Conclusions and Remarks

The system was built as a part of senior electrical engineering capstone project at the University of Southern Maine. The goal of the project was to design and construct a general purpose, programmable high voltage generator circuit to drive experimental electrostatic MEMS micromotors. The programmable controller designed offers a low cost solution to anyone looking to drive MEMs micromotors whether it be for demonstrating concepts to undergraduate students or for use in research on various motor geometries.

The functionality of the programmable controller was tested using a Hewlett Packard 1650A Logic Analyzer. Figures 10 and 11 are screen shots taken of the logic analyzer of sample drive waveforms required for the wobble and rotary side drive motors respectively; and show how the stators of electrodes of such rotary motors would be excited. Note that actual waveforms applied to the stators are inverted and amplified up to 200 volts. For instructional demos to a group of students, rather than doing the demonstration on an actual micromotor which has to be viewed under a microscope, the demo can be done on a larger scale display consisting 12 LEDs (one standing for each pole) and arranged uniformly on a circle on a printed circuit board. Such a display , since it would be driven at low voltage, helps avoid the danger of high voltage shock to the students and can be viewed by the whole group simultaneously in a small classroom or teaching laboratory, . For latter use the high voltage inverters and their high voltage DC source are turned off. Instead, another twelve amplifier driver output circuit similar to the one given in Figure 6 is plugged in, which operates from a low voltage source (+5VDC), and low resistance values are chosen (33 ohms) to drive the LEDs at about 100 mA peak, bright enough to be seen in a room under normal lighting conditions.

In conclusion, the programmable electrostatic MEMS micromotor controller/driver circuit designed and described here has proven itself to be an asset in our research laboratory to test various micromotors and as a demo system to describe to students the principles of operation of wobble and side drive rotor electrostatic motors.



GENERATOR - Timing Waveforms

Markers Off

Accumulate Off

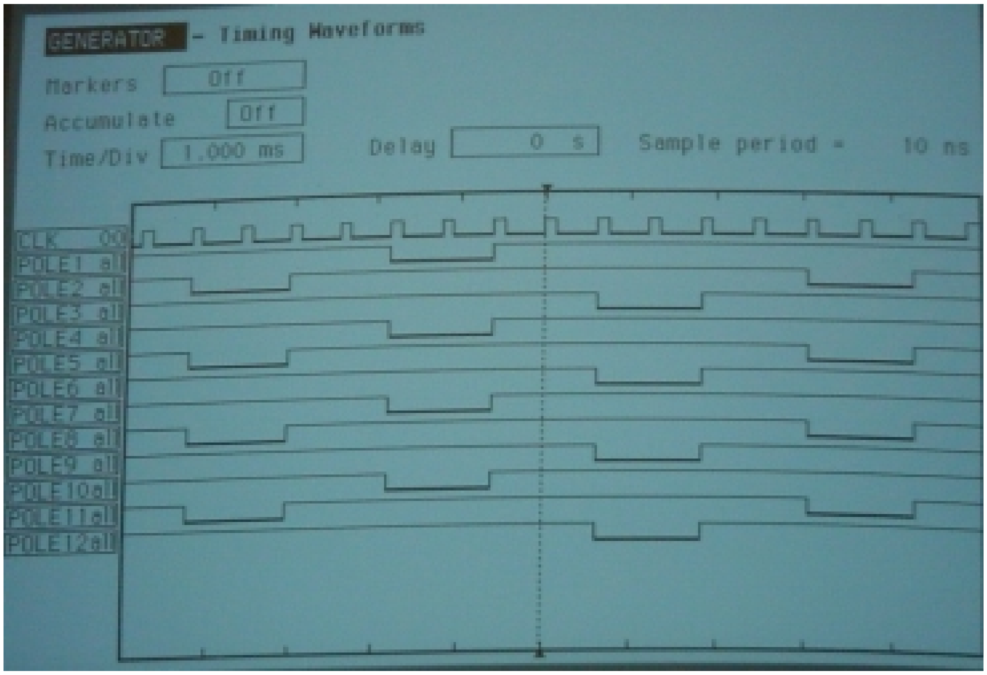
Time/Div 1.000 ms

Delay 0 s

Sample period = 10 ns

Figure 10. Scope Photograph of Drive Waveforms for the Wobble Motor

(Pulse Width chosen = 2 Clock Cycles)



GENERATOR - Timing Waveforms

Markers Off

Accumulate Off

Time/Div 1.000 ms

Delay 0 s

Sample period = 10 ns

Figure 11. Scope Photograph of Drive Waveforms for the Rotary Side Drive Motor

(Pulse Width chosen = 2 Clock Cycles)

REFERENCES:

[1] Bout, David Van den, "The Practical Xilinx Designer Lab Book, Version 1.5", Prentice Hall,1999.

[2] Chris H. Pappas & William H. Murray, III "The Complete Reference Visual C++ 5", Osborne/McGraw Hill, 1997.

[3] Barbarello, James, “Handbook for Parallel Port Design” Howard W. Sams and Company, 1999.

[4] Axelson, Jan, “Parallel Port Complete” Lakeview Research, 2000.

[5] Vijayakumar R. Dhuler, Mehran Mehregany, and Stephen M. Phillips, “An Experimental Technique and a Model for Studying the Operation of Harmonic Side-Drive Micromotors”, IEEE Transactions on Electron Devices, Vol 40, No.11, pp. 1977-1984, November 1993.

[6] Sniegowski, J.J. “Moving the World With Surface Micromachining (One Microgram at a Time)”, Sandia National Laboratories, 1999.

[7] Vijayakumar R. Dhuler, Mehran Mehregany, and Stephen M. Phillips, “A Comparative Study of Bearing Designs and Operational Environments for Harmonic Side-Drive Micromotors”, IEEE Transactions on Electron Devices, Vol 40, No. 11, pp. 1985-1989, November 1993.

ERIC C. WOOD

Eric C. Wood is a senior at the University of Southern Maine graduating in May 2002 with a B.S. degree in Electrical Engineering. He has worked for Hannaford Brothers, Winthrop, Maine for more than three years as a programmer/analyst. His interests are software development, programmable controllers, and home automation.

MUSTAFA G. GUVENCH

Mustafa G. Guvench received his B.S. and M.S. degrees in Electrical Engineering from M.E.T.U., Ankara in 1968 and 1970, respectively. He did further graduate work at Case Western Reserve University, Cleveland, Ohio between 1970 and 1975 and received M.S. and Ph.D. degrees in Electrical Engineering and Applied Physics. He is currently a full professor of Electrical Engineering at the University of Southern Maine. Prior to joining U.S.M. he served on the faculty of M.E.T.U., Ankara and Gaziantep campuses, Turkey and at the University of Pittsburgh. His research interests and publications span the field of microelectronics including I.C. design and semiconductor technology and its application in sensor development, finite element and analytical modeling of semiconductor devices and sensors, and electronic instrumentation and measurement.