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Mechatronics 16 (2006) 303–308
MECHATRONICS

Compact programmable controller for a linear piezo-stepper motor

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Received 3 November 2004; accepted 17 February 2006

Abstract

A design of a compact and low-cost programmable high-voltage pulser for a linear piezo-stepper motor, using an 8 bit reduce instruction set computers (RISC) microcontroller, a high-voltage complementary metal oxide semiconductor (HVCMOS) converter, and an adjustable three-terminal high-voltage regulator is presented. The design consists of 12 independent digital channels of high-voltage output and two-operation modes—normal and smart. The generator is applied as a controller for an approach mechanism in a scanning probe microscope. The motor shows translation of about 1 mm/min with step size of about 100 nm.

Keywords: High-voltage pulsed generator; Piezoelectric transducer; SPM

1. Introduction

The invention of the scanning tunneling microscope (STM) in 1982 by Binnig and Rohrer [1] triggered the development of a family of high-resolution microscopes called scanning probe microscopes (SPM) [2]. Among SPMs techniques, we find the STM, atomic force microscope (AFM) [3], and the scanning near-field optical microscope (SNOM) [4,5]. All SPMs use fine piezoelectric transducers controlled by feedback mechanisms to scan samples with a very sharp tip at very short distances. The difference between the various techniques is that each type maps different characteristics of the sample by using it's own unique interaction mechanism between the tip and the sample.

One important part of the SPM that affects its design and performance extensively is the coarse approach mechanism. This mechanism is used to bring the tip from a setup position, "far away" from the sample (few millimeters), to a scanning position, "very close" to the sample (<1 μm), by fast sub-micron steps. On one hand, the approach velocity, which determines by the step size and rate, should be limited, in order to protect the tip from any damage. On the other hand, this velocity should be fast enough in order to avoid long approach period.

We can classify the approach mechanisms to several categories: macro-mechanical translation, piezo-stepping devices, and inertial sliders. In the macro-mechanical mechanism, manual or step-motorized movement using screws, springs, and levers [6–8] are used to move the tip or the sample. Piezo-stepping device could produce a discrete step by clamping its rear leg to the support surface, expanding the piezo body, clamping the front leg to the surface and releasing the rear leg, contracting the body etc. Clamping is achieved by various methods such us: electro-static attraction [1], friction [9,10], or Burleigh Instrument's commercial inchworm [11]. Inertial sliders [12–15] are similar to the piezo-steppers in that they produce a series of discrete steps, each using one full expansion of a piezo drive. Instead of requiring separate clamping means, they rely on the "tablecloth trick" of slip-stick motion. A translation stage riding on a smooth support, which can be accelerated using a piezo actuator. Due to friction, the stage will follow accelerations up to a certain limit. If the

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doi:10.1016/j.mechatronics.2006.02.002

motion is suddenly reversed (by reversing the piezo voltage as quickly as possible), the translation stage will not follow the reverse movement. These piezo-steppers and inertial sliders can provide nanometer steps over a macroscopic range of travel.

Piezoelectric materials [16,17] can be used to convert electrical energy into mechanical energy and vice versa. For nanopositioning, the precise motion which results when an electric field is applied to a piezoelectric material is of great importance. The applied electric field is generated by an electronic controller, mostly made of several channels of high-voltage generator or high-voltage pulser.

One of the main issues while using high voltage to drive piezoelectric elements is the hysteresis and nonlinearity associated with these actuators [18,19]. It is shown, that by driving piezoelectric actuators using current, or charge amplifiers the hysteresis will almost disappear [20–22]. The issue of hysteresis and nonlinearity is more critical in applications when the piezo is used as a precision scanner or controller [23]. In application where the piezo is used as a motor, the hysteresis and nonlinearity are less critical and can be compensated by a nonlinear calibration.

2. Design considerations

The controller presented here consists of 12 independent high-voltage digital outputs (up to 240 V/1 mA). These outputs can be configured as 12 unipolar channels (0 V, 240 V) or as six bipolar channels (−240 V, 0 V, +240 V). Each channel can drive a single piezoelectric transducer, which can form an array of defined structures. The transducer can be constructed of various types of piezoelectric configurations, such as: tubes, bi-morph plates, shears force elements etc. The controller has two working modes: normal and smart. In the normal mode, all the operation parameters are programmed a priori in the internal flash memory of the circuit. In the smart mode, the operation parameters are dynamically transmitted to the controller via an external data bus, using a dedicated protocol. It is shown that by integrating an 8-bit reduce instruction set computers (RISC) microcontroller, a high-voltage digital device and an adjustable three-terminal high-voltage regulator, one can implement a compact and accurate system at very low costs. This controller supplies voltage pulses at a range of 30–240 V at 10 kHz rate.

The initial consideration in the design was to choose the high-voltage switching device that compatible with piezoelectric elements. Since the required current of these applications is relativity low, in order to achieve a compact design, a high-voltage complementary metal oxide semiconductor (HVCMOS) converter, which receives a transistor transistor logic (TTL) in its input and supplies hundreds of volts at its output, was chosen. This device, Supertex HV510 [24], supplies 12 channels of 240 V/1 mA output each. A simple calculation shows, that a piezoelectric element, with typical capacity of 5 nF, is charged, by a current of 1 mA to a full voltage of 240 V, at 1200 μs, which leads to a pulse rate faster than 800 Hz. For most applications this rate is satisfactory, for example: a rate of 100 Hz with step size of 200 nm provides translation of 1 mm at less than 1 min.

3. Electronic circuit

Fig. 1 depicts the controller circuit diagram: U_1 is the HVCMOS device that receives the 12 data bits serially by DIO and CLK inputs and sends the converted high-voltage signal in parallel through J_2. The data and timing signals

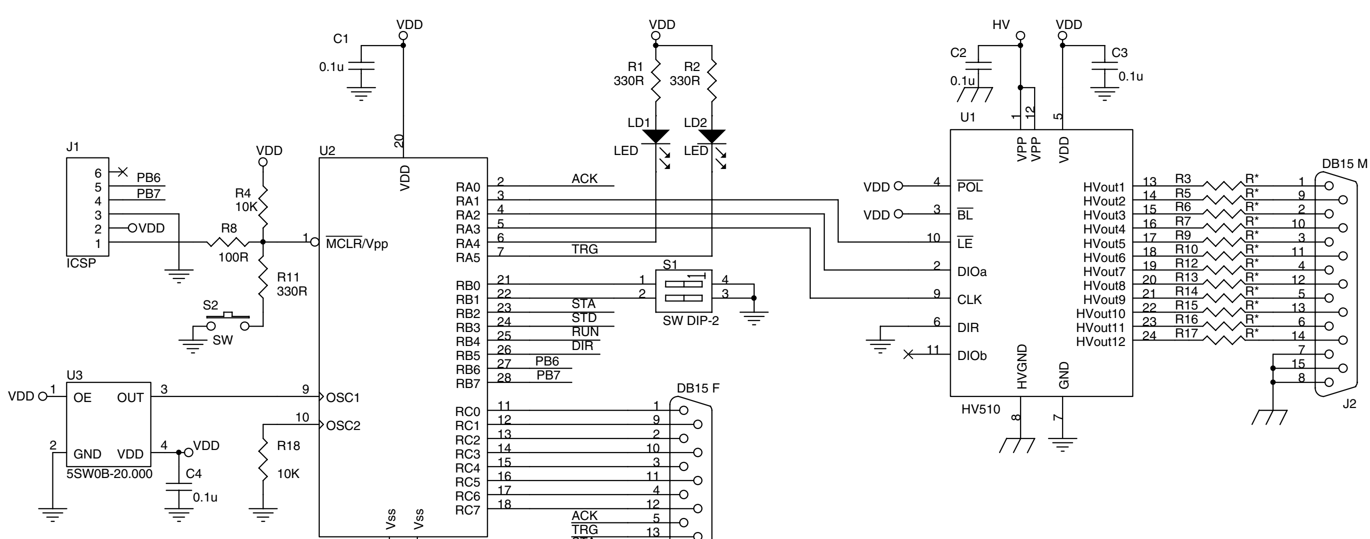

Fig. 1. The controller circuit diagram. U_1 is HVCMOS device that receives 12 data bits serially by DIO and CLK inputs and sends the converted high-voltage signal in parallel through J_2. The data and timing signals are controlled by U_2—PIC16F873 microcontroller.

are controlled by U_2—a microchip 8-bit RISC microcontroller PIC16F873 [25]. This chip includes 4KB FLASH memory for programming, 192 bytes of RAM and 128 bytes E^2PROM. U_3 is a master 20 MHz clock, while S_2 is a master RESET button. R_3–R_{17} are resistors that limit the output current to the piezoelectric elements. The value of these resistors depends on the required time constant and may change between zero to mega ohms. J_3 is a connection to an external port in order to control and configure the system. In the normal mode, the user sets the rate by PORTC (binary combinations of RC0–RC7), and turns the driver on/off and the direction forwards/backwards, by the RUN and DIR pins of J_3, while others parameters are kept constant in the controllers memory. In the smart mode, the driver should be connected, through J_3, to the external computer by a standard parallel port (or any other parallel or serial bus). In this mode, the configuration and commands are performed by software, that communicates with the driver via a dedicated protocol (as will be explained later). J_1 is used to download the compiled program from the personal computer to the internal flash memory. Two voltage supplies are required: VDD—5 V and HV—240 V. One can use LM7805 as a low voltage regulator and VB408 [26] as a high-voltage regulator.

4. Architecture and software design

All the output sequences (strings) are stored in the memory as 8- or 16-bits integer arrays (char or short in C language) depending on how many channels are used. The string consist of a series, with a variable length (STRLEN) that is limited to 100 of outputs combinations that are exported outside with an internal delay between them. The exportation is continuously repeated with an external delay between the two strings.

Fig. 2 describes the flowchart of the controller's embedded program. In the normal mode, the time delay T is in ms, and is the only external parameter that the controller receives via PORTC (block 4). After receiving the time delay, RUN and DIR bits are checked to decided if the exportation is enabled or not, and which string should be exported. After the string exportation, if the time delay T is zero, then the controller waits for the falling edge in RUN bit, otherwise, the controller waits for T ms and returns to the beginning. The TRG bit is an external trigger to indicate that a string was exported. In the smart mode, the configuration, parameters, and commands are stored in the internal nonvolatile memory of the controller. The transfer of these data to the controller is performed by a software that communicates with the controller via a dedicate protocol that uses strobe address (STA), strobe data (STD), acknowledgment (ACK), and PORTC signals.

Since the controller does not include an address bus, one must write any data by two cycles, first writing the address and afterwards writing the relevant data. By using this architecture each parameter in the controller has its own local address (8 bit output is suggest):

0—TDELAY external delay between repeated strings (ms).
1—IDELAY internal delay between combinations in the string (tens of μs).
2—CONTROL enable.

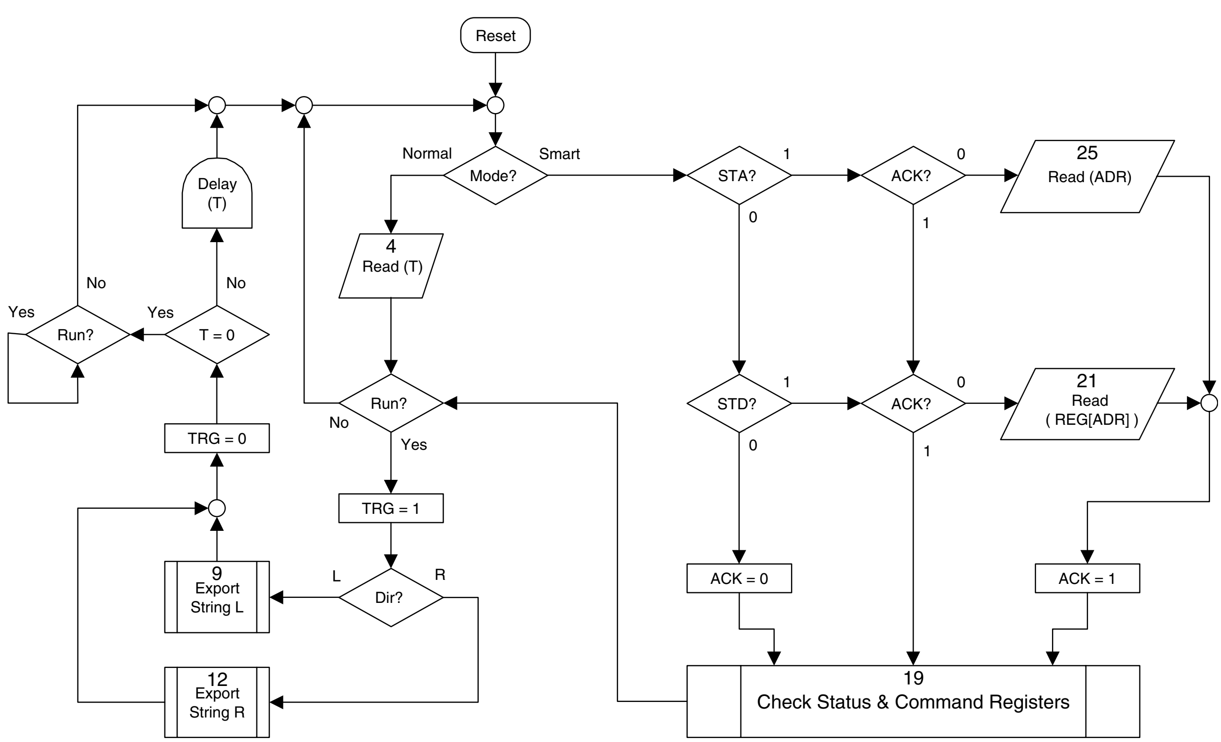

Fig. 2. The flowchart of the controller embedded program for normal and smart modes.

3—STRLEN the number of combinations in the string.
10–59—FSTR the forward string data.
60–109—BSTR the backward string data.
110–127 reserved.

Following the flowchart, in order to write an address, one should export the relevant address to the PORTC, turn the STA to '1', wait to ACK, and finally turn the STA to '0'. In the same way, to write a data, one should export the relevant data to PORTC, turn the STD to '1', wait to ACK, and finally turn the STD to '0'. While either the STA or STD signals do not turn back to '0', no new address or data can be sent to the controller.

The program can be written in assembly, C or any other high level language that supports this microcontroller. We used C language to write the embedded program and the compiler we used was PIC ANSI C from HI-TECH Software [27].

5. Mechanical design

The first decision was to choose the piezoelectric elements [16,17]. Piezoelectric bending elements are electromechanical transducers that possess high motion sensitivity. The element's sandwich-like structure, in which two thin piezoelectric ceramic sheets are bonded to a center support vane, provides mechanical integrity and built-in leverage to amplify the motion of the ceramic layers. In motor applications one ceramic layer expands laterally and the other layer contracts when an electric field is applied to the element. The opposing strains result in a bending or deflection of the element that is proportional to the applied voltage. The elements can generate large displacements and moderate forces at relatively low levels of electrical drive.

The most common and low-cost bending element shapes are rectangular. These elements are typically mounted in cantilever configurations, as shown in Fig. 3. The cantilever's displacement—X_f, and force—F_b, are given by the following two expressions:

$$X_f = 3/2 \cdot d_{31} \cdot (L/T)^2 \cdot (1 + t/T) \cdot V \cdot A \tag{1}$$

$$F_b = 3/8 \cdot Y_{11} \cdot d_{31} \cdot (T/L) \cdot W \cdot (1 + t/T) \cdot V \cdot A \tag{2}$$

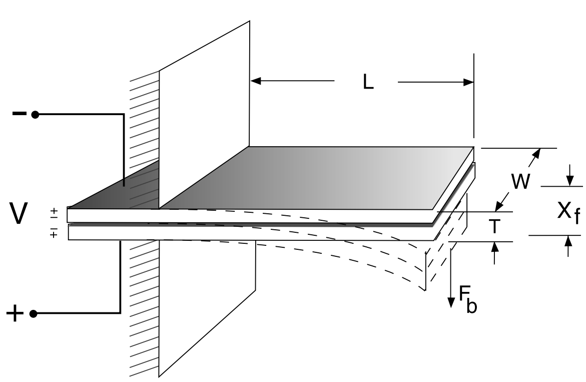

Fig. 3. The cantilever configurations of bi-morph element.

where,

- L cantilever length
- W cantilever width
- T overall cantilever thickness
- t electrode combined thickness
- V applied voltage
- A empirical factor ($\geqslant 1$)
- X_f free deflection
- F_b maximum generated force
- d_{31} piezoelectric strain constant
- Y_{11} Young's modulus

Typical values for piezoelectric strain constant are 100–300 pm/V, and for Young's modulus are 6×10^{10}–10×10^{10} N/M^2.

The general description of the linear piezo-stepper motor [10] is shown in Fig. 4. A quartz tube—10 mm in diameter, 50 mm in length and 25 g in weight—which carries the SPM tip, stands on four pieces each of $5.5 \times 4.5 \times 0.7$ mm bi-morph element. All four elements are glued to an Aluminum base. The effective length of each element is 1.5 mm, because 4 mm out 5.5 mm is used to contact the base. The electrodes thickness is 0.14 mm and comprises of around 20% of overall thickness of the element. The piezoelectric strain constant is about 200 pm/V, and Young's modulus is 6.5×10^{10} N/M^2. Substituting these parameters in Eqs. (1) and (2) leads to the

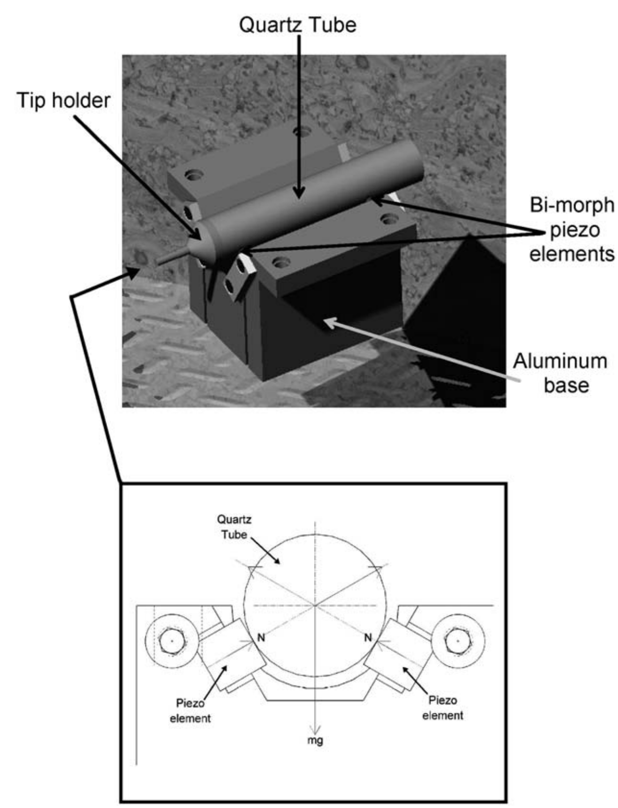

Fig. 4. The general description of a linear piezo-stepper motor made of four legs of bi-morph piezo elements and quartz tube.

following result: The free deflection is $X_f \approx 1.65$ nm/V and the maximum generated force of each element is $F_b \approx 1.2 \times 10^{-2}$ N/V, when the overall force of the four elements together is 4.8×10^{-2} N/V. The friction factor, between the quartz tube and the piezo elements, is $\mu \sim 0.5$, therefore the friction force is $F_\mu = \mu N_F = 0.25$ N, where N_F is the normal force between the quartz tube and the piezo elements.

Each of the four elements is connected to a single output of the electrical driver that supplies voltage pulses in the range of 50–120 V. This means that the theoretical step size is in the range of 80–200 nm and the overall force is in the range of 2.4–5.8 N.

The main idea of the movement—based on a piezo-stepping devices—is to slide each single element against the static force of the remaining three elements, and afterwards moving the four elements together, carrying the tube.

6. Results and discussion

The controller described here can be used by any system that requires high voltage and low current sequential pulses. We used the controller with the above-mentioned motor, when each of the four legs is connected to a single output of the driver in a unipolar mode. In order to implement the above-mentioned movements scenario, the driver sends a string pulses to the piezo elements. The string length is 5 and the sequential pulses (string data) for a forward step are {(0001), (0011), (0111), (1111), (0000)} and for a backward step are {(1111), (0111), (0011), (0001), (0000)} where the 0 and 1 represent 0 V and HV on each element, as shown in Fig. 5. The voltage dependence of the motion per step is measured by a linear voltage differential transformer [28] (LVDT) and plotted in Fig. 6 for both directions. The step size varies linearly, between 100 nm and 300 nm, with the voltage, as expected (in the previews calculation we ignored the empirical factor, it is easy to see that this factor in our system is about 1.5).

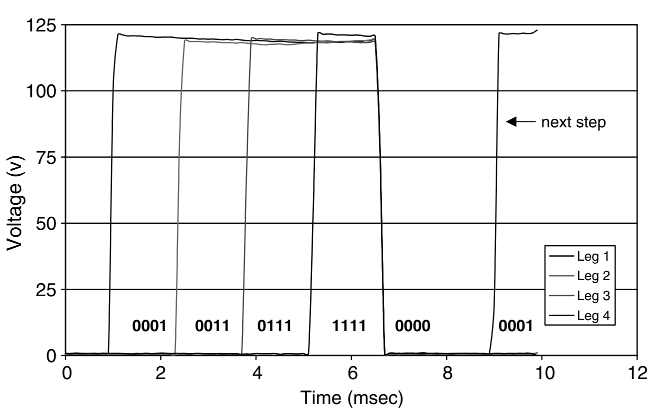

Fig. 5. The voltage waveform that is used for the piezo-stepper motor. The string length is 5 and the sequential pulses for a forward step are {(0001), (0011), (0111), (1111), (0000)} where the 0 and 1 represent 0 V and 120 V on each leg. The internal delay is 1500 μs while the external delay is 8 ms.

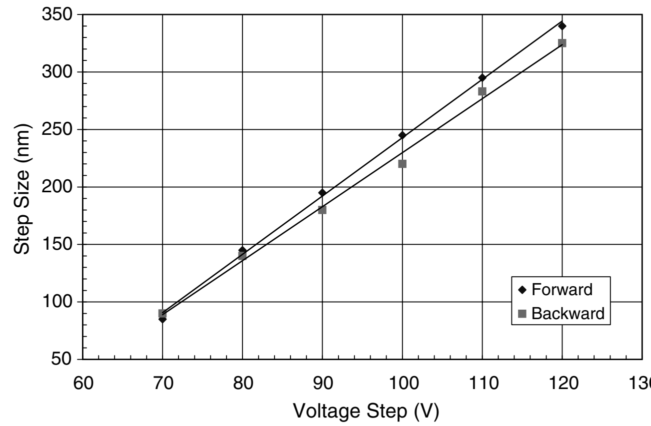

Fig. 6. The step size as a function of the voltage (measure by LVDT).

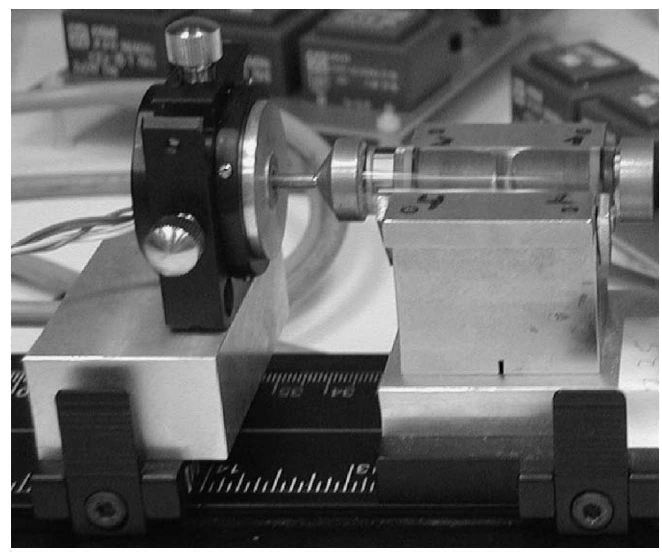

Fig. 7. The overall system: the quartz tube, which carries the tip, the aluminum base with the four bi-morph elements, and the LVDT that measures the step size.

The step's rate is 200 steps per second, which means translation of about 1 mm/min. Fig. 7 shows the overall system: the quartz tube, which carries the tip, the aluminum base with the four pieces of bi-morph elements, and the LVDT that measures the step size.

Commercial motors like New Focus—Picomotor [29] or Burleigh–Inchworm [30,11] are good solutions with a price label above 1000$. This cost is reasonable in systems which worth tens of thousands of dollars (like commercial SPMs). In low-cost systems, where the overall cost is only few thousand dollars, the above cost is too high and one must use such a dedicated design. Moreover, by using dedicated motor, one can make his design more flexible and compact. It is well known that in scientific apparatus, one often needs power supplies, pulsers, or mechanical design which are tailor-made to perform a certain task, which cannot be performed by commercial instruments, or rather be performed by a combination of several commercial instruments. For such systems, a tailor-made design is the best solution from the aspects of cost, compatibility, and availability.

In addition, such controllers can be massively used in systems that involve ion optics [31,32]. In such systems, in which a mixed package of ions is created via a supersonic expansion, ions should be separated according to their mass. Pulsed electric fields are then used to adjust the energy or momentum of the given ions in order to separate them in space and time as in a time-of-flight mass spectrometer. Pulsed fields can be further used to filter ions from neutrals. The pulsed electric fields used for such purpose are in the order of several hundred volts at time scale of microseconds.

In conclusion, the design principles of a general-purpose, programmable, compact and low-cost high-voltage pulse generator have been demonstrated. This design can be used for systems that require high voltage and low current sequential pulses. In particular it can be used for a coarse approach mechanism in SPM. This design is compact in size and very low cost (<$30) compared to any commercial system.

Acknowledgements

The author wishes to thank Prof. Ori Cheshnovski for his help and for allowing him to use the equipment at his laboratory, Mati Kanterovich for performing the measurements and to Dr. Israela Becker for her useful advice.

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