System Integration of High Voltage Electrostatic MEMS Actuators

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Abstract- **A system integration for High Voltage (HV) electrostatic MicroElectroMechanical Systems (MEMS) actuators is introduced on a micro-Printed Circuit Board (PCB). The system includes a programmable microcontroller, a programmable DC/DC converter, a multi output HV interface and electrostatic MEMS actuators. The system produces high output voltages (10-300V) and can control a large variety of MEMS capacitive loads (1 to 50pF) by combining diverse technologies. This system proves that technologies, such as low voltage CMOS of different processes, high voltage DMOS and MEMS, can interact, communicate and even be integrated as a System In Package (SIP), providing significant size and cost reductions.**

I. INTRODUCTION

The necessity to control multiple MicroElectroMechanical Systems (MEMS) electrostatic actuators devices is becoming an important issue for a variety of applications like aerospace Microsystems [1], biomedical systems like automatic DNA samplers [2], consumer electronic systems like ink jet printers[3] and video display projectors like Digital Light Processor (DLP). It could also be used to control Liquid Crystal Displays (LCD) and new photonic devices like Organic Light-Emitting Diode (OLED). MEMS systems are implemented through batch microfabrication or micromachining techniques that have evolved from those used to fabricate integrated circuits. Most MEMS electrostatic actuators have specific requirements for their power supplies (10-300V), activation current (1µA to 5mA) and commutation speed, depending on their loads and functionality. MEMS actuators have a number of characteristics that make the design of control circuitry and power electronics for these devices challenging. Furthermore, the desire to achieve system-level miniaturization can introduce an additional burden as control circuitry can only be dedicated to a single application and as the power electronics often dominate the overall system size. This paper demonstrates that different hybrid technologies can be merged to drive multiple electrostatic actuators by using a programmable microcontroller core. The possibility to fully customize the system is very appealing, since most commercial MEMS sensors or actuators systems consist of dedicated ASICs designed for fixed loads and fixed supply operating voltage. This system can be programmed to fit a wide range of application requirements that may have different or variable loads, output voltages and speed.

II. THE MICRO-PCB BOARD DESCRIPTION

The electronic circuits on the developed micro-Printed Circuit Board (PCB), as shown in Figure 1, are used to drive high voltage MEMS actuators. The system has the capability to control MEMS actuators individually with proper time delay, supply voltage, activation pulse characteristics (Pulse Width Modulation), and frequency by microcontroller software.

The board consists of a programmable DC/DC converter that can produce very high voltage output to supply the high voltage (HV) interface. A rechargeable lithium-ion battery supplies the system for practical portable use. The HV interface drives the multiple MEMS actuators that are represented by variable capacitive loads (1 to 50pF). The microcontroller is programmed to send digital data to the HV interface and to the DC/DC converter that supplies it.

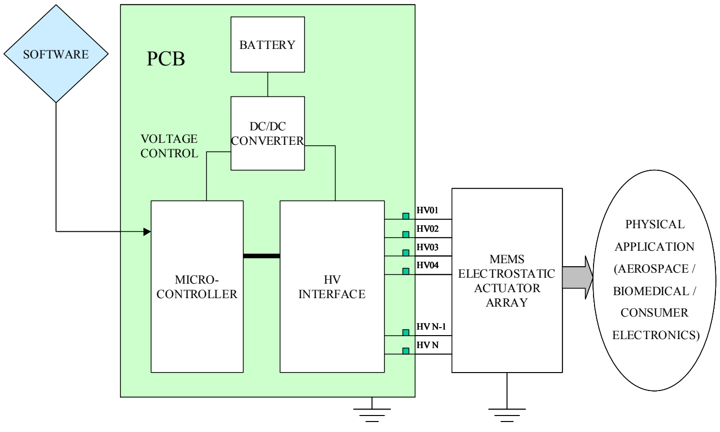

Figure 1. PCB block diagram driving MEMS actuators

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III. SYSTEM BLOCKS

This section presents the different devices that compose the micro-PCB. Four main sections will be discussed: the power supply, the microcontroller, the HV ASIC interface, and finally, the MEMS actuator load. Functionality of those circuits and the obtained results are discussed in the following sections.

A. A DC/DC Converter as Power Supply

The DC/DC converter comprises a Pulse Width Modulating (PWM) and a low-noise boost converter that operates from as low as 3V and switches at 500kHz [4]. At the output of a 36V PWM, Dickson voltage multipliers [5] have been used to increase the output voltage value up to 380V as shown in Figure 3. The complete circuit is shown in Figure 2. Some integrated capacitors inside the Dickson charge pump have been placed to lower the effect of the total parasitic circuit capacitor and leakage current. The output voltage is regulated by a feedback loop that consists of a voltage divider with a digital potentiometer set by the microcontroller. The feedback enters the PWM comparator that controls pulse generation as seen in Figure 2. Finally, output ripples of the total DC/DC circuit are less than 10mVpp.

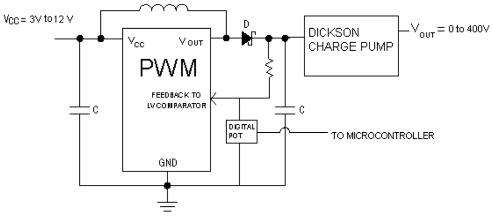


Figure 2. Simple DC/DC converter block diagram

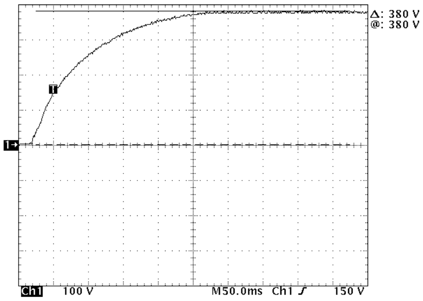


Figure 3. DC/DC converter output measurement

B. The Microcontroller

Due to the need for a very small die area, a 8-bit RISC architecture microcontroller has been selected. Also, for power consumption efficiency, the microcontroller can operate at a voltage as low as 2.7V directly from the battery and has only 16 I/O ports. At 1 MHz, 3V, and 25°C, the microcontroller needs only 0.70mA to operate in active mode [6]. The programmable microcontroller sends serial or parallel data to the HV interface to turn on/off specific outputs depending on the application control algorithm. It has the capability to send different PWM profile to the HV interface and to control the DC/DC to send different supply voltages, to control each system's output independently or in group (Figure 4). This makes the system capable to set each actuator displacement, duty cycle and operation frequency.

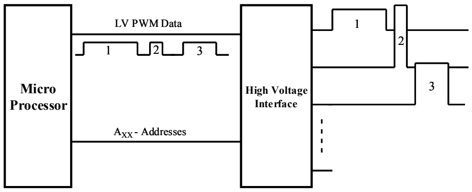


Figure 4. Microcontroller data control

The microcontroller generates the input signals to the HV interface: data, clock, strobe, addresses (parallel case), and the control voltage to the DC/DC converter digital potentiometer. This small low power microcontroller (its MLF package size is only 5mm by 5mm), could be stacked over the HV interface or the DC/DC converter for future integrated applications.

C. High Voltage Interface Architecture and Implementation

The functional block diagram of the HV ASIC interface is shown in Figure 5. This HV interface is a digital data converter with serial or addressable low voltage inputs that controls sixteen (16) parallel HV output channels. This HV interface capacity can be expanded to multiple HV parallel outputs (32, 48, 64, …) to drive larger arrays of MEMS actuators.

The chip offers interesting features that help interactions between the microcontroller and the MEMS actuators units. The first feature is that each output can be programmed to be selected individually, in groups or globally when the addressable mode is activated. This is useful when specific MEMS units need to be addressed.

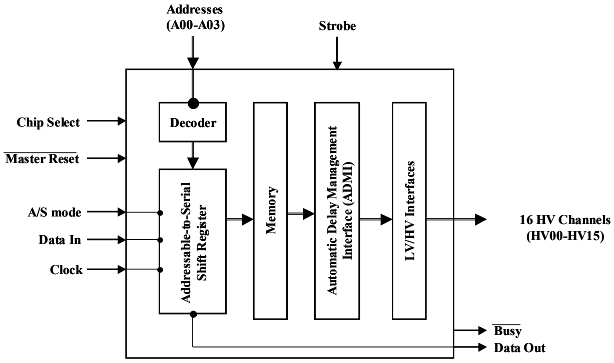


Figure 5. HV ASIC functional block diagram

A second interesting feature is that output drivers can support a range of HV supply voltage going from 10V to 300V. With this feature, the HV ASIC has the ability to be customized for different application requirements. As a third feature, the data acquisition is never delayed or stopped, allowing continuous output transmission. As a fourth interesting feature, a busy logic port, that behaves like a mailbox has been introduced to facilitate communications between the microcontroller and the HV interface. When an external pulse at the Strobe pin occurs, a bit is set at this location. At the same time, the data is read from the memory, goes though the Automatic Delay Management Interface (ADMI) and finally, through the LV/HV drivers. To clear the flag and accept another event on the Strobe pin, all the HV channels need to be in a stable state. By setting the flag, the Strobe pin is disabled, prohibiting any other event that can activate the outputs and possibly introduce unstable states.

Past research has shown that power dissipation for HV IC's is an important issue [7]. When multiple high voltage outputs are frequently requested, minimization of power dissipation becomes a challenge. As shown in Figure 5, an innovative concept has been used to control the energy dissipation. An Automatic Delay Management Interface (ADMI) has been introduced to limit energy dissipation on the die. The idea behind this concept is to limit the number of output events over a period of time. To start another output event, the first one must be at 10% (fall event) or at 90% (rise event) of the supply voltage. This design limits the output switching current (sink/source) per period of time and, at the same time, limits the peak power dissipation at the die level.

The minimization of the die area was a critical aspect of the design for this HV interface. The need for large driver array and portable applications has brought us to revise the original output driver design reported in [8]. This design was improved with respect to required area, frequency of operation and power consumption.

Improvements to the design reduced the area by 70%, while raising the maximum frequency of operation by 100% and reducing current consumption by a factor of ten (10) as shown in table 1. The reported HV drivers are used as flexible blocks and can support a range of supply voltage going from 10V up to 300V. These drivers were embedded in the HV interface chip to be bonded to the external MEMS electrostatic actuators.

Table 1 – High Voltage Driver Improvement by Output

	Number of HV transistor used	Area (um^2)	Operation Frequency (Cload≈25pF)	I_{DD} (uA)
Previous Design	8	200,000	700KHz	4000
Current Design	3	62,000	1.5MHz	400

D. *Electrostatic MEMS Actuator Load*

A typical MEMS electrostatic actuator is the Straight Comb. This MEMS device can be used for diverse applications. In the RF field, it can be used to implement resonators. In the microfluidics field, it can be used to pump small fluid particles or to spray gas particles. The Straight Comb can be used for longitudinal, lateral and vertical actuation, as well as out-of-plane position detection. Arrays of straight combs, as shown in Figure 6, can be placed to produce unique controllable Microsystems. The capacitance of this actuator is dependent of the position and the forces between the fixed and the movable comb fingers. Each straight comb has generally two electrodes, the bottom and the top electrode. Figure 7 (a) shows the four different electrical pins: F (fixed finger voltage), M (movable finger voltage), Eb (bottom electrode voltage), and Et (top electrode voltage). Figure 7 (b) shows the electrical equivalent model represented as a network of variable capacitors between each of the four electrical connections. Electrostatic actuation is based on the attraction force between two oppositely charged plates. An approximation of the forces between the two plates is given by:

$$F = \frac{1}{2}\varepsilon_r \varepsilon_0 A \left(\frac{V}{d}\right)^2 \qquad (1)$$

where ε_0 is the air permittivity, ε_r the permittivity of the gas used between the plates, A the area between the two plates, V the voltage applied and d the displacement desired in the range of 100 nm.

More complex equations and finite element simulations can be made to model the comb forces.

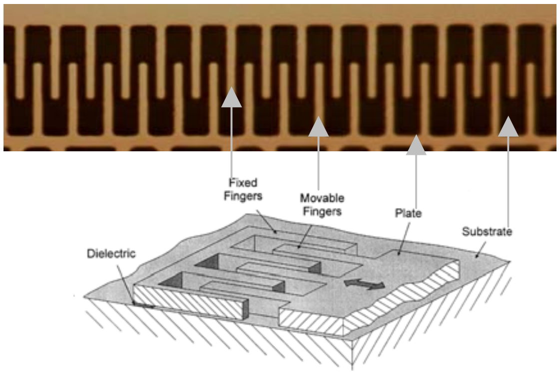
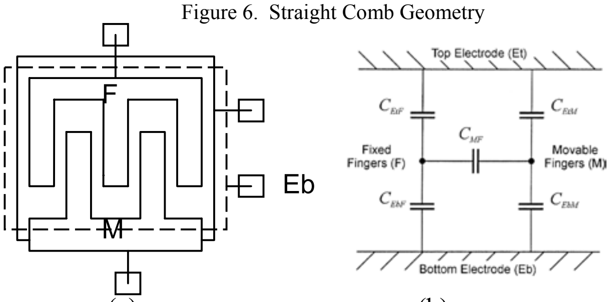


Figure 6. Straight Comb Geometry



(a) (b)

Figure 7. (a) Straight Comb top view (b) Electrical Equivalent Circuit [9].

IV. MEASURED RESULTS AND DISCUSSION

The micro-PCB was built and the microcontroller sends control data to the HV interface that activates MEMS electrostatic equivalent loads. The microcontroller sets the output voltage of the DC/DC controller that feeds the HV interface. The HV interface was implemented, packaged and measurements confirmed that the overall system is functional. The system operates properly with programmed control signal (PWM) data as shown in Figure 8 and Figure 9. The optimized die area (5.6mm^2) of the HV interface, made with DALSA Semiconductor 0.8µm 5V/HV CMOS/DMOS technology, is competitive with similar technologies. Figure 10 shows the layout view of the HV interface that includes 16 HV output channels and can use up to 300VDC supply.

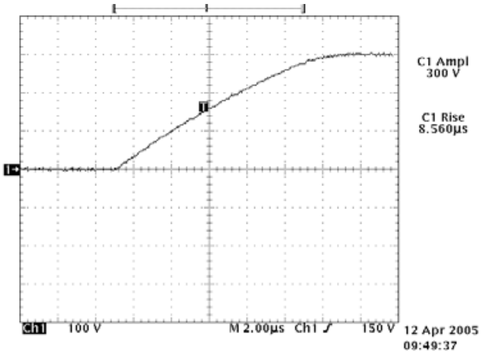


Figure 8. Single HV output channel activating a MEMS load (Total $C_{Lout} \approx 50pF$)

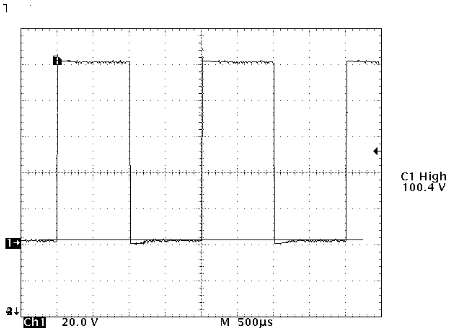


Figure 9. 100V Regulated PWM output data activating a MEMS load

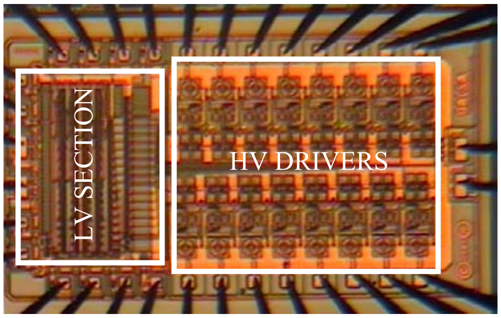


Figure 10. Layout view of HV ASIC interface

V. CONCLUSIONS

The system integration presented in this paper shows that MEMS actuators can be controlled by programmable microcontrollers using custom high voltage interfaces. This system has shown that different technologies, such as CMOS, DMOS and MEMS, can interact, communicate and even, be integrated in the same package, reducing total system size and providing significant cost reduction versus conventional systems. Today's hybrid technologies demonstrate that multi manufacturing technologies can be merged to minimize cost and produce compact systems. The next step is to integrate all chips in a unique package making it a System In Package (SIP).

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ACKNOWLEDGEMENTS

The authors thank the members of DALSA Semiconductor and École Polytechnique de Montréal for helpful discussions and participation in the development of these circuits. They also acknowledge the financial support of Micronet.