MECHANICAL DIGITAL-TO-ANALOG CONVERTERS

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ABSTRACT

We have demonstrated a technique to create a digital-to-analog converter (DAC) from lever arms and actuator arrays. These DACs take digital electrical signals and produce mechanical displacements at the output. A 3-bit DAC with thermal actuator arrays operating on 5V signals has been demonstrated with 2^3 states of displacements. This DAC has a least significant bit (LSB) size of 0.74μm, an integral non-linearity (INL) of ± 0.27LSB, and a differential non-linearity (DNL) of ± 0.25LSB. The DAC was coupled to a hinged micro mirror to test the dynamic and transient response using a laser setup. Such devices could be used as digitally controlled actuators to drive mechanisms in micro optics, mechanical computing, and micro robotics.

INTRODUCTION

Digitally driven actuators offer the benefits of input voltage noise immunity and hence repeatability of output when compared to analog devices. In this paper, we present a technique of configuring arrays of thermal actuators to take digital electrical inputs and produce a displacement at the output. The advantages of such a device are isolation of the output from the load and immunity to on-state input voltage noise. This allows the use of digital drive circuitry for MEMS actuation. Such a device would be useful in applications where a precisely controlled linear displacement is needed. For instance, an n-bit DAC with the output mechanically coupled to a hinged micromirror could be used as a 1:2^n optical switch. Another application would be in microrobotics where a DAC could be coupled to a robot link to actuate the link with discrete positions controlled by a TTL level logic.

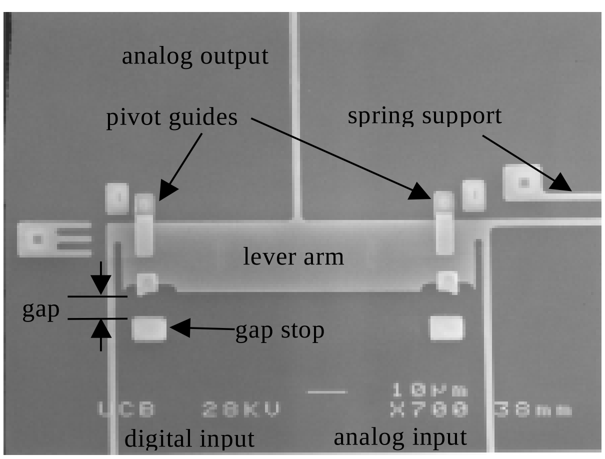

Fig. 1. SEM of a rigid body lever arm with two input beams on either end and an output beam at the middle of the lever arm. The anchor on the left side of the lever arm works as a gap stop to improve repeatability of the digital input displacement.

DESIGN

Mechanical digital to analog conversion can be accomplished by cascading lever arms in series. Fig. 1 shows the SEM of a lever arm that measures 100μm long and 20μm wide and is supported by a folded spring on the right. The lever arm can be regarded as a rigid body that can pivot about either end. The rotation at each end of the lever arm is limited by gap stops. In addition to the gap stops, there are also pivot guides to maintain the planar motion of the lever arms and minimize upward translation of the pivoting end. This lever arm can (1) pivot about the right end in binary fashion so that the left end is either in the original position or rotated to the gap stop and (2) pivot about the right end in analog fashion.

At both ends of the lever arm are input beams. The left input beam is connected to a thermal actuator array [1], which is operated to produce two discrete displacement positions (Fig. 2). The right input beam is connected to the output beam of the previous lever arm stage and transmits an analog mechanical signal to the lever arm. Since the output beam is connected to the lever arm at mid-length, its displacement is equal to half of the sum of the left and right input displacements.

By anchoring the right input beam to the substrate, we can create the least significant bit (LSB) stage. The left input beam is connected to an actuator array that transforms the LSB signal into a displacement. The output beam displacement is equal to half the input displacement. Cascading the right input beam of another lever arm stage to the output beam of the LSB stage creates a 2-bit DAC. The LSB lever arm divides

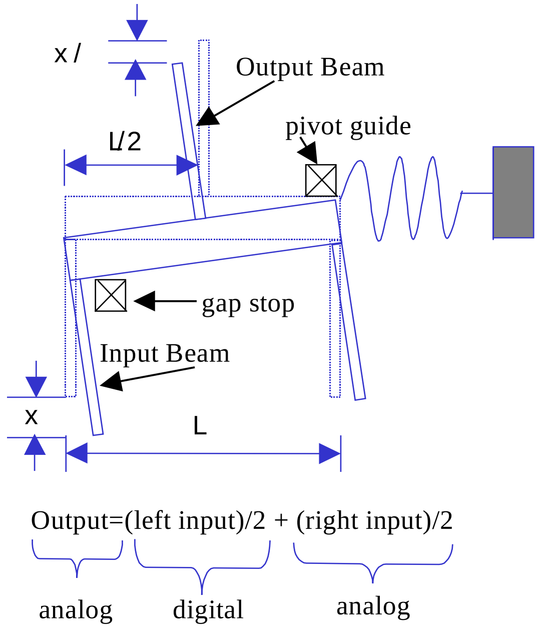

Fig. 2. Diagram of a single stage lever arm in operation. When the actuator array coupled to the left input beam (binary) is turned on, the lever arm rotates until it hits the gap stop. The displacement on the output beam is then ½ of the gap.

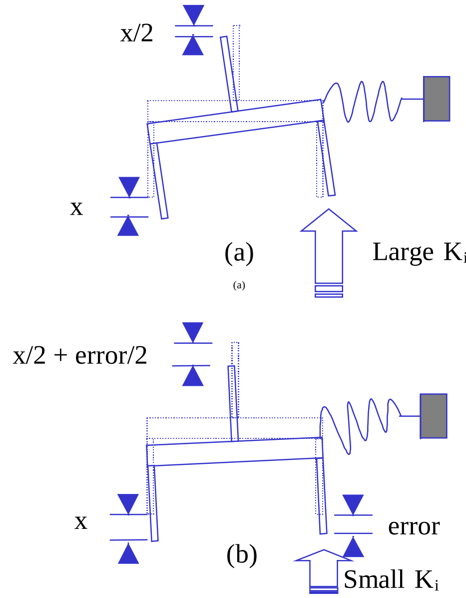

Fig. 3. A small translational spring constant at the input beams causes an error displacement at the output beam.

the LSB (B_0) displacement by half at the LSB output beam. This LSB output beam is connected to the right input beam of the 2nd stage that mechanically adds the LSB output signal to half of the MSB (B_1) input signal and multiplies the sum by half.

Similarly, we can create an *n*-bit DAC by cascading *n* lever arm stages in this fashion. The resulting output is then:

$$Out = \frac{B_{n-1}}{2} + \frac{B_{n-2}}{2^2} + \ldots + \frac{B_0}{2^n} = \frac{1}{2^n} \cdot \sum_{i=0}^{n-1} B_i \cdot 2^i$$

where B_i is the digital input for bit *i*.

Nonlinearity

One source of nonlinearity comes from the finite translational spring constant at the input beams. An ideal DAC lever arm would have ends that translate when given an input and pivot when the other end has input. For example, when the left input beam is displaced, the lever arm should ideally pivot without translation at the right end (Fig. 3a). However, since a finite downward force would appear at the right input beam when the left input beam is displaced, the right end tends to translate. A translation at the right end in this case causes an additional translation at the output beam (Fig. 3b). This additional translation leads to nonlinearity.

To reduce this error, the translational spring constant (mechanical resistance) at the input beams need to be as high as possible. In our devices, the internal spring constant of the thermal actuator array provides the mechanical resistance. Using a MEMS CAD simulator, SUGAR v0.5 [2], the mechanical resistance is calculated to be approximately 70N/m.

RESULTS

In order to demonstrate the feasibility of this technique, we fabricated a 4-bit DAC with the MCNC MUMPs foundry process. The four cascaded lever arms are shown in figure 4. Each input beam is attached to an array of thermal actuators, which is driven by an input electrical signal above the 5V threshold. When actuated, the thermal-actuator array pulls the input beam until the lever arm contacts the left gap stop – a travel of nominally 6 μm. The displacement at the output beam is given by

$$x_{output} = 6\mu m \sum_{i=0}^{3} \frac{2^i}{2^4} B_i$$

where B_i is the digital input for bit *i*.

Figure 5 shows the output beam displacement measured using optical microscopy for the three

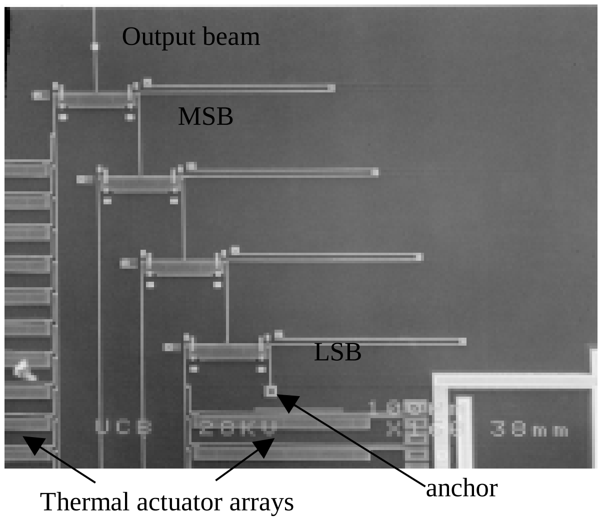

Fig. 4. SEM of a 4-bit DAC created from cascading four lever-arm stages. Each of the input beams are coupled to an actuator array (portions of two arrays are shown). Note that the DAC works despite the 10µm-sized dust on the MSB actuator array.

higher-ordered bits of the DAC (the least significant bit was not tested because the actuator array did not provide enough force to pull the input beam far enough to hit the gap stop). For comparison, figure 5 also shows results from SUGAR v0.5 simulations and results calculated from the ideal equation mentioned above. The displacements calculated using SUGAR are slightly higher than the ideal values because SUGAR simulates the finite stiffness of the actuator arrays and the long thin input beams of this 4-bit DAC.

Maximum Resolution

The maximum resolution is limited by the positioning error of the DAC system. The LSB output displacement can be calculated by:

$$LSB = \frac{gap}{2^n}$$

where n is the number of bits in the DAC and gap is the spacing between the gap stop and the lever arm. Since this smallest step size of the DAC must be greater than the positioning error of the system, the maximum resolution can be calculated by:

$$\frac{gap}{2^m} > \Delta x \Rightarrow m = \frac{\log\left(\frac{gap}{\Delta x}\right)}{\log 2}$$

where m is the resolution, and Δx is the positioning error.

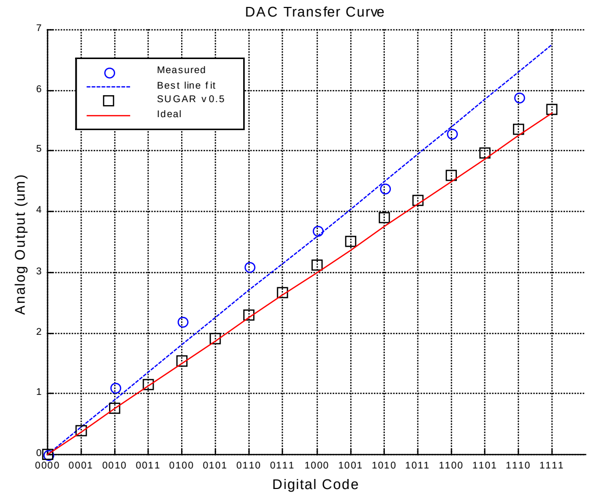

Fig. 5. Output displacement VS input electrical input of a 4-bit DAC. The INL is ± 0.27LSB and the DNL is ± 0.25LSB.

There are several sources of positioning error in the DAC. One is the mismatches between gaps in the DAC due to process variations, including lithography and etching. For example, a 0.1µm gap variation with a 6µm gap would limit the maximum resolution to 6 bits.

The finite stiffness of the input beams and actuator arrays also contributes to the system error. The mechanical resistance of the input beam is in series with that of the actuator array so the total mechanical resistance will be dominated by the stiffness of the more compliant component. To achieve the maximum total mechanical resistance (and hence minimize error), the input beam and the thermal actuator array should both be stiff. However, the input beams used in bits 2 and 3 are long and far more compliant than the actuator arrays, thus lowering the total mechanical stiffness at those bits. This is a source of positioning error and limits the DAC resolution. Future designs will decrease this position error by increasing the stiffness of the input beams.

Maximum Operating Frequency

We measured the resonant frequency of the DAC connected to a scanning micro mirror, as shown by the SEM in figure 6. The position output from the DAC is converted into an angular rotation of the mirror by the hinge at the bottom of the mirror. By projecting a HeNe laser beam onto the mirror and measuring the reflected beam position with a position-sensitive diode (PSD), we were able to characterize the dynamics of the DAC/micromirror system. Figure 6 shows the

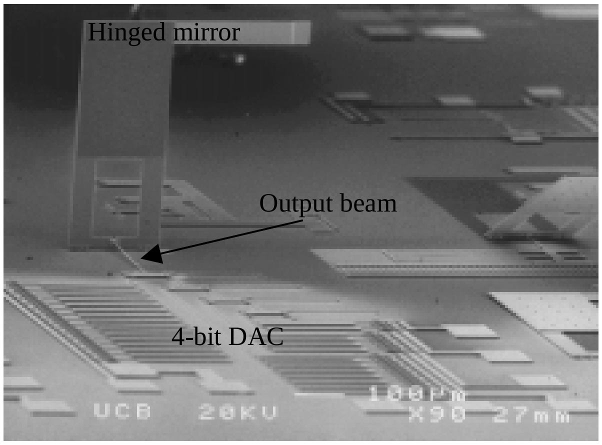

Fig. 6. SEM of a 4-bit DAC driving a hinged micro mirror.

beam position when the MSB of the DAC is switched from off to on.

The oscillation of the optical beam position indicates the system mechanical resonance is at 390Hz. This resonant mode is due to the mass of the micro mirror, and the mechanical compliance of the micro mirror and the DAC system. However, in operation the thermal actuator arrays show signs of in-use stiction to the substrate when driven by a square wave with a DC offset at frequencies above approximately 0.5Hz. This is most likely due to charging of the blanket nitride layer on the substrate. Design changes, including a stiffer mirror structure, a stiffer output beam, and a polysilicon electrode layer under the thermal actuators should allow the system to be operated closer to the maximum frequency of operation of the thermal actuators (about 1 kHz [3]).

CONCLUSION

We have presented a novel method of configuring MEMS actuators so that digital signals can be used to create analog displacements. Although the initial test devices only have three working bits, they demonstrate the feasibility of using this modular design to create an N-bit DAC. These DACs could be used to digitally drive mechanisms such as micro robotic links and micro mirrors with a repeatable output independent of input voltage noise and load. In micro robotics, where sensor feedback is difficult to acquire, a precisely controlled linear output would be useful. In micro optics, a $1{:}2^n$ optical switch could be created driving a DAC with hinged micro mirrors as shown in Fig. 6. Finally, these ADC's would be an essential device for mechanical computing.

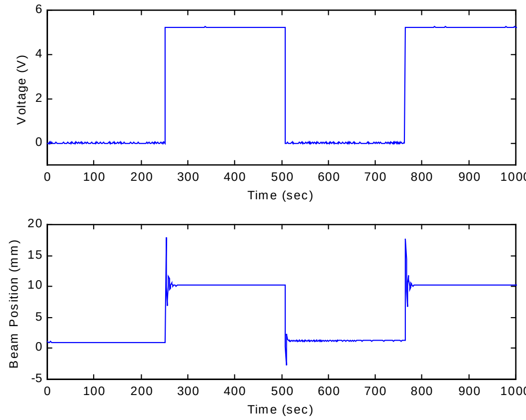

Fig. 7. Beam position (bottom) of the DAC-coupled mirror when the MSB is driven by a square wave of 5V at 0.2Hz (top).

ACKNOWLEDGEMENT

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