The Electronics of a Control System for Micromirrors in a Laser-Scanning Device

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ABSTRACT

The electronics and software developed for the control system of a micromirrors-based laser-scanning endoscope are presented in conjunction with features of the micromirrors and their driving requirements. These micromirrors, which are crucial for the laser-scanning operation of the endoscope device, are embedded in the endoscope head and have been manufactured using silicon MEMS (Micro Electro-Mechanical Systems) technology. The micromirrors are electrostatically deflected and driven by appropriate high-voltage waveforms created in the control system. This computer-based system, using appropriate software, generates the control waveforms, which, after adequate amplification, are driving the scanning micromirrors. The electronics developed is capable of generating control voltages with amplitudes up to 440V pk-pk, within a bandwidth from DC to 20 kHz, and ensures an electrostatical driving of scanning micromirrors with a high positioning accuracy in the sub-pixel range.

1. INTRODUCTION

Laser-scanning techniques are commonly used in various application fields such as medical imaging, laser display and material processing. In modern systems, the scanning procedure is often performed using MEMS-based devices for the deflection of a laser beam over the corresponding target.

The driving electronics is an important part of the present control system of a laser-scanning endoscope, which provides color imaging at near-video rates using the optical signal backscattered from the target tissue. Two silicon micromirrors are used (deflected in directions orthogonal each to another) for the scanning of a composite laser beam with wavelengths at 655 nm (red), 532 nm (green) and 473 nm (blue).

The control system under consideration generates the appropriate voltage waveforms that are applied on the micromirrors electrodes for their electrostatic deflection. This system is based on a PC-resident data-acquisition board and uses 16-bit D/A converters for the generation of the above waveforms, which are subjected to amplification effected by two high-voltage modules.

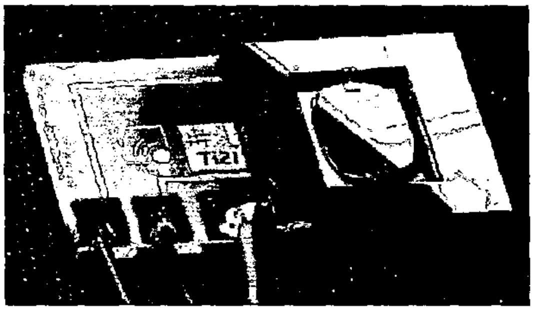

Fig. 1: Silicon mirror plate with frame support

In this article we shall first give a short description of the MEMS micromirrors realized in conjunction with the corresponding control specifications, and then a more detailed description of the high-voltage amplifier modules developed in this work will be presented.

2. THE SCANNING MICROMIRRORS

In the endoscope device developed the two micromirrors are embedded in the endoscope head in a serial arrangement appropriate for two-dimensional scanning (and de-scanning) of the composite laser beam over the target tissue. The first micromirror, having a size of 3x4 mm^2, is used for the line-scanning operation (line-scanning mirror-LSM) and is driven in a resonance mode at a frequency of about 1.2 kHz. The second micromirror has a size of 4x4.8 mm^2 and is used for the frame-scanning operation (frame-scanning mirror-FSM) in a sawtooth-like sweep. Both mirror types are capable of maximum mechanical deflections of ±3°.

The micromirrors have been manufactured by combining bulk silicon technology with metal surface micromachining [1]. With this technology, the micromirrors consist of an Aluminum coated Silicon mirror plate that is laterally suspended by two torsional Nickel springs. Nickel has over Silicon the important advantage that it is not brittle and so it does not break easily. The torsional Nickel springs maintain the movable mirror plate in a surrounding Silicon frame. A second glass chip with metallized electrodes is aligned and fixed under the mirror chip, as shown in Fig. 1.

3. MICROMIRROR DRIVING CONCEPT AND REQUIREMENTS

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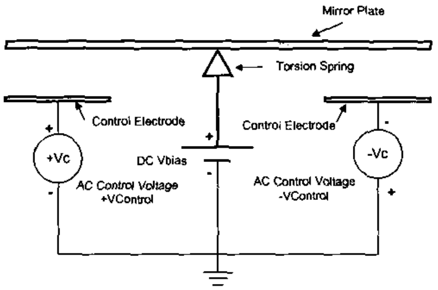

Fig. 2: Mirror bias and control arrangement

The scanning micromirrors are deflected as a result of electrostatic forces developed by the application of appropriate high voltages on the driving electrodes. The application of a voltage between the mirror plate and the underlying control electrodes yields attractive electrostatic forces that are proportional to the square of the applied voltage. Due to this dependence, the micromirror movement exhibits a highly non-linear dynamic behavior.

In order to compensate for this non-linearity effect, a DC-bias voltage V_{BIAS} was applied to the mirror plate while one electrode was supplied with an AC-Control-voltage ($+V_{CONTROL}$) and the second one with an identical AC-Control-voltage ($-V_{CONTROL}$) phase shifted by 180°. In Fig. 2 a simplified model of the way in which the bias and control voltages are applied on the electrodes of each micromirror is given.

It can be shown that the effective torque M_{EL1} - M_{EL2} scales linearly with the control-voltages applied on the two control electrodes when a bias voltage higher than the control voltages is applied. M_{EL1} and M_{EL2} denote the torques exerted on the one and the other part, respectively, of the mirror plate as a result of the control voltages. It is important to note that with the above configuration the effect of bi-directional mirror plate movement exists if the increase in the voltage applied onto the one side (mirror plate-electrode) has exactly the same value with the decrease in the voltage applied onto the other side. Then, for all configurations, independently from whether the electrodes or the mirror plate are biased, the balance of torques implie the following equations:

$$M_{EL1} \propto (V_1)^2 = (V_{BIAS} + V_{CONTROL})^2 \quad (1)$$

$$M_{EL2} \propto (V_2)^2 = (V_{BIAS} - V_{CONTROL})^2 \quad (2)$$

$$\begin{aligned} M_{effect} &= M_{EL1} - M_{EL2} \propto \\ & V_{BIAS}^2 + 2 \cdot V_{BIAS} V_{CONTROL} + V_{CONTROL}^2 - \\ & (V_{BIAS}^2 - 2 \cdot V_{BIAS} V_{CONTROL} + V_{CONTROL}^2) \\ & = 4 \cdot V_{BIAS} V_{CONTROL} \quad (3) \end{aligned}$$

There are several advantages when a DC-bias is applied onto the micromirror. First, a linearization in the mirror movement is achieved in which the deflection angle varies linearly with the applied control voltage; indeed, the first derivative in Eq. 3 with respect to the control voltage is constant. Secondly, the sensitivity in the control voltage can be significantly increased (as it can be seen by Eq. 3) resulting to a reduction of the amplitude of the required control voltage, which simplifies the design of the control amplifier. Also, the introduction of the bias voltage V_{BIAS} allows the bi-directional control of the mirror by applying on the control electrodes the waveform voltages described above.

Table 1: Driving specifications for the micromirrors (for imaging at 20 frames/sec, with resolution of 500x500 pixels)

	FSM	**LSM**
Maximum frequency of the driving signal	20 Hz	5 kHz
DC bias voltage	400-800V	200V
AC control voltage (peak-to-peak)	400 V	400 V

From experimental results obtained for the FSM mirror when it is actuated with a ramp waveform it has been found that the application of AC control voltages with amplitude of 400V pk-pk is adequate, because it provides maximum angular mirror deflection without collapsing or deformation of the mirror plate, while the DC bias-voltage can be varied in the range of 400-800V. The LSM mirror is set in the resonant mode of operation because the voltage control requirements are reduced by an amplitude deflection amplification factor (Q-factor) due to resonance. However, the application of a bias voltage results in a decrease of the Q-factor and of the resonant frequency. From experimental results it has been found that the reduction in the resonant frequency was less than 2% for bias voltages up to 200 V. For this reason the bias voltage on the LSM mirror was limited to 200V. The scanning operation is bi-directional, i.e., imaging is also performed during the retrace period of the LSM mirror. With bi-directional scanning, the frequency requirements for the LSM mirror are reduced by a factor of two.

The various driving requirements for the micromirrors are summarized in Table 1.

4. THE CONTROL SYSTEM

The entire data-acquisition, control and processing system of the endoscope device has been based on a PC-resident data-acquisition card (PCI-6110E of National Instruments Co). With this card, the digitization of the analog signal outputs of the optical detectors for the reflected and backscattered light is performed together with the generation of the two control waveforms. Correspondingly, the control system comprises the two analog outputs of the data acquisition card, the associated software and the high-voltage modules connected at the analog outputs of the acquisition card.

The role of the control software is to command the generation of the two control voltage waveforms via the D/As of the card used, which, after amplification from the high-voltage modules, drive the scanning micromirrors. Using the developed software, the control waveforms for both scanning mirrors can be programmed regarding their shape, amplitude and frequency. In addition, a number of other parameters are programmable such as the phase difference between the two driving waveforms, the retrace time and the relaxation time for the FSM. In Fig. 3 these parameters can been seen clearly. The phase difference must be fine adjustable because

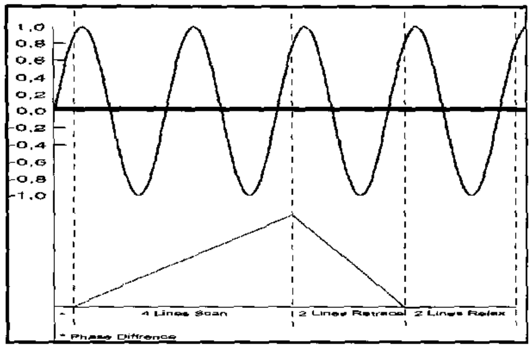

Fig. 3: Scanning waveforms example - 4 lines bi-directional scan

first the resonant moving LSM presents a phase lag of nearly 90° between the driving signal and the mirror position and secondly the synchronization of the image acquisition procedure with the scanning operation is performed with an open loop control scheme based on the control signal of the FSM. The relaxation and retrace times of the FSM control waveform are also software programmable in order to adjust the spectral content of the control waveform, taking into account the resonant frequencies of the mirror and thus avoiding undesired oscillations in the mirror movement.

The necessary waveforms are synthesized, using appropriate algorithms, in accordance with the physical characteristics of the mirrors, the data-acquisition board restrictions and the user requirements.

5. HIGH-VOLTAGE MODULES CIRCUIT DESIGN

The high-voltage modules comprise two identical high-voltage amplifier circuits and a common power supply unit. According to the micromirrors driving requirements (Table 1) each high-voltage module produces two output waveforms with a phase difference of 180° and a maximum amplitude of 215 V.

For the design of the high-voltage amplifier circuits we have selected the PA88 operational amplifier from APEX Co. Its output can swing up to ±215 V, with a 225 V symmetrical supply, and presents a slew rate of 30 V/us and a gain bandwidth product (GBW) of 2.1 MHz [2].

The micromirror devices are mainly capacitive loads and the estimated maximum capacitance (in the case of the maximum tilt angle) lies between 0.1-0.6 pF. As a result of the stray and cable interconnect capacitances, the above value is increased to 200-220 pF (for a 2 m cable with 100pF/m capacitance). The maximum load current (for Vo=220V, f=5KHz, C=200pF) equals to:

$$I_0 = V_0 \cdot \omega \cdot C = 1.4mA$$

The above current requirements are well within the capabilities of the selected operational amplifiers, which can continuously supply 100 mA of output current.

For the generation of the two waveforms from each high-voltage module, when using one amplifier for each output, three connection schemes are possible, as shown in Table 2. After studying the performance curves of the PA88 amplifier, the third configuration had to be selected in order to achieve both the goals of maximum swing and enhanced stability. In both other cases one amplifier must operate at unity gain. The recommended compensation for a gain of 1 is R_c=100 Ohms and C_c=68pF, but, as it can be seen from the data sheets of the operational amplifier [2], with this compensation the full power bandwidth is much less than the desired 20 kHz. From the same data sheets it results that the only compensation scheme that can provide 20 kHz full power bandwidth is with C_c=3.3 pF. This is the recommended compensation for a gain of 100. So this was the gain that has been chosen for the amplifiers A and B in the third configuration. It has to be noted here that the computer control voltages are the outputs of 16-bit DACs which have a standard range of -10V to +10V; hence, from this point of view, the only limiting requirement for the selection of gain is that it must be more than 22. The compensation network R_c-C_c has to be placed as close as possible to the PA88 amplifier in order to avoid spurious oscillations.

For the selected gain of 100 and from the data sheets of the operational amplifier [2] one can see that the phase margin equals to 90°, which is a very satisfactory starting point for good stability, under the described capacitive loads, taking also into account that the output resistance of PA88 without load is 100 Ohms.

The schematic diagram of the high-voltage module is given in Fig. 4. For the two scanning mirrors two identical high-voltage modules have been constructed. The two outputs of each high-voltage module are connected to the corresponding two control electrodes of the driven micromirror while the bias voltage is connected to the mirror plate following the configuration of Fig. 2 for the FSM. For the LSM mirror a DC restoration (realized with the C7,D5 and C8,D6) is performed on the generated waveforms. With this DC restoration a DC offset equal to the maximum amplitude of the sinusoidal control signal is added to each waveform. The mirror plate is grounded and no external bias is applied. This configuration is equivalent to applying a DC bias equal to the maximum amplitude of the sinusoidal signal, that is 200 V. This DC restoration is not realized in the FSM high-voltage module.

With the arrangement followed, when the differential voltage between the high voltage module outputs is zero, both parts of the mirror plate are electrostatically attracted by the same force (due to the bias voltage) which results to an equilibrium of the mirror. When the differential voltage between the high-voltage module outputs is maximum, the mirror is tilted to one direction at the maximum positive inclination and when the difference voltage between the outputs is minimum, the mirror is tilted to the symmetrical direction at the maximum negative inclination.

6. PERFORMANCE MEASUREMENTS

A number of tests have been conducted in order to determine the performance of the developed high-voltage amplifiers.

First of all, extensive tests have been made regarding the noise level at the analog outputs of the high-voltage amplifier sections, as this noise increases the positioning inaccuracy of the corresponding micromirror. The achieved positioning accuracy of the micromirrors has been measured and found better than 0.1 %, which translates to a 60-dB dynamic range. The noise measured after short-circuiting of the input terminals has been found to be less than 3 mV pk-pk (for 20-kHz bandwidth) at the high-voltage outputs, which translates to a dynamic range approximately equal to that of the micro-

***Table 2:** Operational amplifier configurations*

Amplifier A			Amplifier B		
Input from	**Configuration**	**Gain**	**Input from**	**Configuration**	**Gain**
Computer	Non-inverting	High	Amplifier A	Inverting	1
Computer	Inverting	High	Amplifier A	Inverting	1
Computer	Non-inverting	High	Computer	Inverting	High

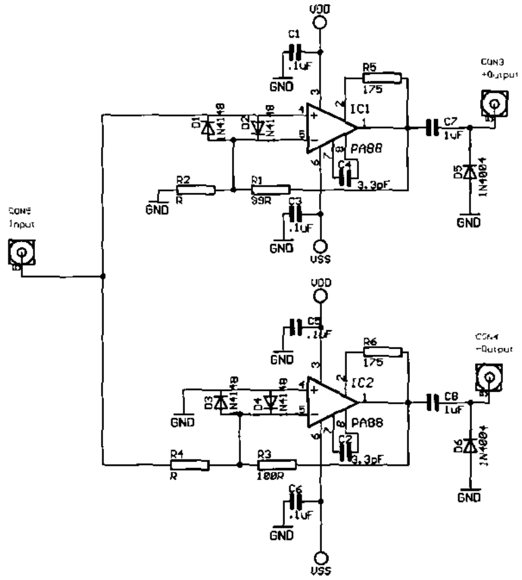

Fig. 4: Schematic diagram of the high-voltage amplifier module – DC restored output

mirrors developed.

The phase and amplitude frequency responses have been also measured. It is important to have identical performances for each pair of the high-voltage stages. The reason for it is that differences in gain imply non-symmetrical angle deflections from the equilibrium position, and phase differences can also induce non-symmetrical positioning, especially for the non-resonant moving mirror. It is also important that the phase difference between the two high-voltage modules must be known and constant, due to the synchronization scheme used in the developed control system. The measurements performed assured that the above constraints have been fulfilled indeed, leading to positioning inaccuracies lying in the sub-pixel range of the image.

7. SUMMARY AND CONCLUSIONS

Apart from the simplicity, high bandwidth and low cost, the control electronics described in this work presents a number of advantages, which mainly are:

- output voltage in the order of 440 V with a bandwidth of 20 kHz.
- stability in driving the required capacitive loads
- low noise level depending on application
- low quiescent current (less than 4 mA)

The described control system, with its high-voltage amplifiers, constitutes an inexpensive solution for electrostatic deflection applications. Compared to the commercial systems, which have high cost, the present one offers satisfactory performance with simplicity in the design and construction.

For applications that require higher bandwidths the APEX PA85 operational amplifier can be selected using the same design as the one already described. The PA85 amplifier has the same specifications as the PA88 one but with a GBW of 100 MHz. Moreover the PA85 is pin-to-pin compatible to the PA88 amplifier and therefore, with the proposed amplifier exchange, the bandwidth of the high-voltage amplifier can be easily extended to the range of 500 kHz.

The present control system can be adapted, with small modifications, and applied to a number of applications where capacitive loads are driven such as electrostatic deflection, piezoelectric positioning, electrostatic transducers driving, electro-optical modulation and high-speed laser-scanning.

8. ACKNOWLEDGMENTS

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9. REFERENCES

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