A flexible micromirror linear array for high-resolution projection displays

Francis Picard
INO

Céline Campillo
INO

Timothy D. Pope
INO

Keith K. Niall
DRDC Toronto

Philipp W. Peppler
Warfighter Training Research Division, AFRL

Carl Larouche
INO

Hubert Jerominek
INO

Defence R&D Canada – Toronto

Technical Report

DRDC Toronto TR 2003-055

March 2003

Author

Keith K. Niall, PhD

Approved by

Lochlan Magee, PhD

Head, Simulation & Modelling for Acquisition, Rehearsal and Training Section

Approved for release by

K. M. Sutton

Chair, Document Review and Library Committee

Author Affiliations:
1 Institut national d’optique, Québec (Québec), Canada
2 Defence R&D Canada – Toronto, Toronto, Ontario, Canada
3 Warfighter Training Research Division, Air Force Research Laboratory, Mesa, Arizona, United States of America

Abstract

Contemporary military flight simulators constrain pilot training, in that they display scene features with insufficient resolution. Air-to-air and air-to-ground targets are not projected in enough contrast and resolution for a pilot in training to perceive them at real world slant ranges. To resolve this training gap, simulator display geometries require the development of ultra-high resolution projectors with greater than 20 megapixel resolution at 60 Hz frame rate. A unique micromirror able to modulate light intensity in an analog fashion and with switching times shorter than 5 µs has been developed to address this need. When combined with a scanner, a microlaser and Schlieren optics, a linear array of these flexible micromirrors can display images exhibiting thousands of lines at a frame rate of 60 Hz. The approach selected for light modulation and the micromirror fabrication process flow is reviewed. Static and dynamic performances of these electrostatic MOEMS are described. Preliminary results following the integration of the described modulator into a prototype projector are reported. Developments toward a fully addressable 2000 x 1 flexible micromirror array are presented. The specifications and design of the CMOS circuit required to control this micromirror array are described. Packaging issues related to these large arrays are discussed.

Résumé

Les simulateurs de vol actuels restreignent l'entraînement des pilotes dans la mesure où la résolution de l'affichage des caractéristiques de scène est insuffisante. Les cibles air-air ou air-sol ne sont pas projetées avec un contraste et une résolution suffisants pour qu'un pilote à l'entraînement puisse les voir en distance oblique réelle. Pour résoudre cette difficulté, la géométrie de l'affichage des simulateurs exige le développement de projecteurs à ultra-haute résolution, offrant une résolution supérieure à 20 mégapixels à une fréquence image de 60 Hz. Un micromiroir unique permettant une modulation analogique de l'intensité de la lumière, avec des temps de commutation inférieurs à 5µs, a été développé pour répondre à ce besoin. L'approche retenue pour la modulation de la lumière et le processus de fabrication du micromiroir sont examinés. Les performances statiques et dynamiques de ces MOEMS électrostatiques sont décrites. Les résultats préliminaires obtenus après intégration du modulateur décrit à un prototype de projecteur sont exposés. Les travaux réalisés en vue du développement d'un réseau de micromiroirs souples 2000 x 1 entièrement adressable sont présentés. Les spécifications et la conception du circuit CMOS nécessaire pour commander ce réseau de micromiroirs sont décrites. Les questions relatives à l'intégration de ces grands réseaux sont étudiées.

This page intentionally left blank.

Executive summary

Ultra-high resolution projectors will improve the visual systems of military flight simulators dramatically. Currently there are changes in aspect angle and aspect rate which fixed-wing flighter pilots can discriminate at long standoff distances, but which cannot be displayed with adequate resolution by the visual systems of contemporary flight simulators. Providing resolution performance without such limitations requires the development of projection systems with unprecedented resolution. A new MEMS spatial light modulator is being developed for use in a high-resolution microlaser projector for flight simulation displays. The active element of this modulator is a linear array of microbridges acting as flexible micromirrors. The mirror array is illuminated with a laser source and produces an image line as output. A complete 2D image is obtained by using a scanning device that sweeps this image column line across the image. 510 x 1 micromirror arrays have been fabricated successfully, using surface micromachining techniques. The refined fabrication process requires four, and can be achieved in three photolithographic steps. The resulting structures are relatively flat in microscopic terms, and exhibit smooth reflective surfaces. Three aspects of the performance of these micromirrors have been characterized: their static response, their dynamic response, and their damage threshold. Static response was characterized by measuring the mirror deflection as a function of the voltage between the micromirror membrane and the underlying electrode. An optical method was used to characterize the dynamic response of the micromirror. The dynamic responses of the micromirrors are presented, separately for those with compressive stress and tensile residual stress. Finally, a doubled YAG laser was focussed on groups of micromirrors to evaluate their damage threshold. The test showed that no visible damage occurs for laser intensities up to 8000 W/cm^2.

A prototype projector has been constructed around the 510 x 1 flexible micromirror arrays that have been fabricated. Characterization of this prototype has begun, and contrast values up to 300 have been measured on the output image. Contrast could be improved by specific changes in the projector's configuration. Developments toward a fully addressable 2000 x 1 flexible micromirror array are ongoing. A high-voltage CMOS process circuit has been designed to allow individual control of all the micromirrors in these extended arrays. The well-established Flip Chip technology has been selected to connect chips to the modulator array. When integrated, these advances are expected to enable a high-performance projector with a resolution of 20 megapixels operating at a frame rate of 60 Hz.

Picard, F.; Campillo, C.; Pope, T.D.; Niall, K.K.; Peppler, P.W.; Larouche, C. & Jerominek, H. 2003. Flexible micromirror linear array for high resolution projection display. DRDC Toroonto TR 2003-055. Defence R&D Canada - Toronto.

Sommaire

Les projecteurs à ultra-haute résolution amélioreront de manière radicale les systèmes visuels des simulateurs de vol militaires. À l'heure actuelle, il y a des modifications de l'angle d'aspect et du rapport d'aspect que les pilotes d'avions de combat à voilure fixe peuvent discriminer à grande distance, mais que les systèmes visuels des simulateurs de vol actuels ne peuvent afficher avec une résolution satisfaisante. Un nouveau modulateur spatial de lumière MEMS , conçu pour un projecteur laser haute résolution d'affichage de simulation de vol, est en cours de développement. L'élément actif de ce modulateur est un réseau linéaire de microponts servant de micromiroirs souples. Ce réseau de micromiroirs est illuminé par une source laser et produit en sortie une ligne-image. On obtient une image 2D complète en utilisant un dispositif de balayage colonne-ligne. On a réussi à fabriquer des réseaux de micromiroirs 510 x 1 à l'aide de techniques de micro-usinage de surface. Ce processus de fabrication raffiné se fait en quatre étapes de lithographie, et celles-ci peuvent être ramenées à trois. Les structures produites sont relativement planes du point de vue microscopique, et présentent des surfaces réfléchissantes lisses. Trois aspects de la performance de ces micromiroirs ont été caractérisés : la réponse statique, la réponse dynamique, et le seuil d'endommagement. Pour la caractérisation de la réponse statique, on a mesuré le fléchissement du miroir en fonction de la tension entre sa membrane et l'électrode sous-jacente. Une méthode optique a été utilisée pour caractériser la réponse dynamique du micromiroir. Les réponses dynamiques des micromiroirs sont présentées, séparément pour les cas où des contraintes de compression et des contraintes résiduelles de traction sont présentes. Enfin, un laser YAG doublé a été focalisé sur un groupe de micromiroirs afin d'évaluer leur seuil d'endommagement. L'essai a montré qu'aucun dommage visible ne se produit pour des intensités de laser allant jusqu'à 8000 W/cm^2.

Un prototype de projecteur a été construit autour des réseaux de micromiroirs souples 510 x 1 qui ont été fabriqués. La caractérisation de ce prototype a commencé, et des valeurs de contraste allant jusqu'à 300 ont été mesurées sur l'image de sortie. On pourrait améliorer le contraste en apportant certaines modifications à la configuration du projecteur. Des travaux en vue du développement d'un réseau de micromiroirs souples 2000 x 1 sont en cours. On a conçu un circuit de traitement CMOS haute tension afin de permettre la commande individuelle de tous les micromiroirs de ces réseaux étendus. La technologie bien établie de la puce à protubérances a été retenue comme moyen de raccordement des puces au réseau modulateur. Une fois intégrés, ces progrès technologiques devraient permettre d'obtenir un projecteur à haute performance offrant une résolution de 20 mégapixels à une fréquence image de 60 Hz.

Picard, F.; Campillo, C.; Pope, T.D.; Niall, K.K.; Peppler, P.W.; Larouche, C. & Jerominek, H. 2003. Flexible micromirror linear array for high resolution projection display. DRDC Toroonto TR 2003-055. Defence R&D Canada - Toronto.

Table of contents

List of figures

List of tables

Acknowledgments

We thank Brian Welch, Andrew Fernie of CAE Inc. and Martin Shenker of Martin Shenker Optical Design Inc. for their contribution and support. The damage threshold results are due to Jérôme Reecht and Eric Garon of INO. Sophie Bernier, Michel Doucet, François Duchesne, Marc Girard, Jérôme Godbout, Michel Jacob, Frédéric Lévesque, Maxime Savard and Simon Thibault of Institut national d'optique contributed to the projector prototype development. The CMOS control circuit was designed by Zuxin Qin, Martin Renaud and Frédéric Drapeau of Goal Electronics. This work was supported by Defence Research & Development Canada under Public Works Government Services of Canada contracts W7711-007650 and W7711-017753, by the Air Force Research Laboratory and by a contract granted by L3 Communications. Some of this material was presented at Photonics West (San Jose, CA: Jan. 28, 2003) in a session on *MOEMS display and engineering systems*, sponsored by SPIE. SPIE is the International Society for Optical Engineering.

Introduction

Ultra-high resolution projectors will improve the visual systems of military flight simulators dramatically. Currently, there are changes in aspect angle and aspect rate which fixed-wing fighter pilots can discriminate at long standoff distances, but which cannot be displayed with adequate resolution by the visual systems of contemporary flight simulators. For example, air-to-air and air-to-ground targets are not projected with enough contrast and resolution for a pilot in training to perceive them at real world slant ranges. Currently, the approach to handling these situations is to add small field of view, high-resolution projectors for air targets. There are inherent limitations in this approach in terms of the number of targets that can be represented at high resolution as well as in the contrast of the target relative to the background image. Providing the required resolution performance without these limitations requires new projection systems with unprecedented resolution. In practice, this implies the development of ultra-high resolution projectors with greater than 20 megapixel resolution operating at 60 Hz frame rate. This need is being addressed by INO and its partners working toward the development of a new MEMS spatial light modulator.

The active element of this modulator is a linear array of microbridges acting as flexible micromirrors. This mirror array is illuminated with a laser source and produces an image line at the output of an optical relay. Each pixel of the image line corresponds to one flexible micromirror which modulates the pixel intensity in an analog fashion with switching times in the range of 5 μs. The light modulating scheme (see Figure 1) requires Schlieren optics[1] which translate the micromirror curvature into a corresponding light intensity at the Schlieren relay output. The micromirror curvature (and pixel intensity) is controlled using electrostatic actuation. A complete 2-D image is obtained by using a scanning mechanism that displays

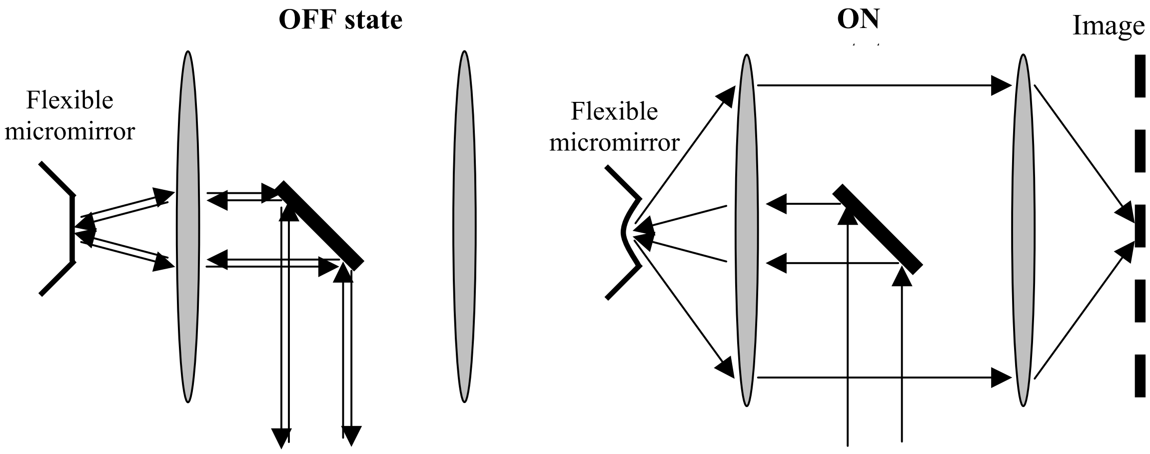


Figure 1. *Light modulation approach using flexible micromirrors*

each image line sequentially. In addition, projection optics are used to tailor the final image.

In the following sections, the process flow used to fabricate the flexible micromirror arrays is reviewed briefly. The performances of these electrostatic MOEMS including the static and dynamic responses are described. Preliminary results following the integration of the described modulator into a prototype projector are reported. Developments toward a fully addressable 2000 x 1 flexible micromirror array are presented. The specifications and design of the CMOS circuit required to control this micromirror array are described. Finally, packaging issues related to these large arrays are discussed.

Flexible micromirror array fabrication

510 x 1 micromirror arrays have been fabricated using surface micromachining techniques[2]. The micromirror design has been based on general rules that emerged from simulations[3] or from the developed fabrication process. However, material properties and residual stress characteristics were not perfectly known at the time of simulation. Therefore to incorporate possible differences between the simulations and the actual structure performance, micromirrors exhibiting dimensions varying slightly about the dimensions selected from the simulations have been produced. Nevertheless each fabricated array consisted of only one mirror design. Table 1 summarizes the parameters used for the micromembrane fabrication. The parameter definition is given in Figure 2.

***Table 1**. Fabrication parameters*

MIRROR PARAMETER	DIMENSION (μm)
Mirror length	20, 25 and 30
Mirror width	10 and 25
Gap size	3.5 and 4.5
Distance between mirrors	2, 3, and 5
Fabrication parameters	

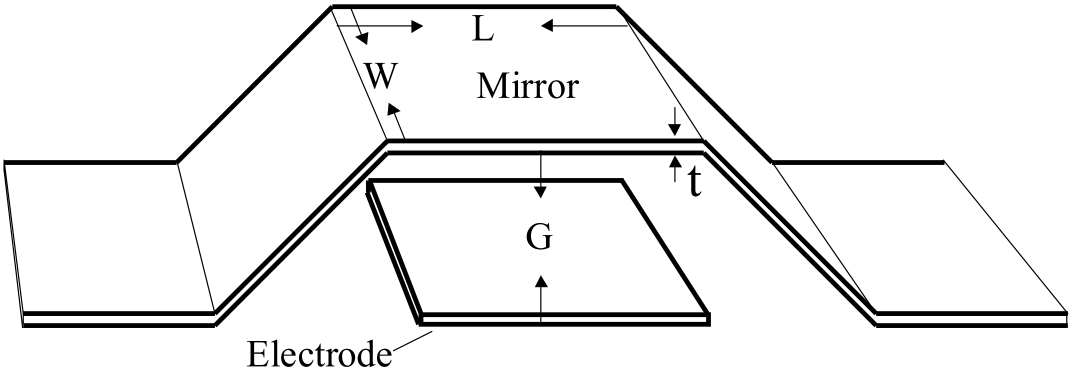
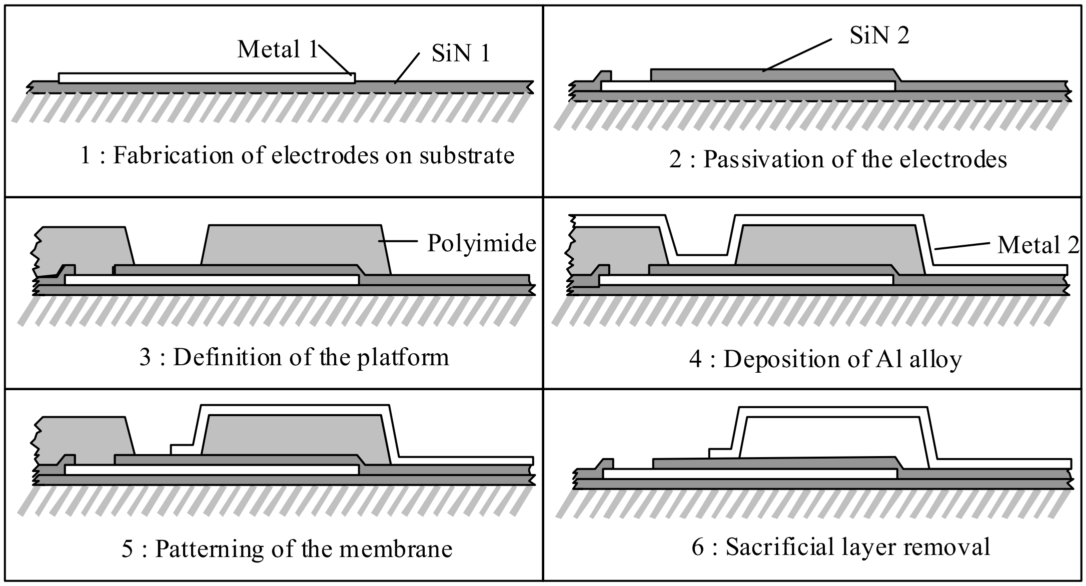


***Figure 2.** Flexible micromirror structure (W: mirror width, L: mirror length, G: mirror/substrate gap size, t: membrane thickness)*

All possible combinations of membrane dimensions for a given gap size were fabricated simultaneously on one silicon wafer. The gap size was the same for all structures on a given wafer but was varied from wafer to wafer.

Fabrication process

The developed fabrication process can use 4 or even just 3 photolithographic steps. The starting material is a silicon wafer on which a silicon nitride (SiN) film has been deposited for electrical isolation. A first metallic layer is deposited and patterned to produce the bottom electrode (see Figure 3).



1 : Fabrication of electrodes on substrate

2 : Passivation of the electrodes

3 : Definition of the platform

4 : Deposition of Al alloy

5 : Patterning of the membrane

6 : Sacrificial layer removal

Figure 3. *Flexible micromirror fabrication process flow*

This metallic layer material can be aluminum or gold. The electrode is then passivated using a SiN layer, and windows are opened in the SiN to provide bonding pads. This passivation - step is optional, i.e., it is not absolutely required to achieve functional micromembranes. The membrane fabrication starts with the definition of the platform in a relatively thick sacrificial polyimide layer. The next step comprises the deposition and patterning of an aluminum alloy thin film. The aluminum alloy layer is deposited using Physical Vapor Deposition (PVD). This aluminum alloy film is patterned using a photoresist mask and wet etching. This produces the micromembrane itself. Finally, the sacrificial polyimide layer is isotropically etched using a plasma asher which generates a gap between the membrane and the substrate.

Fabrication results

The process described above has been used to fabricate the required micromirror arrays. The obtained structures exhibit a smooth reflecting surface and are relatively flat (see Figures 4, 5 and 6). At the mirror level, the structures show typically a membrane width which is narrower than the nominal width. Moreover, the legs supporting the mirror are found to be slightly wider at the substrate level than at the mirror level. These small defects come from the fact that the photoresist used to mask the Al alloy for the etching step does not cover the wafer topography conformally. This results in a photoresist mask which does not match perfectly the photomask pattern. This difference combined with some undercut occuring during the Al alloy wet etching caused the observed geometrical imperfections. The texture on the leg surface is just the reproduction of the surface relief of the sacrificial polyimide which supported the leg before being finally removed. This texture is typical of polyimide wall obtained by dry etching. Finally, small defects can be observed at the membrane edges (see Figure 5). The characterization performed on the membranes indicates that these defects do not distort significantly the mirror profile.

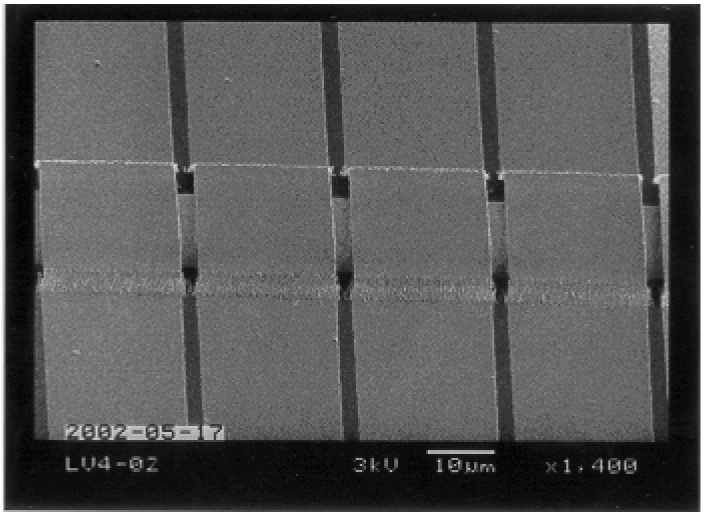


Figure 4. *Flexible micromirrors (nominal dimensions are L: 30 µm, W: 25 µm, t: 0.15 µm, G: 4.7 µm, spacing between mirrors: 2 µm)*

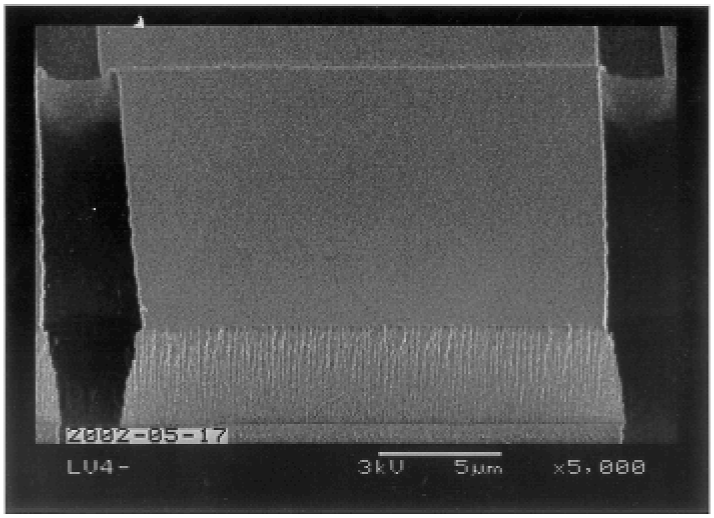


Figure 5. *Flexible micromirrors (nominal dimensions are L: 20 µm, W: 25 µm, t: 0.15 µm, G: 4.7 µm, spacing between mirrors: 3 µm)*

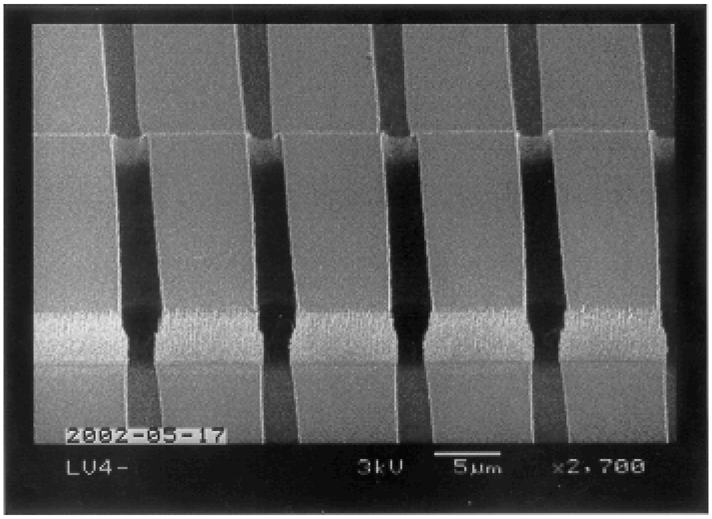


Figure 6. *Flexible micromirrors (nominal dimensions are L: 25 µm, W: 10 µm, t: 0.15 µm, G: 4.7 µm, spacing between mirrors: 2 µm)*

Flexible micromirror characterization

Three main aspects of the micromirror performance have been characterized: the static response, the dynamic response and the damage threshold. The static response was characterized by measuring the mirror deflection as a function of the voltage applied between the membrane and the underlying electrode. The membrane deflection was measured using a microscope equipped with a 10x Mireau interference objective with a numerical aperture of 0.25. The wavelength of the light illuminating the mirror under test was 548 nm. This produced an interference pattern in which two consecutive dark or light fringes are generated by mirror regions separated by a vertical distance of 0.27 µm. The voltage was applied gradually across the MEMS light valve and the corresponding mirror deflection was measured by recording the number of fringes between the mirror center and the mirror edges.

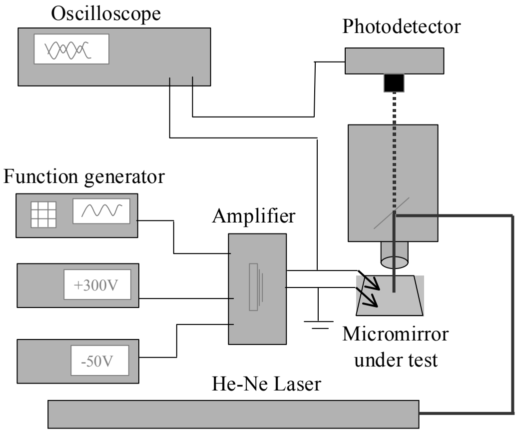


Figure 7. *Set-up for the micromirror dynamic response characterization*

An optical method (see Figure 7) has been used to characterize the micromirror dynamic response. The micromirror under test is illuminated with a laser beam and the reflected diffraction pattern is observed through a microscope. When the micromirror curvature is changed, the observed diffraction pattern is modified and some regions of the intensity profile show an important intensity variation. A photodetector is positioned at the microscope output to measure the intensity corresponding to such high contrast regions. The photodetector response time was short enough (about 10 ns) to provide intensity measurements resolved in time. The voltage waveform applied to the micromembrane as well as the photodetector signal are recorded simultaneously using an oscilloscope which allows to evaluate the micromirror dynamic performance.

Finally, a doubled YAG laser source was focussed on groups of micromirrors to evaluate damage threshold. The micromembranes were illuminated with a fixed laser intensity. After each illumination session of a few minutes, the micromirrors were examined with a microscope to verify if visible damage had occurred. Laser intensity was then increased and the procedure repeated until the mirrors were damaged.

Flexible micromirror static response

The micromirror curvature for an applied voltage of 0 V depends on the residual stress in the membrane. A compressive residual stress causes a convex initial curvature while a tensile residual stress results in a downward membrane deflection. The residual stress can be modified, to some extent, by varying the aluminum alloy deposition parameters. For example, it is well known that the stress of thin metallic films deposited using PVD can be changed by varying the gas pressure in the deposition system. Using such deposition parameter variation, it has been possible to fabricate micromirrors exhibiting various residual stresses and initial curvatures.

Examples of static response for micromirrors (see Figures 8 and 9) exhibiting residual compressive and tensile stresses are presented. In the case of the membrane with a compressive stress, it is necessary to apply a voltage to bring back the mirror curvature to a minimum value corresponding to a deflection of 0 µm. For the presented example (see Figure 8), this offset voltage is about 136 V and a deflection of 0.8 µm corresponding to a f-number of 2 is reached with 233 V. The membrane with a tensile residual stress (see Figure 9) exhibits a downward deflection at 0 V. In the example shown, this deflection is 0.25 µm which represents a significant part of the required analog deflection range. A deflection of 0.8 µm corresponding to an *f*-number of 2 is achieved with 158 V.

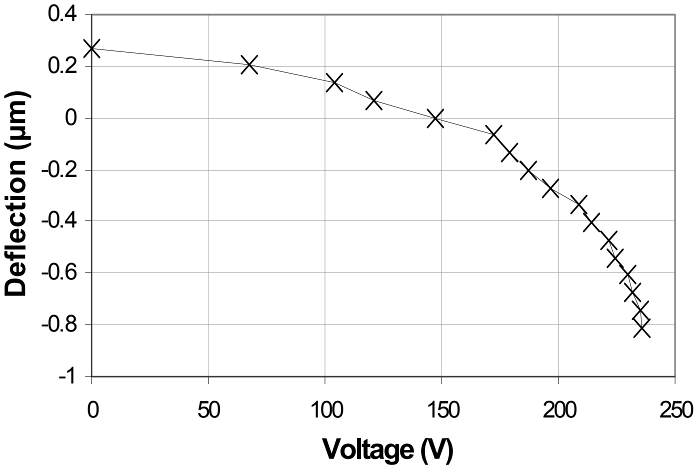


Figure 8. *Static response of a micromirror with compressive residual stress (nominal micromirror dimensions are L: 25 µm, W: 25 µm, t: 0.15 µm, G: 4.7 µm)*

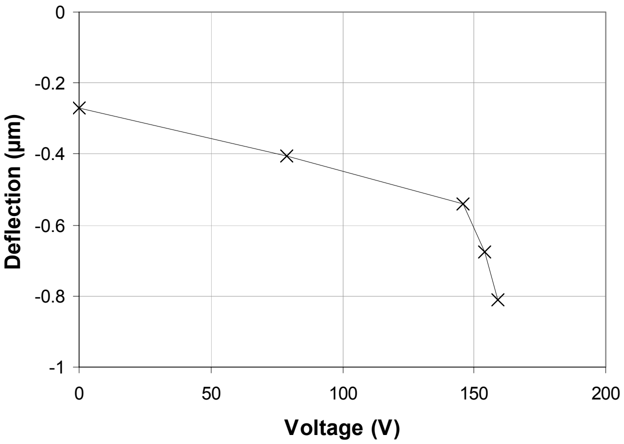


Figure 9. *Static response of a micromirror with tensile residual stress (nominal micromirror dimensions are L: 25 µm, W: 25 µm, t: 0.15 µm, G: 4.7 µm)*

From the presented examples, it is clear that a membrane with a tensile residual stress has the advantage of reaching the maximum required deflection at a lower voltage than a membrane with a compressive residual stress. Moreover, for such a membrane, the available deflection range is swept with a larger voltage span which somewhat reduces the voltage resolution requirement. However, membranes with a residual tensile stress also present major drawbacks. Firstly, the available analog deflection range is reduced. Secondly, the deflection state corresponding to the projector black level cannot be adjusted with a voltage offset. This can potentially have an important impact on the achievable projector contrast. Although it typically requires a higher activation voltage and a better voltage resolution, a membrane with a compressive residual stress is a better trade-off for projection applications as the achievable contrast is a key characteristic for such applications.

Flexible micromirror dynamic response

The dynamic responses for micromirrors exhibiting either a compressive or a tensile residual stress are presented. In the discussed examples, the membranes are moved from the minimum to the maximum deflection and then back to the minimum deflection. The voltage waveforms used to control the membranes are also shown. In the compressive residual stress case (see Figure 10), the activation voltage waveform is added to the voltage offset which is required to achieve a membrane deflection of 0 µm. In the considered example the applied voltage waveform transient time is a little less than 2 µs. In this case when the membrane is activated, it stabilizes in about 10 µs. With the voltage waveform used, the stabilization time is even longer when the micromembrane is deactivated. These relatively long settling times combined with important membrane oscillations about the equilibrium position indicate that the applied voltage waveform is not perfectly adapted for the activation of the tested micromirror. The voltage variation rate is too high and should be reduced by increasing the transient time to 3 or 4 µs.

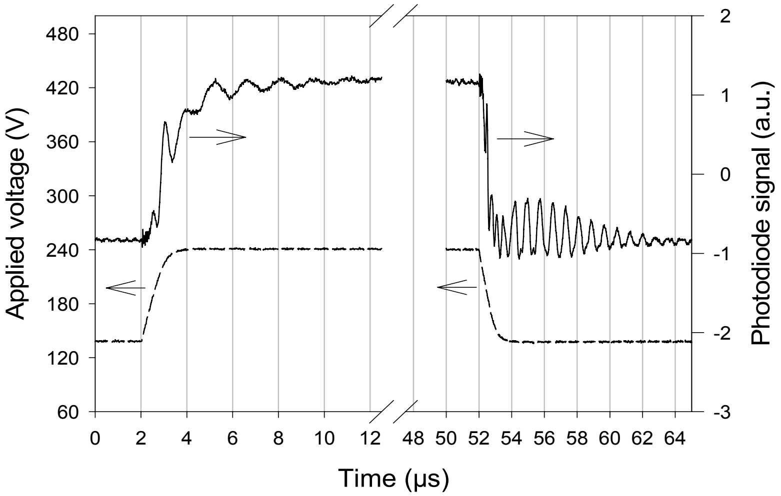


Figure 10. *Dynamic response of a micromirror with compressive residual stress (nominal micromirror dimensions are L: 25 µm, W: 25 µm, t: 0.15 µm, G: 4.7 µm)*

In the case of a membrane with a tensile residual stress (see Figure 11), no voltage offset is applied to the membrane under test. In the considered example, a waveform with a transient time of 3 µs has been used to control the micromirror. When activated, the micromembrane stabilizes in 4 µs and the settling time required to bring it back to its minimum deflection position is less than 5 µs.

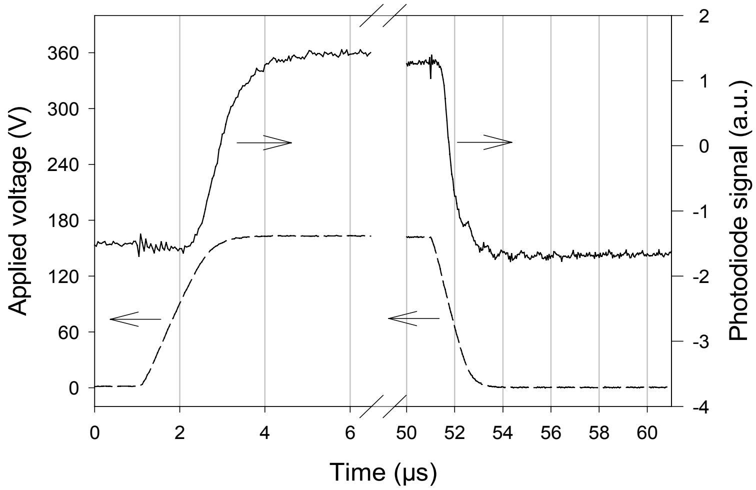


Figure 11. *Dynamic response of a micromirror with tensile residual stress (nominal micromirror dimensions are L: 25 µm, W: 25 µm, t: 0.15 µm, G: 4.7 µm)*

Flexible micromirror damage threshold

The test performed to determine the membrane damage threshold demonstrated that no visible damage is produced on the micromirror for incident laser intensities up to 8000 W/cm^2. However, permanent membrane deformations are observed for a laser intensity of 16000 W/cm^2. These experimental results are in good agreement with the simulations[3] which estimated the damage threshold at 8850 W/cm^2. These simulations also predicted that thermally generated stresses exceeding the material yield would cause the device failure.

Projector prototype

A projector prototype based on the fabricated 510 x 1 flexible micromirror arrays has been demonstrated (see Figure 12). Due to packaging constraints and to the fact that the control electronics had to be completely external to the package for this demonstration, groups of 5 adjacent micromirrors were connected in parallel. This resulted in a linear array of 102 individually addressable light modulators. The electronics designed to control these modulators is based on state-of-the-art high voltage amplifiers and digital-to-analog converters (DAC's). A Field Programmable Gate Array (FPGA) has been used to transfer the image data to the 102 control channels. Table 2 lists the main characteristics of the fabricated control electronics.

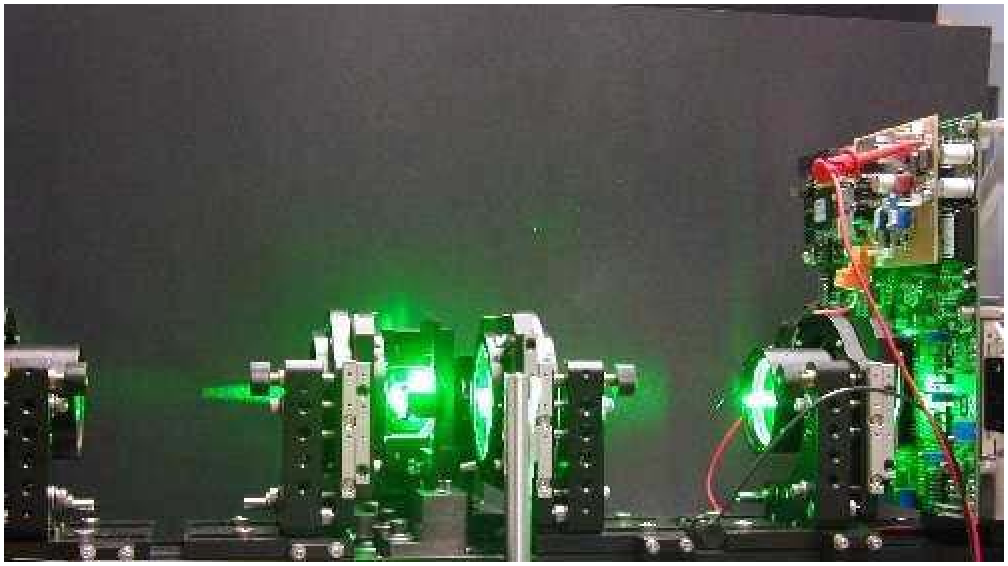


Figure 12. *Part of the projector prototype. The optical relay and the control electronics are visible on the picture*

The offset voltage is used to adjust the flexible micromirror sag to a minimum which corresponds to the projector black level. For the developed prototype, the offset is adjusted globally for all micromirrors. The grey level number scales with the required activation voltage range and is maximum (512) for an activation voltage range of 200 V. This feature comes from the circuit design and the selected DAC's. For the demonstrated projection system, the maximum number of lines which can be displayed is determined by the amplifier slew rate (an not by the micromirror response time). Nominally, the maximum line number is fixed by the frame rate and by the time required by the high voltage amplifier to sweep the entire maximum activation range.

Table 2. *Characteristics of the projector prototype control electronics*

Offset voltage range	-300 to +300 V
Activation voltage range	-100 to +100 V
Activation voltage data	9 bits
Activation voltage data resolution	0.4 V
Number of grey levels	512
Number of image lines	494
Frame rate	60 Hz

Characteristics of the projector prototype control electronics

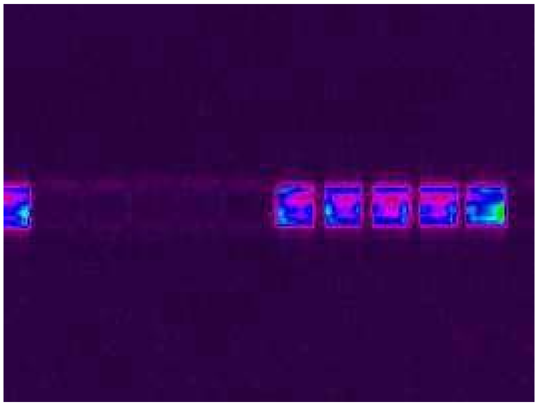


Figure 13. *Image of ON and OFF micromirrors at the optical relay output*

The projector prototype included an illumination system based on a doubled YAG laser. A line of light produced by this system illuminates the micromirror array. The light reflected by the micromirror array is collected by an optical relay which produces an image of the modulator array. A stop is positioned in the Fourier plan of the relay to block part of the collected light. The intensity of a given modulator image at the optical relay output depends on the amount of light coming from this modulator and not blocked by the stop (see Figure 13). The amount of light avoiding the stop is controlled by the curvature of the micromirrors part of the modulator. A galvanometer and projection optics located at the optical relay output produce the final 2-D image.

Characterization of this prototype has begun. Contrast values up to 300 have been measured. These are only preliminary results and it is believed that the projector contrast could be improved quite significantly by optimizing the projector configuration. Activities in this direction are ongoing. The contrast is defined here as the ratio between the intensity for a fully *on* pixel and the intensity for a fully *off* pixel, the intensity being measured at the optical relay output. For these measurements, a charge coupled device (CCD) camera combined with a commercial beam analyser were used. A 10X objective magnified the image at the relay output prior to recording by the CCD camera.

Figure 14 shows the intensity of a group of pixels recorded as a function of time at the relay output when the modulator state is switched between two particular states. The intensity was measured with a high speed photodetector. The speed at which the pixel intensity can be modulated is in good agreement with the response time measurements performed with the set-up of Figure 7. The 200 kHz ripple superimposed on the main intensity variation was produced by waveform noise corresponding to the high voltage signal generated by the voltage amplifier. This noise contributed substantially to the reduction in measured contrast values, and activities are ongoing to eliminate it. Still it is interesting to note that the micromirror positions varied with this noise, which response indicates a sensitive micromirror response time on the order of a few microseconds.

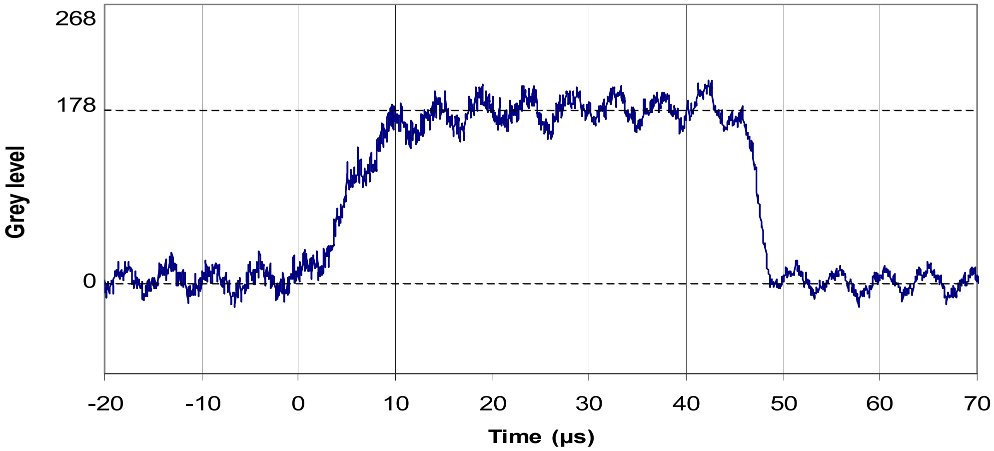


Figure 14. *Intensity of a group of pixels as a function of time. Intensity is expressed as grey levels. In this example, 268 grey levels were available for display.*

Development toward a 2000 x 1 micromirror array

Developments toward a fully addressable 2000 x 1 flexible micromirror array are ongoing. A high voltage CMOS circuit has been designed to allow individual control of each micromirror in the array. The main specifications of the developed chip are listed in Table 3. Figure 15 presents a conceptual block diagram of the circuit.

Table 3. *Control circuit specifications*

Individual offset range	47 V
Individual offset resolution	0.09 V
Individual offset data	9 bits
Activation voltage range	200 V
Activation voltage resolution	0.1 V
Image data	11 bits
Data refresh rate	300 kHz
Refresh mode	Simultaneous
Time constant of the exponential activation waveform	0.17 μs, 0.26 μs, 0.44 μs or 0.6 μs (selectable)
Channel number	100
Clock frequency for data	30 MHz

Control circuit specifications

The offset voltage is used to set the black level which corresponds to a flat micromirror (see section 3.1). A coarse offset voltage can be applied to the common electrode located underneath all the micromirrors using an external source. This coarse offset value is the same for all micromirrors in the array. A fine offset value can be selected for each individual mirror. This fine offset, called individual offset in Table 3, is applied directly on the micromirror. In this way, the total offset value for each mirror may be adjusted to correct for any nonuniformities. The individual offset values result from a calibration procedure and are loaded in the circuit only once before operating the projector. The activation voltage values corresponding to the required grey levels are added to the individual offset values and applied on each micromirror. The high activation voltage resolution allows the implementation of data processing algorithm to correct for the eye response and for any mirror to mirror nonuniformity. The data set activating the modulator array can be refreshed simultaneously for all micromirrors up to 300000 times per second. For a projector operating at a frame rate of 60 Hz, this would allow display of 5000 image lines. The selectable time constant, which corresponds roughly to one-fifth the voltage settling time, gives some flexibility in adjusting the activation waveform shape to minimize the micromirror overshoot and settling time.

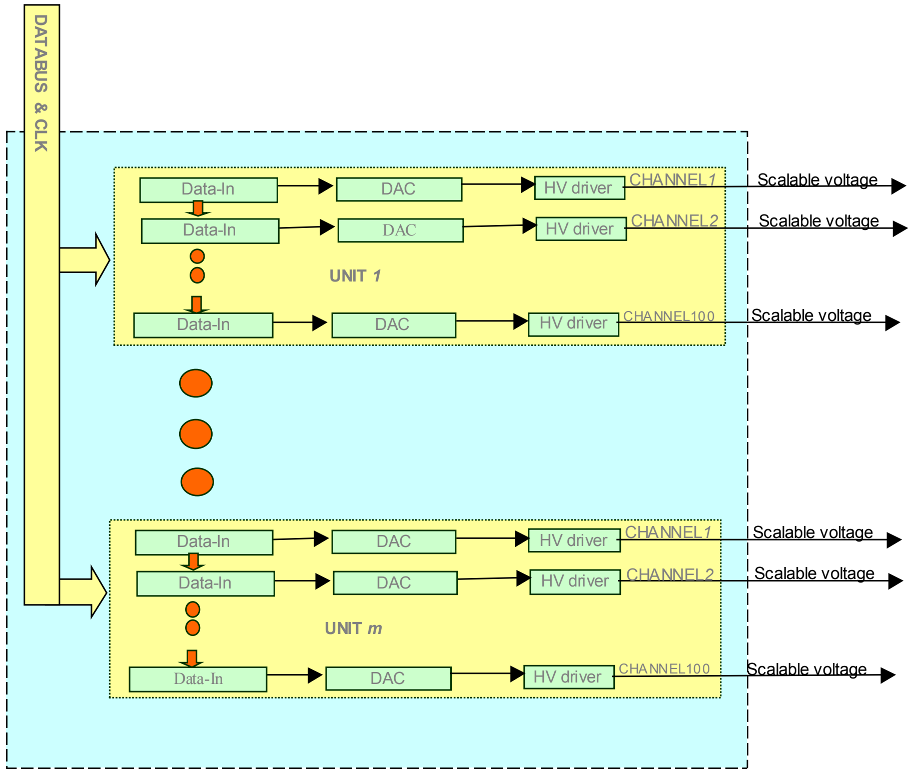


Figure 15. *Block diagram of the control circuit. Each unit corresponds to one integrated circuit chip.*

The high-voltage CMOS process used to fabricate the control circuit has relatively large critical dimensions, typically of the order of 3 to 4 µm. A chip comprising the electronics to control the 2000 micromirror part of the array would have been very large, resulting in fabrication yield problems. An alternative solution is to limit the number of control channels per chip and to use many chips to control the entire array. In the current design, each control chip comprises 100 channels and 20 chips are required to control the modulator array. The image data are fed to each chip in a serial manner through an 11-bit data bus operating at 30 MHz.

The resulting chip assembly is relatively extensive. The well-established Flip Chip technology has been selected to connect the chips to the modulator array. This will allow the implementation of a quasi 3-D interconnection scheme preserving some assembly compactness. Currently, the layout for the designed control circuit has been completed and the chip fabrication is underway. Moreover, development activities are ongoing to reduce the micromirror response time and activation voltage by optimizing its structure. The resulting advances in reducing the activation voltage could have a significant impact on the selection of a CMOS fabrication process for a second generation control circuit. This would result in an immediate reduction of the fabricated chip size and of the chip/array assembly complexity.

Conclusion

Further developments in ultra-high resolution projectors are needed to improve military flight simulation. A new type of MEMS light modulator has been developed with the objective of addressing this need. This light modulator is based on micromembranes acting as flexible micromirrors. Characterization of these MEMS micromirrors shows that they are appropriate for high-resolution projection display applications, given their very short settling times. A projector prototype based on a linear array of these flexible micromirrors has been demonstrated. Preliminary characterization shows contrasts up to 300 and high modulation speeds shown by dynamic characterization of the micromirrors. Contrast could be improved significantly by optimizing the projector configuration. Developments toward a fully addressable 2000 x 1 flexible micromirror array are ongoing. An electronic circuit for the control of this array has been designed already. The fabrication of this circuit follows the design of a high voltage CMOS process. The corresponding circuit layout has been completed and the control chips are under fabrication. Globally, technological advances have already been made or are ongoing on several fronts in the development of an ultra-high resolution MEMS-based projector. When combined into a system, these advances are expected to result in a high performance projector with a resolution of 20 megapixels operating at a frame rate of 60 Hz.

References

1. J. A. Van Raalte, "A new Schlieren light valve for television projection", *Applied Optics*, **20**, pp. 2225-2230, 1970.

2. M. Madou, *Fundamentals of microfabrication*, CRC Press, Boca Raton, FL, 1997.

3. F. Picard, C. Campillo, K. K. Niall, C. Larouche & H. Jerominek (2002). *MEMS-based light valves for ultra-high resolution projection displays*, DRDC Technical Report 2002-141, 29 pp.

List of symbols/abbreviations/acronyms/initialisms

AFRL	Air Force Research Laboratory
CMOS	Complementary Metal-Oxide-Silicon
DND	Department of National Defence
DRDC	Defence Research & Development Canada
INO	Institut national d’optique
MEMS	Microelectromechanical System
MOEMS	MicroOptoElectroMechanical System

DOCUMENT CONTROL DATA SHEET

1a. PERFORMING AGENCY DRDC Toronto ; INO: 2740, rue Einstein, Sainte-Foy, QC	2. SECURITY CLASSIFICATION UNCLASSIFIED Unlimited distribution -
1b. PUBLISHING AGENCY DRDC Toronto	

3. TITLE

(U) A flexible micromirror linear array for high-resolution projection displays

4. AUTHORS

Francis Picard; Céline Campillo; Timothy D. Pope; Keith K. Niall; Philipp W. Peppler; Carl Larouche; Hubert Jerominek

5. DATE OF PUBLICATION March 19 , 2003	6. NO. OF PAGES 29

7. DESCRIPTIVE NOTES

8. SPONSORING/MONITORING/CONTRACTING/TASKING AGENCY
Sponsoring Agency:
Monitoring Agency:
Contracting Agency :
Tasking Agency:

9. ORIGINATORS DOCUMENT NO. Technical Report TR 2003-055	10. CONTRACT GRANT AND/OR PROJECT NO. ADMT-TD , Thrust 6b	11. OTHER DOCUMENT NOS.

12. DOCUMENT RELEASABILITY

Unlimited distribution

13. DOCUMENT ANNOUNCEMENT

Unlimited announcement

14. ABSTRACT

(U) Contemporary military flight simulators constrain pilot training, in that they display scene features with insufficient resolution. Air-to-air and air-to-ground targets are not projected in enough contrast and resolution for a pilot in training to perceive them at real world slant ranges. To resolve this training gap, simulator display geometries require the development of ultra-high resolution projectors with greater than 20 megapixel resolution at 60 Hz frame rate. A unique micromirror able to modulate light intensity in an analog fashion and with switching times shorter than 5 µs has been developed to address this need. When combined with a scanner, a microlaser and Schlieren optics, a linear array of these flexible micromirrors can display images exhibiting thousands of lines at a frame rate of 60 Hz. The approach selected for light modulation and the micromirror fabrication process flow is reviewed. Static and dynamic performances of these electrostatic MOEMS are described. Preliminary results following the integration of the described modulator into a prototype projector are reported. Developments toward a fully addressable 2000 x 1 flexible micromirror array are presented. The specifications and design of the CMOS circuit required to control this micromirror array are described. Packaging issues related to these large arrays are discussed.

(U) Les simulateurs de vol actuels restreignent l'entraînement des pilotes dans la mesure où la résolution de l'affichage des caractéristiques de scène est insuffisante. Les cibles air-air ou air-sol ne sont pas projetées avec un contraste et une résolution suffisants pour qu'un pilote à l'entraînement puisse les voir en distance oblique réelle. Pour résoudre cette difficulté, la géométrie de l'affichage des simulateurs exige le développement de projecteurs à ultra?haute résolution, offrant une résolution supérieure à 20 mégapixels à une fréquence image de 60 Hz. Un micromiroir unique permettant une modulation analogique de l'intensité de la lumière, avec des temps de commutation inférieurs à 5µs, a été développé pour répondre à ce besoin. L'approche retenue pour la modulation de la lumière et le processus de fabrication du micromiroir sont examinés. Les performances statiques et dynamiques de ces MOEMS électrostatiques sont décrites. Les résultats préliminaires obtenus après intégration du modulateur décrit à un prototype de projecteur sont exposés. Les travaux réalisés en vue du développement d'un réseau de micromiroirs souples 2000 x 1 entièrement adressable sont présentés. Les spécifications et la conception du circuit CMOS nécessaire pour commander ce réseau de micromiroirs sont décrites. Les questions relatives à l'intégration de ces grands réseaux sont étudiées.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) MEMS; projection displays; semiconductor devices; flight simulation