Multiple MEMS mirrors synchronization techniques, modeling and applications

Guy Amor, Elan Roth, Dadi Sharon, Nir Gorelik, Sivan Kinstlich, Sivan Nagola
ST Microelectronics LTD
AMS MMD division
guy.amor@st.com
http://www.st.com

Abstract

MEMS Mirrors provide a great way to spatially scan light and is being used for a wide range of applications such as raster scanning RGB light for Display Engines or scanning infra-red light for depth cameras (3D sensing) by using structured light or Time of Flight (TOF) techniques. Yet, in some cases it is required to deploy multiple MEMS Mirrors that ought to work in tandem, such as implementing a Display Engine for a binocular HMD (Head Mount Display, AR/VR/MR) generating two images, one per eye. In such a case, it is necessary to synchronize the movement of the MEMS mirrors, so that the images that are presented to the viewer, would create a homogenous and consistent image. Another possible use case is to increase the Field Of View, such as for an Automotive Lidar application, so that each Scanning Engine with a mounted MEMS Mirror would cover a subset of the scanned scene, yet collectively would provide an increased scanned FOV. The scanning of each segment by one Scanning Engine would be done sequentially and in a synchronized manner with the other Scanning Engines. This paper will present a viable synchronization mechanism for two main types of MEMS Mirror: Resonant Mirror and Quasi Static Mirrors. The paper will discuss the challenges and considerations of the System Clock, Master / Slave modes, overcoming jitter and noise and modeling by simulations the expected results. Additionally, the paper will present the actual results of such system implementation as a result of this work.

1. Introduction

1.1 MEMs mirrors for light scanning and projection applications

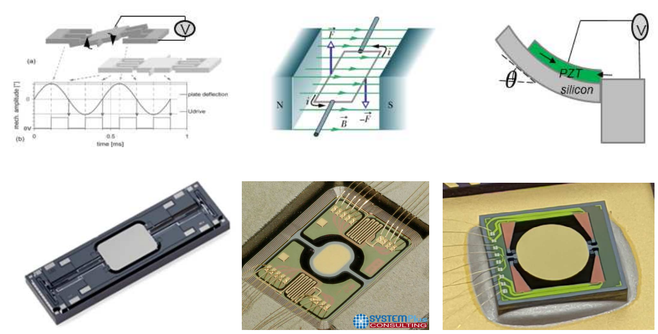
MEMs mirrors are being used in emerging technologies for visible projection and nonvisible IR scanning in a variety of applications. MEMs mirrors for scanning applications provides small footprint, low power and low cost solution. Popular applications leveraging MEMs scanning technology are AR/VR/XR head mounted displays (HMD), all day wearable smart glasses and pico-projectors for visible projection and structured light or ToF 3D depth sensing applications like 3D cameras and LiDAR for consumer, industrial and automotive. A good example of a combination of the visible and nonvisible scanning using LBS (laser beam scanner) in a single product is the Accuvein AV500 vain visualization product which uses ST's MEMs for nonvisible IR scanning to detect the vein location and then projects a visible red or green laser to outline the veins map directly on the skin in order to assist medical personnel to access or avoid veins. Other commercially available products that use ST's MEMs are intel's 1'st and 2'nd generation real-sense 3D depth camera and LiDAR a well as North's (recently acquired by google) all day wearable smart glasses. Every day innovative companies find new creative ways to utilize MEMs mirror scanning technology for creating new products and applications. ST's newly formed LaSAR alliance is an ecosystem of technology developers, suppliers and manufacturers collaborating to accelerate the development of AR smart-glass solutions and shorten the time to market.

(a) (b) (c) (d)

Figure 1: (a) Accuvein av500 vein visualization[1]; (b) north's smart glasses[2]; Intel's 2'nd generation L515 LiDAR camera [3]; ST's LaSAR alliance of technology developers, supplier and manufacturers aco-system

1.2 MEMs mirror background

MEMs mirror or micro-mirror is an opto-mechanical beam steering device that together with laser light source and some optics comprises a micro-scanner optical engine. The incident light wave, usually a laser beam, is deflected by altering the mirror tilt angle. An optical engine for display or any 2D scanning application may use a single bi-axial mirror with two rotational axis or two mono-axial mirrors. A micro mirror is comprised of three main components: (1) reflecting surface, (2) actuation, and (3) sensing. The reflecting surface area and shape is designed according to the optical needs. The design strategy is to make this surface flat – in terms of surface roughness and radius of curvature, rigid – for less dynamic deformation while the mirror is moving and with reflective coating in the desired wavelength range (Typically Aluminum coating for the visible wavelength and gold for IR). The actuation method can be either electrostatic, electromagnetic or piezoelectric. The actuator design takes into account the micro mirror operation mode - resonant or quasi-static, the actuation efficiency and the desired mechanical opening trading off the actuator size and power consumption. The sensing principle depends on the process and the available technology and can be capacitive – for electrostatic micro mirrors and piezoresistive - for electromagnetic and piezoelectric micro mirrors and is some rare cases also optic, acoustic or other means for sensing the mirror position. The sensor stability over changing environmental conditions and sensitivity will determine the sensing capability for closing control loop and for synchronizing the light source to the mirror position.

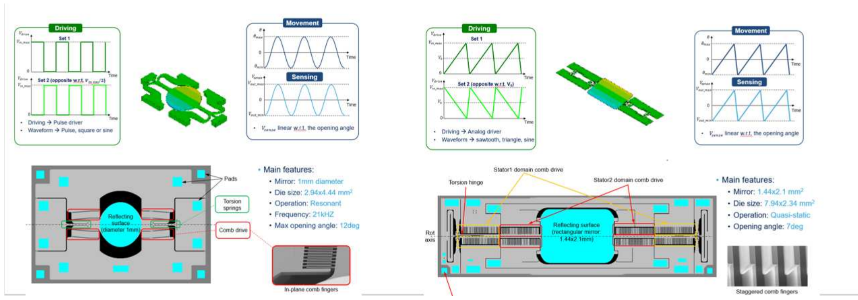


(a) (b) (c)

Figure 2: (a) MEMs mirror components. (b) Electrostatic comb drive mono-axial Quasi-static mirror ,(c) electromagnetic single coil bi-axial one resonance one quasi-static mirror; (d) piezoelectric resonant 2khz mono axial gold coated mirror for LiDAR applications

1.3 Resonant vs. Quasi-statis actuation mode

MEMs mirror, is a resonant structure that can be actuated in resonant mode or in a quasi-static mode. In both cases the mirror structure is the same with different design targets. In resonant mode operation, the driving frequency is near the natural frequency of the mirror while in quasi-static mode, the mirror is actuated in low frequency well below its natural resonance frequency. Generally speaking, resonant mirrors are simpler to manufacture, actuate and control. Resonance mirrors can be driven using a simple digital control signal and a relatively simple pulse driver. Near the resonance frequency, the gain of the mirror is maximal, thus less force is required from the actuator which result in a smaller actuator. MEMs mirror operated in resonant mode, are stable and highly repeatable and requires a relatively simple control scheme and in some cases can also be operated in open loop. Resonant operation mode results in a sinusoidal or near sinusoidal movement of the mirror regardless of drive signal which can be a pulse, square wave or harmonic function. Quasi-static mirrors on the other hand, usually requires more complex digital drive signal, a DAC and an analog driver. Quasi-static mirrors operate in frequencies where the gain of the mirror is relatively low at the drive frequency and thus requires much more force from the actuator relative to resonant mode drive. In addition, in quasi-static operation mode, the control is more complex, especially if we desire to drive the mirror in a uniform velocity or any other drive shape rather than a sinusoidal waveform. The advantage of quasi-static operation mode is that we can actuate the mirror in many ways rather than only sinusoidal movement. Quasi-statis actuation requires control loops in order to suppress the excitation of the resonance frequency of the mirror and to extend the bandwidth of the mirror.

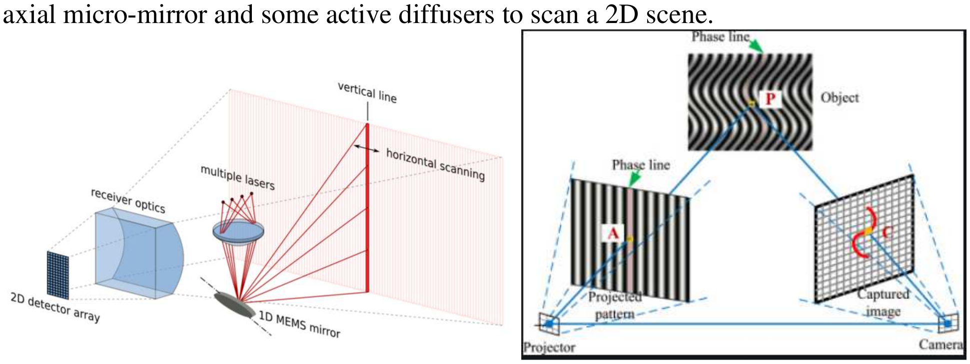


(a) (b)

Figure 3(a) Electrostatic resonant mirror with square wave drive and sinusoidal movement/sense; (b) same structure with different design targets for electrostatic quasi-static mirror with triangle wave drive and motion

1.4 1D scanning

1D scanning engine is comprised of a mono-axial MEMs mirror and a light source that together with some optics a 2D scanning may be implemented. For instance by using a laser array or by using a single laser and cylindrical lens that expands the laser spot to a vertical line which is scanned horizontally by the MEMs. In the same manner a structured light scanner can be implemented. For example, Intel Realsense 1'st generation 3D camera uses ST's resonant mono-axil micro mirror for structured light scanning. On the same principle, some LiDAR application may use a single mono-axial micro-mirror and some active diffusers to scan a 2D scene.

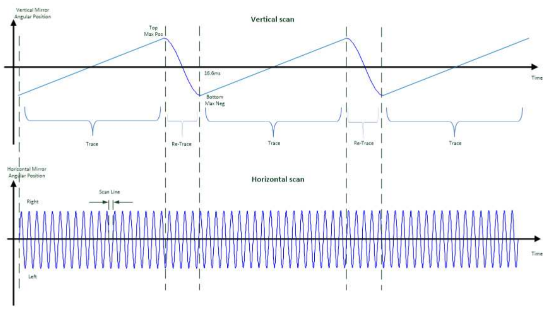


(a) (b)

Figure 4: (a) 1D MEMs scanning LiDAR with vertical laser beam scanning horizontally [4];(b) Structured light 3D depth camera principle[5]

1.5 2D scanning

Two-dimensional scanning requires two usually orthogonal rotational axes and can be implemented by a single bi-axial MEMs structure or with two monoaxial separate MEMs structures. Each one of the axis can operate in resonant or quasi-statis mode. When both axes are in resonant mode the scan pattern that is produced is a Lissajous curve and when both axes are in quasi-static mode of operation the scan is referred to as a point-to-point or vector scanning. For some applications like in visible projection, where a 2D raster like scan is required, one axis will scan in resonant mode (fast axis) while the other axis will scan in a quasi statis mode (slow axis). Usually in a raster scan, it may be desired to have equal spacing between the scanned lines thus the quasi-static mirror is actuated in a uniform velocity. This is required for both uniform brightness and uniform special resolution. The geometry distortion can be corrected by either the video source, digitally by the mirror controller or optically depending on the application



(a)

(b)

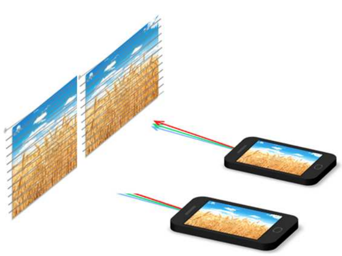
(c)

Figure 5: (a) 2-D raster scan using resonant axis and quasi-static axis. (b) resulted scan pattern illustration using two mono-axial micro mirror structure in raster scan; ST's 2D scanner reference design evolution

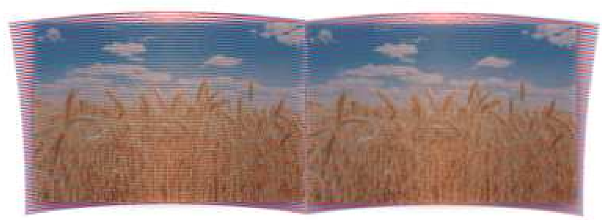
2. Related Work

2.1 Increasing the system's FoV

Laser beam scanning (LBS) for near eye projection is an emerging technology and market that leverages on MEMs scanning mirrors which provides a wide range of advantages such as lightweight, low power, low projection latency, always in focus, low blur and scalable FoV (field of view). Many times, these applications require a large scanned FoV. Implementing a large scanned FoV is limited by micro-mirror maximal opening angle. In order to extend the projected FoV, one possible solution is to add additional scanners each covering a subset of the scanned scene and collectively covers a larger FoV.



(a)



(b)

Figure 6:(a) adding additional individual scanners to the system. (b) combining the individual scanners into wider FoV

2.2 Synchronized projection

In HMD binocular applications like AR/VR/XR and binocular smart glasses, where a simultaneous yet separate projection for each eye is required, having a synchronized scan can simplify the system architecture by having a single video source and a passive splitter (no rate adaptation is required) this together with the low latency projection can reduce fatigue, dizziness and nauseousness. Doubling the number of MEMs scanners in Lidar system, that typically requires a fairly large scanned FoV, having a synchronized scan can simplify the overall system architecture by enabling the processing of a complete scanned scene point cloud that is comprised of few individual scans that can be done simultaneously.

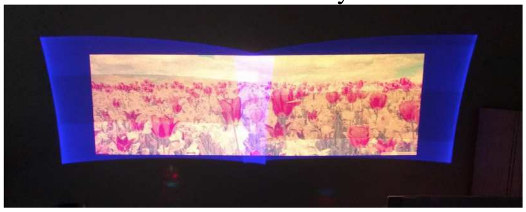


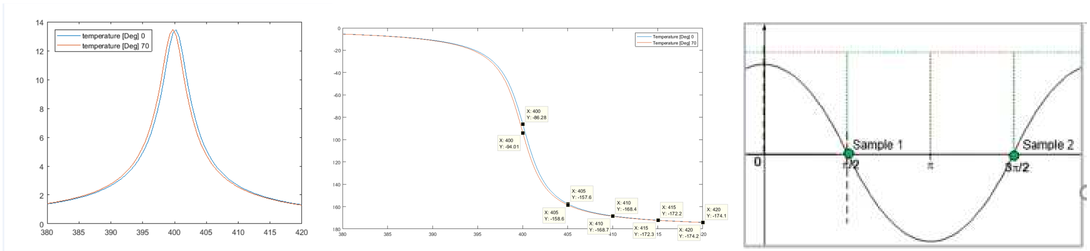
Figure 7: proof of concept of enlarging the projected FoV by combining the projection from two scanners. The implementation takes care of smooth transition, brightness uniformity and color matching. The blue background outlines the scan area versus the active projected area by keeping the blue laser on the entire time.

2.3 Resonant mirror actuation working point, open loop and closed loop

Traditionally, resonant mirrors are driven close or at their resonance frequency. This is done in order to achieve the maximum gain response of the mirror for larger opening angles versus the drive voltage or current. For high Q (quality factor) mirrors, the bandwidth at which we can open the mirror is very narrow while in low Q mirror, the bandwidth is higher thus it is possible to drive the mirror off resonance providing that we have sufficient actuator force to open the mirror to the desired opening angle. How far we can move away from the resonance is limited by the maximum drive voltage we can apply or the maximum current the mirror device can withstand and the desired opening angle we want to achieve.

The resonance frequency of the mirror is a design target and determined by the reflective area inertia and the spring stiffness. Mirrors designed with low resonance frequency (<5K), will have lower Q (<200) and will have a much broader operational bandwidth. These mirrors are usually designed for monoaxial scan of nonvisible applications like structured light 3D camera, direct ToF flash LiDAR or other 3D sensing applications for resolving one axis of the FoV using MEMs mirror with the other axis is resolved using a different technique, such as by using an array of detectors. Other uses for such mirrors are emerging every day. These mirrors can be driven in open loop assuming the system architecture can handle the mirror gain and phase change and have enough margin to compensate for the gain loss by increasing the drive force.

Mirrors with high resonance frequency (>20khz) will tend to have less mass (smaller reflective area) and a stiffer spring in order to in order to meet the target resonance frequency. These mirrors are usually used for visible projection for implementing the fast axis of a raster scanner. These mirrors will have a high Q (>800) and a narrow operational bandwidth. Although these mirrors are stable under constant environmental conditions, any change in the mirror temperature (mainly the spring), will change the resonance frequency of the mirror and considering the narrow bandwidth of these mirrors, driving these mirrors in open loop, will result in a more substantial change of the mirror opening angle and as the result the projected FoV. A control loop that tracks the mirror resonance can be a simple phased locked control loop. Implementing a closed loop which locks the mirror phase by changing the drive frequency, provides both constant mirror gain and thus stable opening angle and also a constant phase between the drive and the mirror position and thus allows the system to use the drive signal as an indication for the mirror position. Since the mirror movement is pure sinusoidal with good approximation due to the narrow band of the mirror that filters any pulse or square wave drive harmonies, placing two sampling points on the mirror sense position feedback signal is sufficient for closing this control loop.



(a) (b) (c)

Figure 8: (a) resonance shift over temperature of a low Q 400Hz resonant mirror; (b) phase shift relative to the drive of the same mirror; (c) since the movement is sinusoidal, placing two samples in strategic positions relative to the drive is enough for locking the mirror phase

2.4 Resonant mirror for slow axis

The benefits of having resonant mirror rather than a quasi-static mirror in a system are obvious. As already mentioned, resonant mirrors have a smaller size, less power consumption, highly stable movement, simpler to manufacture and easy to control. Let's examine the possibility to replace the uniform velocity slow scanner with a low frequency resonant mirror and use the relatively linear portion of the sinusoidal movement for projection. We will have to compensate for the nonuniform scan velocity in another way in the system by controlling the modulation time or intensity according to scan density. By replacing the quasi-static mirror with a resonant one, we can also increase the bandwidth of the slow axis and increase the refresh rate of the raster scan which usually is not possible with quasi-static mirror, due to the low bandwidth of quasi static scan mode. Quasi static mirrors are designed in such way that the actuator would provide sufficient force to drive the mirror in DC, thus the mirror spring cannot be too stiff, which would results in a relatively low resonance frequency, nominally < 1Khz. With a proper control loop, the system bandwidth can be further extended, however, it is not simple to achieve a scan frequency of above 200Hz. With such a low frequency resonance mirror, it is much easier to have a scan frequency of 300Hz up to 2Khz with the proper mirror design.

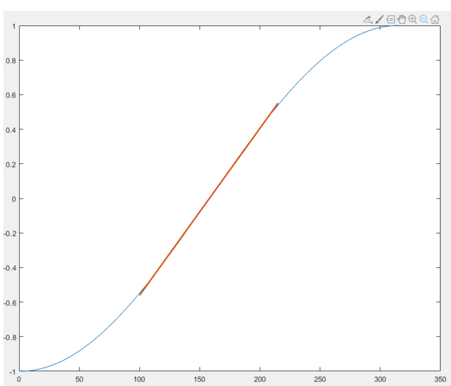
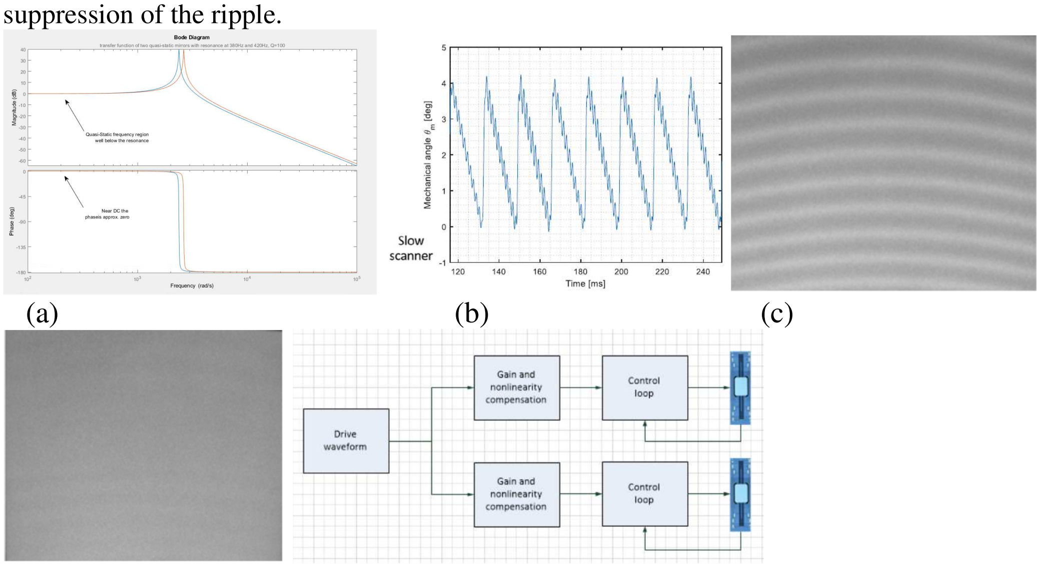


Figure 9: Usable approximately linear portion of a resonant mirror sinusoidal motion

2.5 Synchronized scan of two (or more) Quasi-static mirrors (prior art)

In some cases, it is desired to drive two or more mirrors synchronized with each other, in both frequency and phase. In quasi-statis mirrors, although the drive and control are complex, driving two mirrors in a synchronized way is relatively trivial. The same source generates a normalized drive, and each mirror driver, makes the proper adjustment to the drive in order to achieve the same opening angle if required and also compensate for the drive non-linearity of each of the mirrors. The phase of the mirror is not an issue since the phase in DC is close to zero.

However, quasi-static mirrors are not so easy to control. When the desired motion and as a result the drive signal has high frequency components (for instance in a sawtooth drive) which excites the natural frequency of the mirror and creates a superimposed sinusoidal movement on top of the desired motion. This undesired superimposed movement is visible during the image projection and is manifested as none nonuniform projection with bright and shaded areas matching the mirror natural frequency. In the absence of proper sense signal like in the case of capacitive sense, with some filtering it is possible to detect the excitation of the mirror's natural frequency and to suppress it with feed forward and input shaping techniques. When a proper sense signal, such as PZR sensor in ST's This-film PZT mirrors is implemented, it is possible to use closed loops control in order to suppression of the ripple.



(a) (b) (c)

(d) (e)

Figure 10: (a) quasi-static mode working point gain and phase (bode); (b) quasi-static mirror natural frequency exited by sawtooth drive; (c) visible ripple in the projected image due to resonance excitation; (d) ripple suppression using feed forward and closed loop techniques resulted in homogeneous projection; (e) possible architecture for synchronized quasi-static mirrors actuation

2.6 Non-Synchronized scan of multiple resonant mirrors

Assuming we have a two or more resonant mirrors which we would like to drive at the same frequency. Due to manufacturing process spread, each mirror may have a slightly different resonance frequency. Considering we choose to drive them both at the resonance frequency of one of the mirrors using the same drive control signal and have a phased lock control loop on the resonant mirror. Now we have a system in which one mirror is driven at the resonance frequency having a control loop tracking the resonance, while the other mirror is driven off resonance and in open loop with changing the drive frequency. The system must monitor the off resonance driven mirror opening angle and compensate for the gain change due to the change of the drive frequency. Since both mirrors are driven at the same frequency, they will both move at the same frequency, one mirror having constant opening angle amplitude and constant phase while the other having variable opening angle amplitude and variable phase relative to the drive. The phase difference may be important in some applications and we have to take into account that the phase changes rapidly around the resonance frequency. So for the open loop mirror, we have to implement a mechanism that compensates for the changing opening angle amplitude and somehow compensate for the phase.

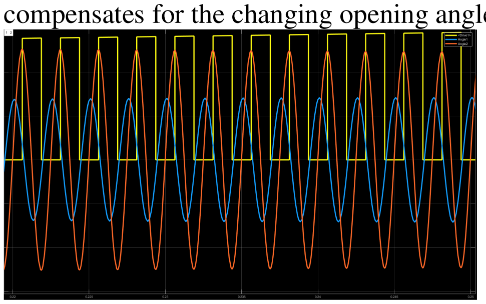


Figure 11: Driving two resonance mirrors in 400hz being one with 400Hz resonance and the other at 410hz resonance both actuates at the same frequency, having different amplitudes and phase;

3. Implementation

3.1 Synchronized scan of two or more resonant mirrors (The problem we have solved)

We have seen that providing the same drive signal to two resonant mirrors will result in different mirror opening amplitude and different phase due to the different gain and phase of each mirror for the same drive frequency. In this article we will suggest some practices and methods for driving two or more resonant mirrors with close but not identical resonance frequencies in a synchronized way while maintaining same opening angles and same phase. Now instead of setting the drive frequency to be at the resonance frequency of one of the mirrors, let us set it at neither of them. If we will choose a drive frequency too far away from any of the resonance frequencies of the mirrors, we may not have enough force to open the mirror to the desired amplitude. Choosing the drive frequency to be at the crossing point of the gain plot, will ensure we are not too far from any of the resonance frequencies.

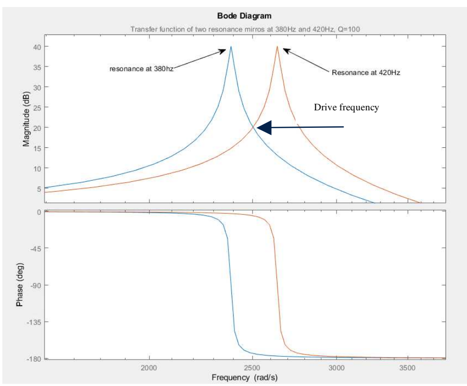


Figure 12:(a) choosing the drive frequency for two resonance mirrors to be at the cross point of the magnitude plot.

Assuming we have sufficient actuating force to open the mirrors to the desired amplitude at this working point both mirror, will actuate at the same frequency each one having different amplitude and phase. Since both mirrors actuated in open loop each mirror resonance frequency drifting independently, causing both the opening angle amplitude and the phase of each mirror to change individually depending on environmental conditions. If we want to have both mirrors completely synchronized we have to implement a control loop that will maintain constant opening angle and another control loop that will compensate for the phase difference.

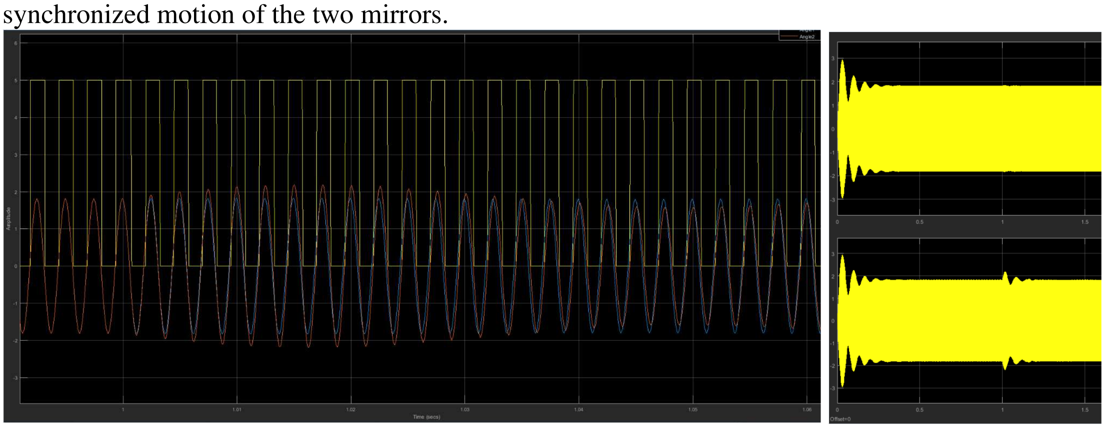
3.2 Constant opening angle control loop

Each one of the mirror's controller implements a control loop that senses the mirror's amplitude and compensates the drive amplitude to maintain a constant mirror opening angle amplitude. The mirror amplitude sense implementation depends on the type of sensor the mirror provides. For Electro-static mirrors with capacitive sense, it is not straight forward implementation, but having some constant sampling points on the capacitive sense in strategic location, may indicate a change in the amplitude. Although the absolute amplitude may be unknown, the control loop will be able to maintain a constant opening angle. In Electro-Magnetic and Piezo-Electric mirrors having a thin-film piezo-resistive sensor (PZR) which is linear with respect to the mirror tilt angle, a real time opening angle can be inferred from the sensor. Hence implementing a control loop that ensures a constant opening amplitude is straight forward.

3.3 Phase match control loop

Another system consideration is matching the phase of the two mirrors. Having a single drive frequency for the two resonant mirrors, results in different scan phase for each mirror. In this case an additional control loop has to be implemented. The implementation of this control loop, may relay again on the mirror's sense signal, identifying the zero cross point-when the mirror crosses the rest position. In a capacitive sense, this would be the point in which the current direction changes polarity. An analog zero cross circuit or digital zero cross circuit are both acceptable. In Electro-Magnetic and Piezo-Electric mirrors having a thin-film piezo-resistive sensor, the sense signal may be filtered and stripped off the DC component before entering a digital zero-cross detector. By having the digital zero-cross signal of both mirrors, an FPGA or ASIC digital implementation can calculate the phase difference and shift the drive signal of one of the mirrors such that the zero cross signals will have the same phase.

After implementing the two control loops, we end up with a system which drives two resonant mirrors in open loop with regard to tracking the resonance frequency, but with two control loops that compensates for the amplitude and phase of each mirror in order to enable a completely synchronized motion of the two mirrors.



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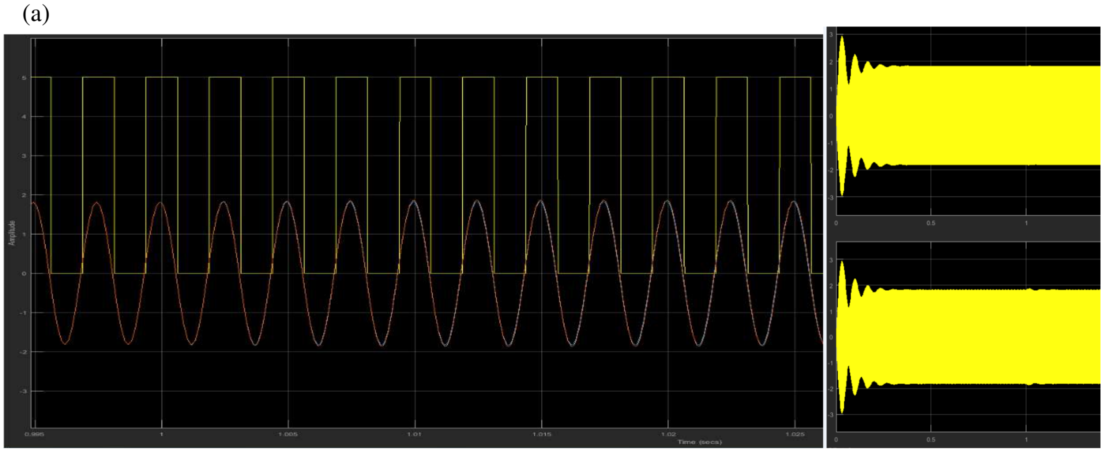


(b)

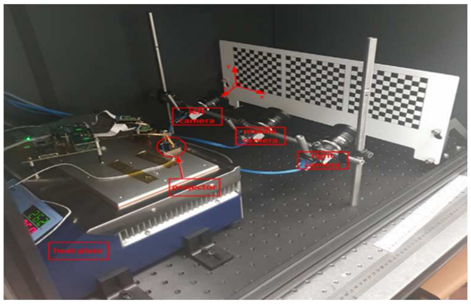
Figure 13: (a) large phase shift of the drive signal resulted in a visible transient effect on the mirror amplitude; (b) small phase shift the of the drive signal resulted in a negligible transient effect on the mirror amplitude

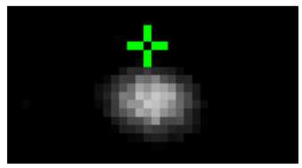
4. Evaluation

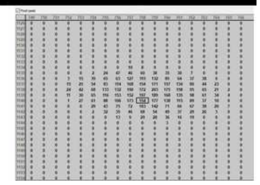
4.1 Evaluation and performance

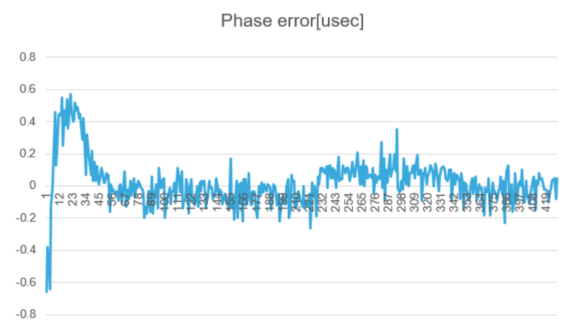
The performance of such a system implementation together with the suggested control loops was validated using a camera based validation station. The validation station is comprised of three high resolution industrial cameras with high refresh rate, each one capturing part of the entire FoV for better resolution. When the laser is modulated on pre-defined mirror angles, and by using image processing techniques the validation station is able to perform an optical measurement of spot drift and jitter over time. The performance of the system was also tested over temperature, using a commercial heat plate. The opening angle stability, was measured by processing the images of a solid line projection. In addition, the phase between the mirrors was measured on the zero-cross signal using an oscilloscope.

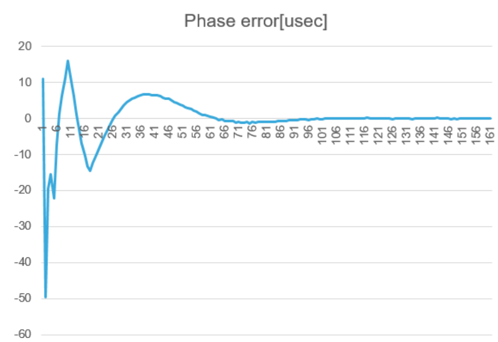
The validation was is done on dozens of pairs of nominally 400hz resonant mirrors, which had a resonance frequency spreading from 370Hz to 430Hz. The maximum phase difference between the two mirrors measured over temperatures between 0°c to 50°c operation was under 400ns in all conditions. Each one of the micro-mirrors opening angle has a maximum of 10 millidegrees error over a mirror opening angle amplitude of ±13° degrees of half mechanical opening (Optical FoV of 52° degrees).

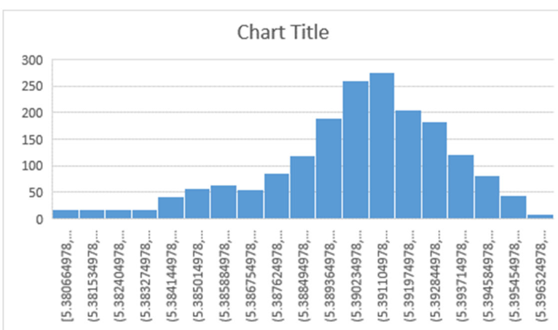












5. Conclusions and Future Work

In this paper we have shown our approach for synchronously driving multiple low Q resonant mirrors. The additional control loop suggested in this paper, provides excellent scanned FoV and phase synchronization between the actuated micro mirrors. This solution enables projection and 3D sensing applications to further extend the scanned FoV beyond the mechanical limitations of the MEMs mirrors simply by adding additional scanners and maintain a simple architecture of the video source streaming multiplication or a 3D point cloud rendering. Future work may extend these proposed techniques to support applications that requires higher resonance frequencies with mid-range Q factor resonance mirrors with narrower bandwidth.

References

[1] – image taken from https://www.accuvein.com/products/catalog/av500-vein-viewing-system/
[2] – image taken from https://strategyonline.ca/

[3] – image taken from https://www.intelrealsense.com/lidar/
[4] - SENSORDEVICES 2018 : The Ninth International Conference on Sensor Device Technologies and Applications
[5] - https://www.osa-opn.org/home/articles/volume_29/january_2018/features/lidar_for_self-driving_cars/