D4.3

Dissemination report on MR Head Up Display demonstrator

Project number	101014977
Project acronym	REALHOLO
Project title	Phase modulating micro mirror array for real holographic mixed-reality displays
Start date of the project	1st January, 2021
Duration	60 months
Call	H2020-ICT-36-2020

Deliverable type	Report
Deliverable reference number	ICT-36-2020/ D4.3 / 1.0
Work package contributing to the deliverable	WP4
Due date	December 2025 - M60
Actual submission date	7th January 2026

Responsible organisation	Realview imaging LTD
Editor	Shlomi Alon-Braitbart
Dissemination level	PU
Revision	1.0

PHOTONICS PUBLIC PRIVATE PARTNERSHIP

The REALHOLO project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 101014977. This project is an initiative of the Photonics Public Private Partnership.

Abstract	Integration of MEMS-SLM into a commercial medical holographic system which mainly includes system level adaptation design, mechanical adaptation design, mechanical assembly, software design, software adaptation and system level integration as described in this report. Full integration as planed was not possible due to unavailability of active chips and lack of Display Port interface implementation. Applicative potential regarding optical and mechanical on the HOLOSCOPE-i system is demonstrated.
Keywords	MMA, SLM, HOLOSCOPE-i, Holographic display, meta pixel, diffraction, optical calibration, optical alignment, phase correction

Editor

Shlomi Alon-Braitbart (Realview)

Contributors

Genadi Shmidov (Realview)

Shaul Gelman (Realview)

Yuval Yoreh (Realview)

Ofir Bril (Realview)

Executive Summary

In order to demonstrate the application of a medical volumetric true-holography mixed reality HUD, which the commercially available HOLOSCOPE-i system is, the MEMS-SLM along with all its components needed to be integrated into the optical head of the HOLOSCOPE-i system. The HOLOSCOPE-i system is a commercial medical system with CE approval and FDA clearance for use in cardiac catheterization labs enabling real-time intra-operative 3D/4D holographic visualization of the treated area and treating tools for the operating physician. A successful integration demonstrates the applicative potential of the MEMS-SLM device to significantly improve image quality and resolution, and in the long run reduce system's price.

Design and execution of this task required multidisciplinary effort which included system level analysis and design, optical design, mechanical design, software, algorithms and optical measurements. Coherent light RGB laser lighting module has been redesigned and manufactured. Mechanical adapters needed to be designed and manufactured. System software had to be modified to account for the SLM rectangular pixel format as well as the pixels density.

A single eye channel has been assembled in full excluding the active chip which was not available to date. The assembly proves that the MEMS-SLM can be integrated to achieve full viewing experience with no mechanical obstructions or ergonomic issues.

Subjective and performance testing plan of MEMS-SLM integrated to the HOLOSCOPE-i system is presented. The plan is designed to evaluate key image property metrics using the existing LC SLM as reference. Luminance-ratio and ghost-images-relative-luminance metrics have been selected, since they target the performance parameters which are most expected to be impacted by the MEMS-SLM technology in the context of the HOLOSCOPE-i system operation parameters and user experience.

Subjective evaluation study design comparing the viewing experience between two HOLOSCOPE-i systems: a commercial system with LC SLM and a modified system with MEMS-SLM is presented. The study design attempts to modestly quantify and compare the subjective experience generated by the two SLM technologies.

Full implementation of the integration plan was not possible due to delay in active chips supply and lack of DP interface implementation due to substantial challenges in such an innovative design and development of the MEMS-SLM and in spite of the hard work and great efforts invested by all partners of the consortium. Hopefully the project will be continued and full evaluation will be carried out in the near future as part of a potential follow-up project to mature the MEMS-SLM to a fully commercial level device.

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Chapter 1 Introduction

This document summarizes the work carried out in WP4 to reach the goal of integrating the MEMS-SLM device into an existing optical head unit of the HOLOSCOPE-i system, which is part of a commercial medical true-holograpy mixed-reality HUD (Head Up Display) system. The HOLOSCOPE-i is a complicated multi-disciplinary system integrating technology from a broad spectrum of domains such as optics, mechanics, software, electronics, real-time high computation, Human-Machine-Interface etc. Main goal of integration is to replace the current LC based SLM for light modulation and demonstrate its operation without modifying the optical system, since custom optical design is out of scope of project resources and timeline. System level design considerations along with actions taken at the various disciplines to achieve this goal are presented in what follows. Due to delays in the supply of fully operational MMA-SLM devices and the temporary abandonment of DP interface development, some of the original planed tasks and goals could not be achieved, and actual demonstration and comparison to LC SLM could not be carried out. The complete plan will be laid out, and available results presented.

Document is structured as follows:

- Outline of the integration process as a whole and the plan in detail. It specifies the general tasks and dependencies on the way to integration.
- Discussion of the expected optical performance and software modifications due to the fact that the optical system was designed and optimized to accommodate a specific LC SLM which has different optical characteristics than the MEMS-SLM.
- Mechanical integration description.
- Outline of the calibrations for SLM alignment and hologram optimization, and basic bench testing prior to system mounting.
- Outlines of the evaluation plan.
- Objective evaluation plan and methodology.
- Subjective evaluation plan and methodology.
- Conclusions and achievements are discussed along with results and future potential explorations.

Chapter 2 Integration plan

2.1 background

The HOLOSCOPE-i system is a medical volumetric true-holography display and interaction system capable of providing real-time video rate volumetric interference-based holograms within hands reach, while allowing for a wide range of interactions with and within the hologram as illustrated in Figure 1. It is FDA cleared and CE approvedfor use in cardiac catheterization labs. The system is comprised of 4 main parts (bottom up as presented in Figure 1):

- Cart – acts as the base of the system and enables system mobility.
- Computer module – holds the system computer to allow real-time holograms computation and over-all system management as well as being part oif the mechanical system structure.
- Extension arm – a zero-gravity arm that holds the optical head and allows for its effortless spatial manipulation with no weight nor any requirement for any wearable for the user.
- Optical head – holds the entire optical apparatus for hologram projection as well as sensors for user interaction which includes user tracking sub systems (eyes, hands and voice).

Figure 1: HOLOSCOPE-i system main parts and usage illustration

System level design and modifications to support the MEMS-SLM integration into the HOLOSCOPE-i were performed to include software coding, hardware/mechanics design, tools design etc. All hardware modifications were performed in the optical head unit, but in order to provide a full viewing experience an entire system is needed. This is due to the optical head needs power as well as data to operate, and in addition viewing ergonomics is an important part of the viewing experience. For that reason, a full system has been assigned for integration.

2.2 Integration plan

In order to integrate the MEMS-SLM the following tasks need to be performed:

- Optical evaluation of performance impact due to SLM geometry.
- Mechanical design manufacturing and implementation.
- Software adaptation design and implementation.
- HOLOSCOPE-i system preparations for integration: initial calibrations and disassembly of LC SLM and laser module.
- MEMS-SLM benchtop characterization and operative verification.
- Single eye channel assembly of MEMS-SLM apparatus on optical head.

- Optical alignment and calibration of single eye channel.
- Assembly and calibration of second eye channel.

The inter dependencies and time flow are presented in Figure 2. Original month of delivery is indicated.

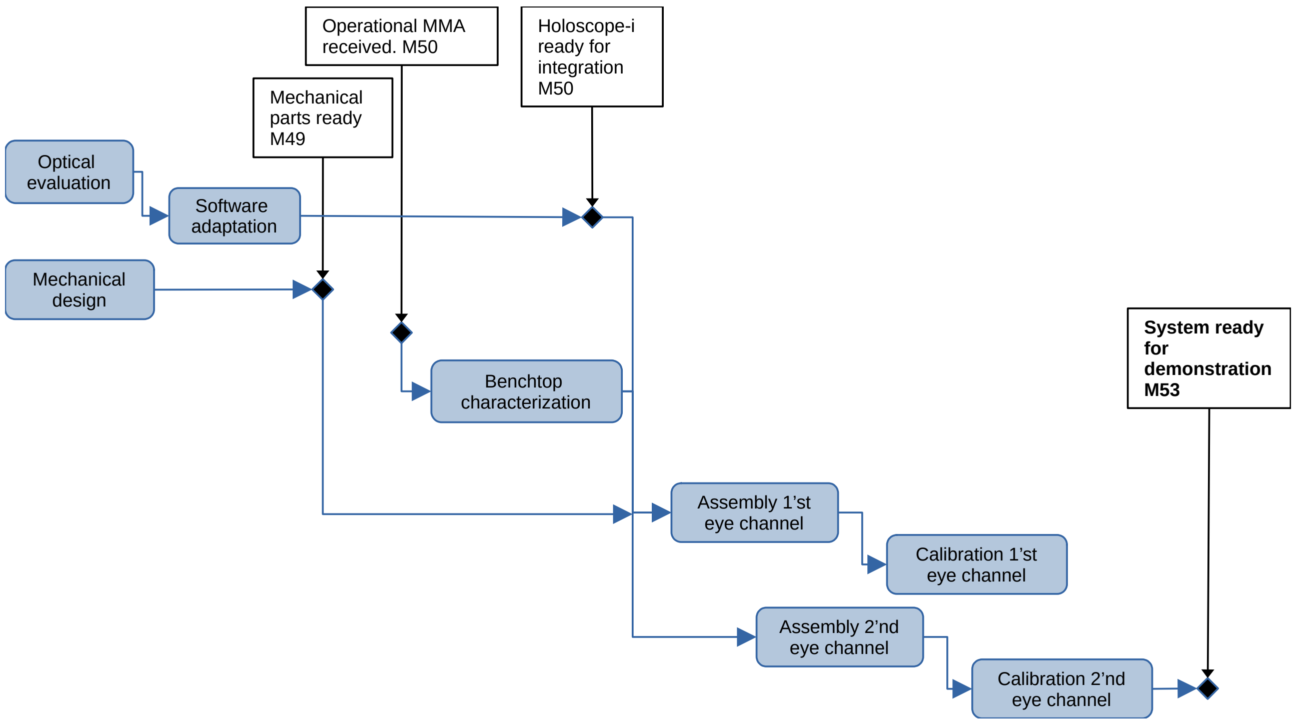


Figure 2: Integration plan outline

Optical evaluation, mechanical design and software adaptation can be performed independent of MMA readiness based on CAD models and MMA design. Benchtop characterization and assembly require a fully operational MMA device, although it is possible to verify the mechanical design by assembling only the hardware electronics without an active chip. This allows to correct unexpected mechanical issues early and prevent further delay.

Chapter 3 Optical performance and software design

3.1 Optical performance

The optical system of the HOLOSCOPE-i was designed and optimized for a LC SLM having a square aspect ratio with a given pixel pitch. This determines the maximal diffraction angle per color, and dictates a square Fourier image. The MEMS-SLM has a rectangle pixel pitch and more than twice the active area of the LC SLM. This dictates a different diffraction angle per dimension. As a result of these discrepancies the image is expected to be clipped and exhibit some vignetting according to the field and aperture stops as designed. In one dimension the MMA pitch is very similar to the LC SLM pitch and the enlargement of the image is small enough to be accepted by the optics. In the other dimension the diffraction angle is much larger which requires compensation.

To minimize the impact of optical characteristics differences between the SLMs the following actions as illustrated in Figure 3 are done:

- Limit the aperture by illuminating only part of the active area using a rectangle mask at the laser output.
- Limit the horizontal angular span from the SLM. This can be done by limiting in calculation the spatial frequency and optionally grouping pixels together to a meta-pixel reducing the effective pitch. The chosen approach is explained in 3.2

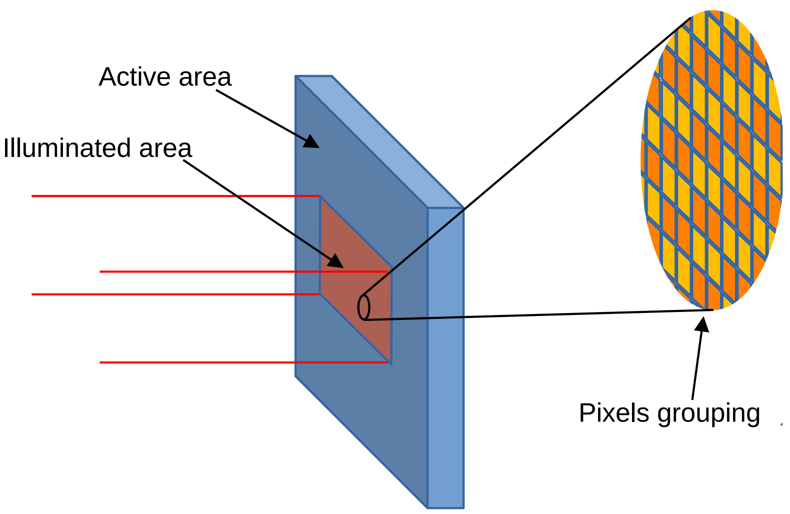


Figure 3: Aperture limit and pixels grouping

3.2 Software design/adaptation

3.2.1 Computation

The computational flow can be lumped conceptually to 4 stages (Figure 4):

- *Pre CGH (Computer-Generated-Holography) rendering*: accepting the volumetric data and preparing it for hologram computation.
- *CGH computation*: computing the hologram interference-patterns. This stage is where most of the computational power is spent. It is GPU based and highly optimized.
- *Post CGH processing*: accepting the CGH result and addresing it on the SLM for holograms projection.
- *Output interface*: this is just the hardware interface to the SLM. It is HDMI in double buffer configuration for commercial system and DP for MEMS-SLM.

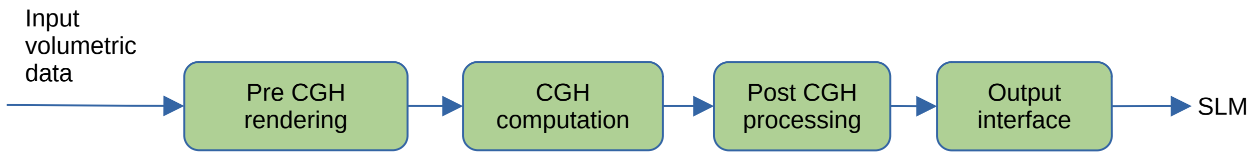


Figure 4: Computational flow

The computational CGH algorithm and its software implementation is fixed to a predetermined resolution and modifying it to better fit the MMA-SLM properties is out of scope of this project since the optimization is within the GPU-level deep implementation.

Since the original SLM pixel is square, the computation resolution is the same for the vertical and horizontal directions. Having a rectangular pixel pitch results in a different diffraction angle per axis. This needs to be compensated. The degrees of freedom we have in the software is to manipulate the image prior to CGH computation, and manipulate the phase frame, which is the output of the CGH computation. This means that compensation can be achieved in 2 ways as illustrated in Figure 5:

1. Keeping the MMA native resolution, applying pre scaling and padding to a square. Pre scaling is required since otherwise the hologram will be stretched horizontally, so down-scaling (compressing) the image in the horizontal direction prior to calculation by the opposite stretch factor will eventually result in the correct aspect ratio after projection (Figure 5 top). The compression needs to yield in an image narrower than the original size. As a result the resolution will decrease by the same ratio, but the viewable hologram frame will stay complete.
2. Grouping 2 adjacent pixel to a meta pixel. This will reduce the difference between the horizontal and vertical diffraction angles and will require an up-scaling (stretching) in the horizontal dimension and cropping back to square prior to CGH calculation. This approach increases the resolution but dumps the edges of the frame.

Both methods result in information loss, the first by reduction of resolution and the second by losing part of the image, but the trade-off is not symmetric. The second method by virtue of improving the effective aspect ratio of the pixel has less information loss. In addition, if visual quality of the image is to be compared, reduction of resolution will have a more significant impact on perceived quality than image edge cropping. The improved resolution will have little advantage in this setting, since the designed resolution is already on the edge of human perception.

For all of the above considerations the second method was chosen for implementation.

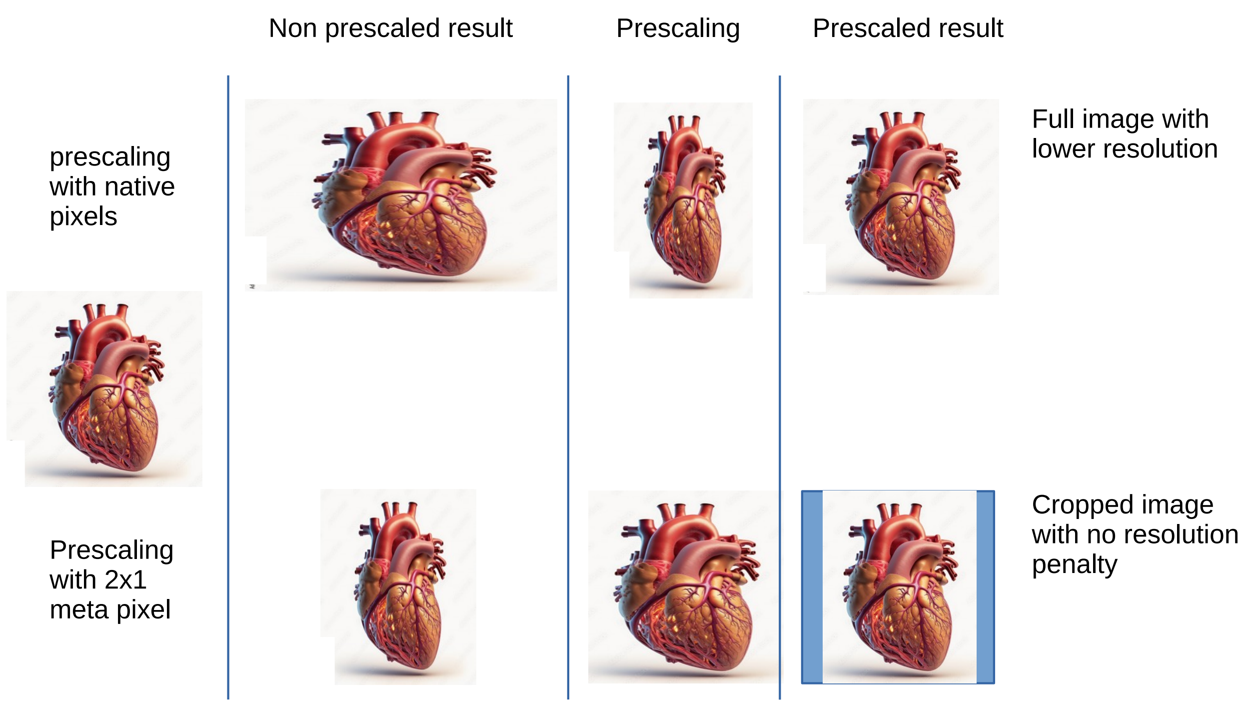


Figure 5: Native resolution vs. meta pixel

3.2.2 *Output interface*

The MEMS-SLM is designed to accept Display Port (DP) so it is necessary to convert the HDMI signal to DP. This is simply done using a HDMI to DP converter in hardware.

Chapter 4 Mechanical integration

4.1 Mechanical design

4.1.1 General design

The HOLOSCOPE-i optical head, is densely packed with optics, electronics and other modules as expected from a highly optimized design of a commercial system where space, weight, industrial design, ergonomics, manufacturability, serviceability and other parameters are considered. In order to integrate the MMA apparatus, the space around the SLM needed to be rearranged such that the optical distance between the MMA active area and the first optical element is the same as the original SLM to maintain the optical properties of the system.

The size of the electronics board holding the MMA is too large to be placed in the original SLM location. For this reason the optical axis needed to be re-designed and opto-mechanically folded to the side of the optical head (Figure 7). Any other position would not allow for assembly of 2 MMA units simultaneously. This forced the following modifications:

- Design and manufacture a modified laser module: the original laser module form factor could not fit the space left after optical axis folding. A shorter laser module needed to be designed and manufactured which compressed the beam expander and the spatial filter to a single tube.
- Some of the electronics cards needed to be detached and migrated.

In addition, mechanical adapters needed to be designed and manufactured. A THORLABS KS2RS tilt and roll mount was chosen as the MMA mount, and an adapter was designed for attaching it to the MMA mechanics (Figure 6). Tilt around 2 axes is needed to angularly align the MMA projection to the optical axis, and roll is required for hologram alignment. In addition, the adapter allows for some lateral adjustment to center the MMA on the optical axis.

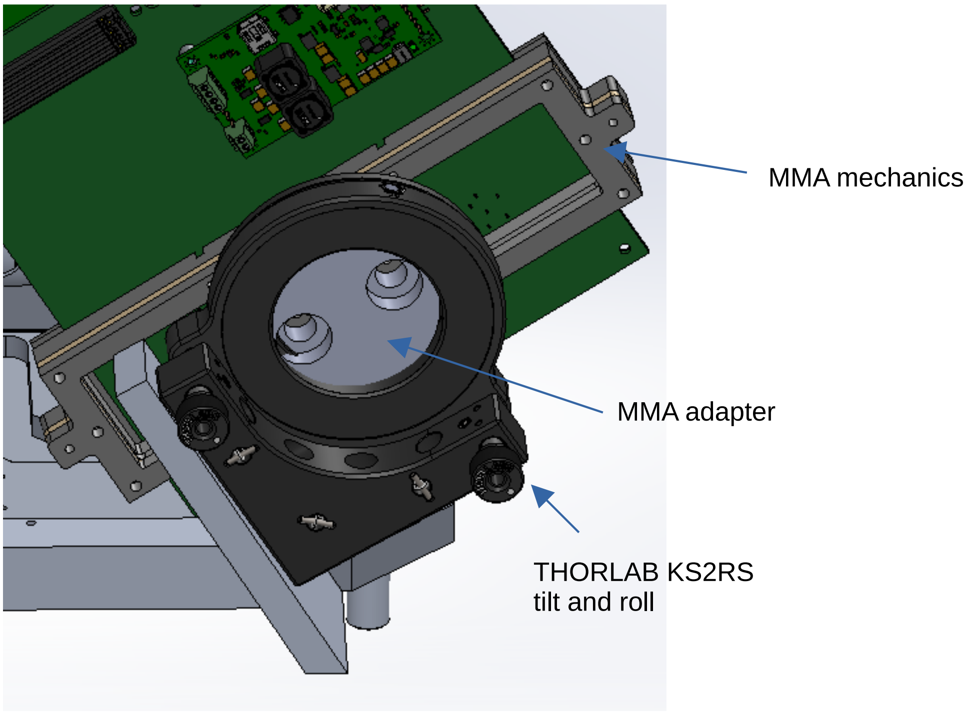
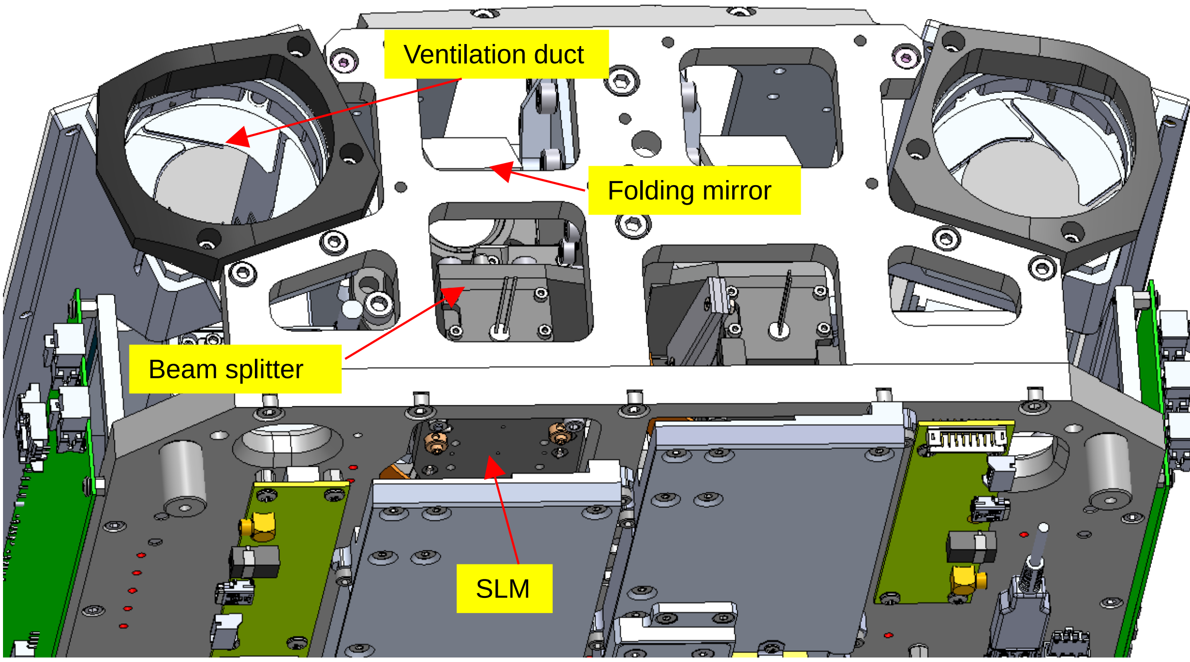


Figure 6: MMA mechanical mount and adapter

4.1.2 SLM positioning

As stated above, it is important to keep the optical path length between the SLM and the first optical element in order to preserve the overall properties of the optical system. From observing Figure 7 it is obvious that the original bottom position is not feasible. Other options include back, top and side positions. Back and top positions did not meet the distance criteria and had an overlapping issue between SLM boards and mechanics. Therefor the only viable position remains the sides of the optical head as seen in Figures 6 and 7.

Original positioning



Modified positioning

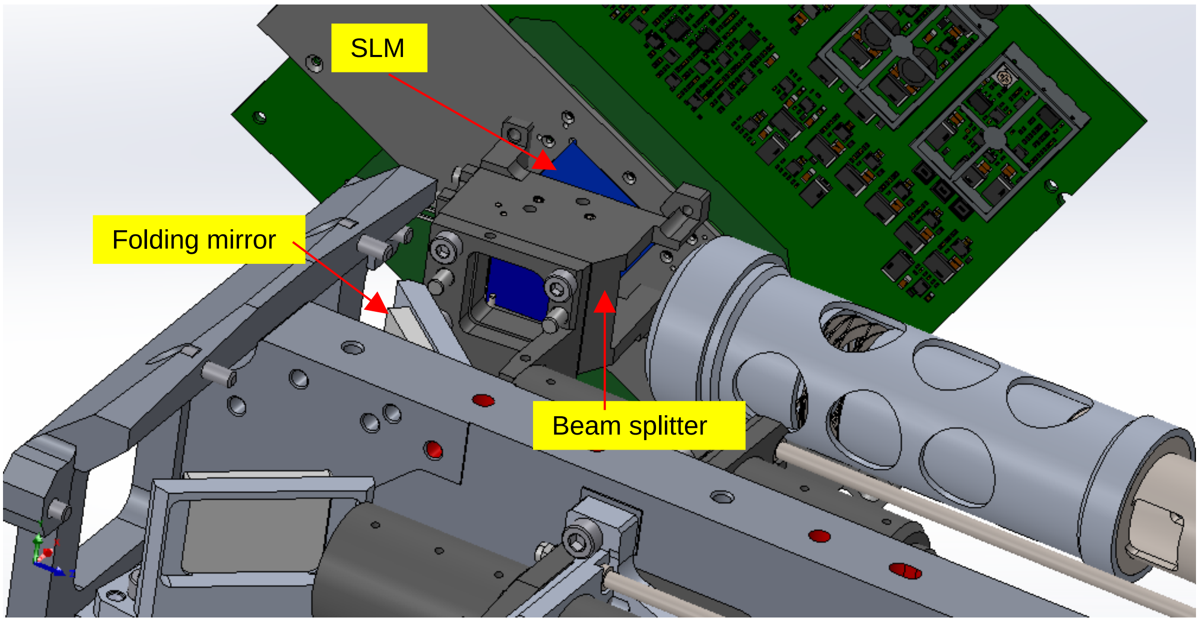


Figure 7: SLM positioning modifications

4.1.3 Laser module

The original laser module is comprised of a RGB laser source with a small diameter collimated output beam and a beam expander. The source and beam expander are situated side by side and connected via two folding mirrors. Folding the SLM optical path sideways did not leave space for the laser module so a new module had to be designed to fit the new space which had more length but less width. For that purpose the beam expander was incorporated as part of the laser source construction, such that the spatial filter is part of the beam expander. This allowed for a tight fit into the chassis.

4.1.4 Thermal considerations

Since the optical head covers will not be present, as the MMA apparatus does not fit into the original space, and the optical head will be open, the ventilation duct (Figure 7) can be removed safely. In practice the ventilation duct will need to stay connected, for electrical integrity reasons, and will be put aside.

The MMA thermal apparatus itself, as it turns out, is not sufficient by itself to manage the desired chip temperature. For this reason 3 heat sinks are attached to the back of the MMA mount board as shown in Figure 8.

4.1.5 FPGA and PSU

FPGA board is situated on top of the optical head using mechanical adapters along with the PSU as shown in Figure 9.

4.1.6 Nitrogen purging

MEMS-SLM packaging is not an hermetically sealed package. This calls for constant purging the MMA chip with Nitrogen while in operation. For that purpose, a Nitrogen bottle with a low flow system has been integrated. The purging tube will be inserted and glued to a dedicated hole in the stiffener which houses the MMA chip. Glue will be applied on the outer perimeter of the tube to keep any out gassing effects out of the chip.

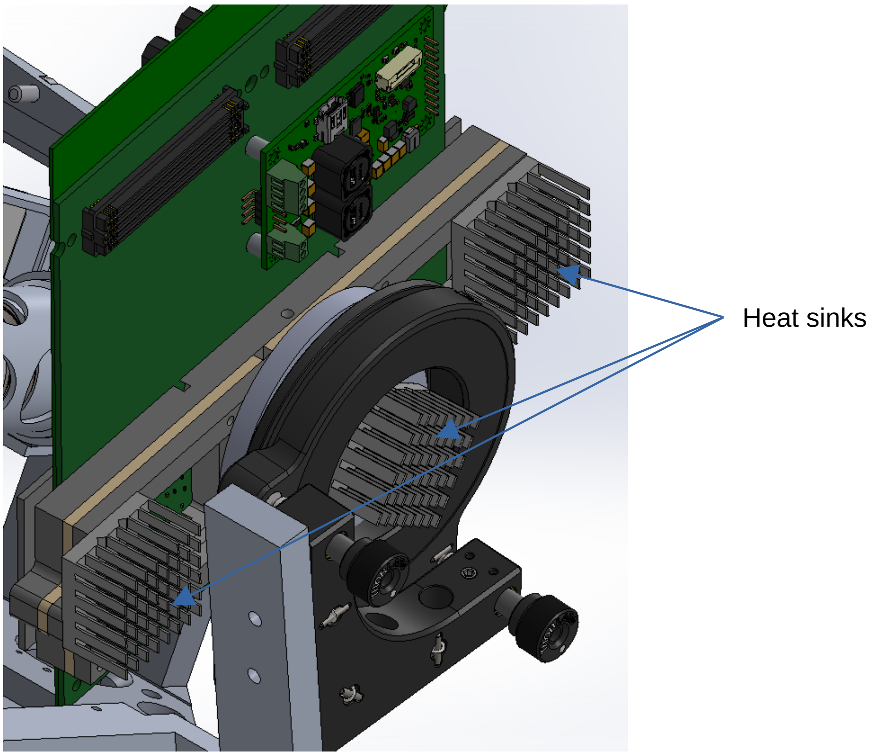


Figure 8: Heat sinks positioning

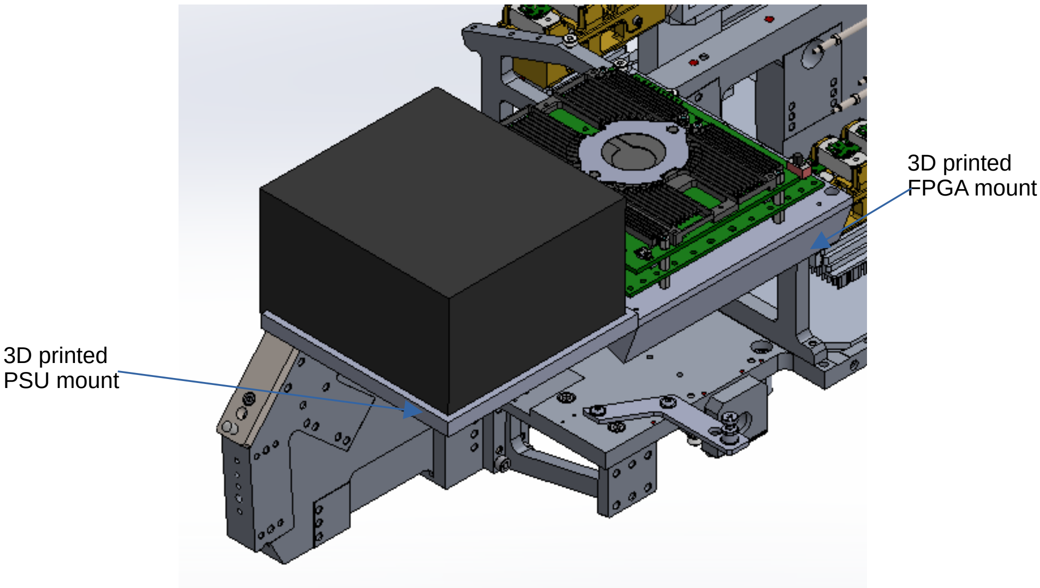


Figure 9: FPGA and PSU mounting

4.1.7 Design overview

The full design is presented in Figure 10. All the relevant components are shown for the left eye, and the optical path is displayed. The optical path starts at the laser module which illuminates the BS. Light is split by the BS towards the SLM, and modulated light is reflected back through the BS to the folding mirror and then into the rest of the optical system.

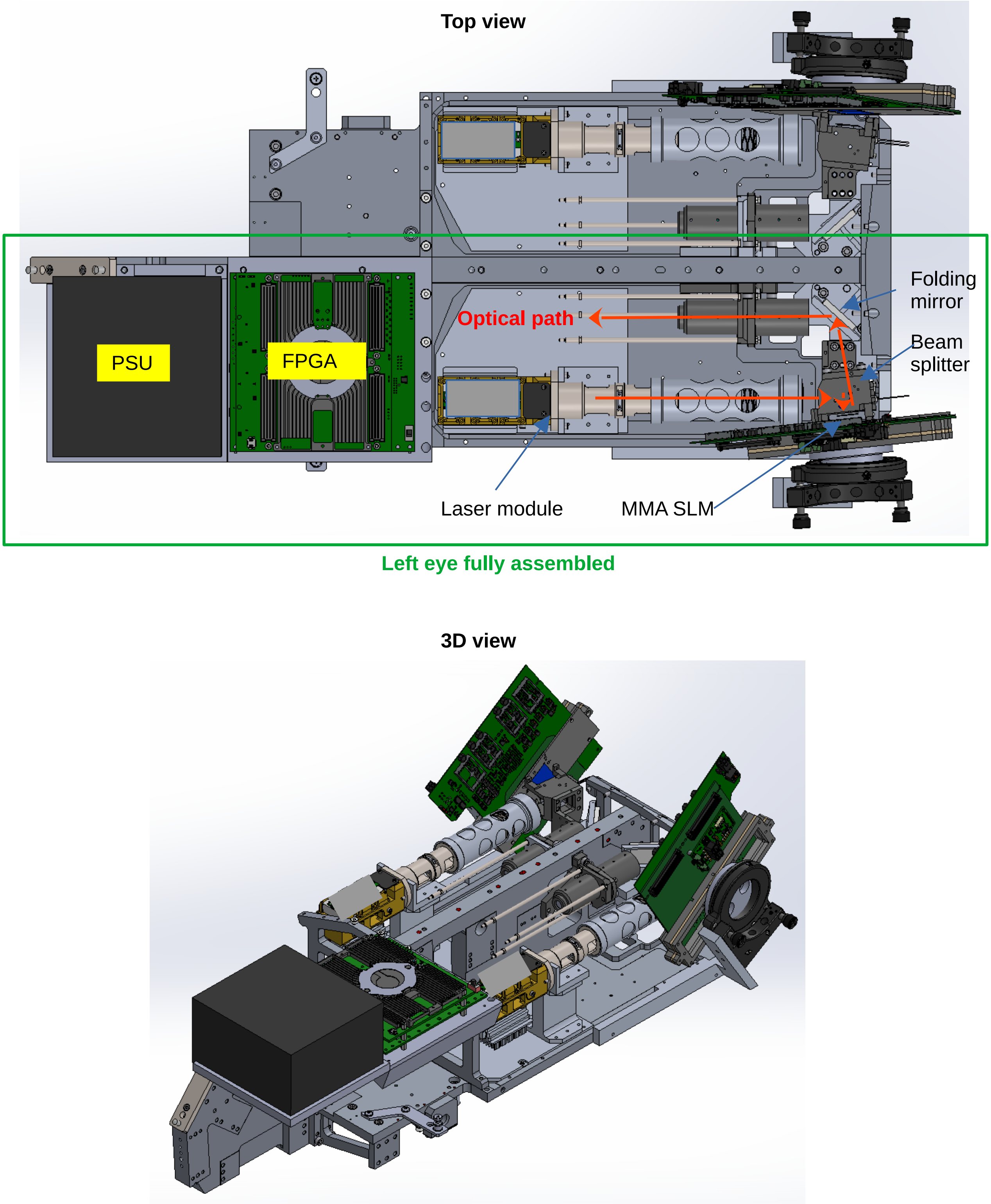


Figure 10: Design overview

4.2 Mechanical assembly

4.2.1 Laser module

Laser module assembly was comprised of two stages (see Figure 11):

1. *Laser diodes optical bench assembly*. RGB laser diodes has been assembled and aligned according to Realview's standard procedure which includes:

    1.1 Diode collimation.

    1.2 Colors angular alignment.

    1.3 Beam shaping through anamorphic prism set.

2. *Beam expander*:

    2.1 Lenses assembled within the expander tube.

    2.2 Beam expander tube has been aligned for collimation using a Zygo interferometer.

3. *Spatial filter*:

    3.1 Beam expander tube assembled on the diodes optical bench.

    3.2 Pinhole was placed at the optics focal plane and centered using a XYZ translation stage for spatial manipulation. A power meter is used for feedback.

    3.3 After positioning optimization, the pinhole was fixed.

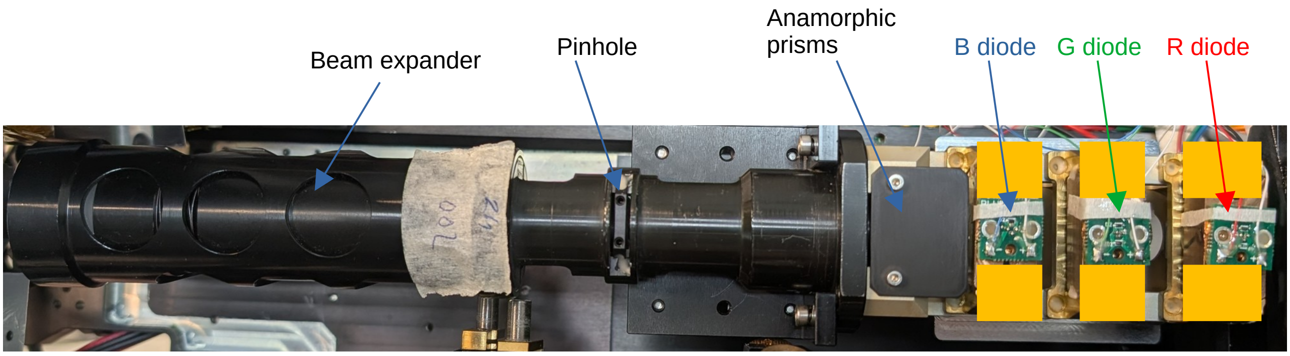


Figure 11: Assembled RGB laser module

The laser module is mounted on the chassis with a dedicated adapter presented in Figure 12.

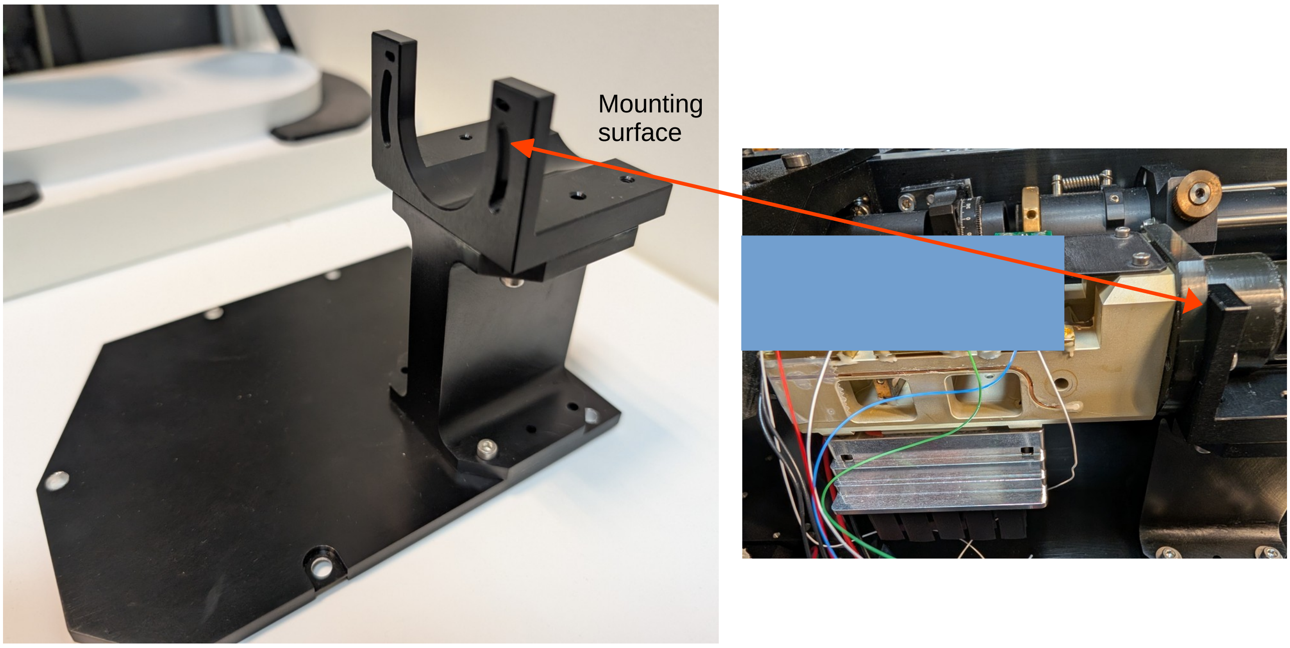
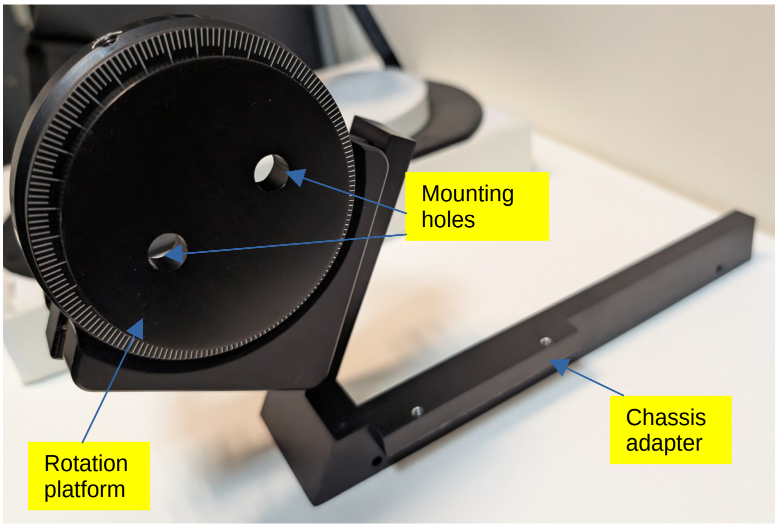


Figure 12: Laser module chassis mounting

4.2.2 MEMS-SLM mount

SLM mounting assembly is shown in Figure 13. SLM is stable after rotation plate is locked, and tilt manipulation works as expected.

Front



Back

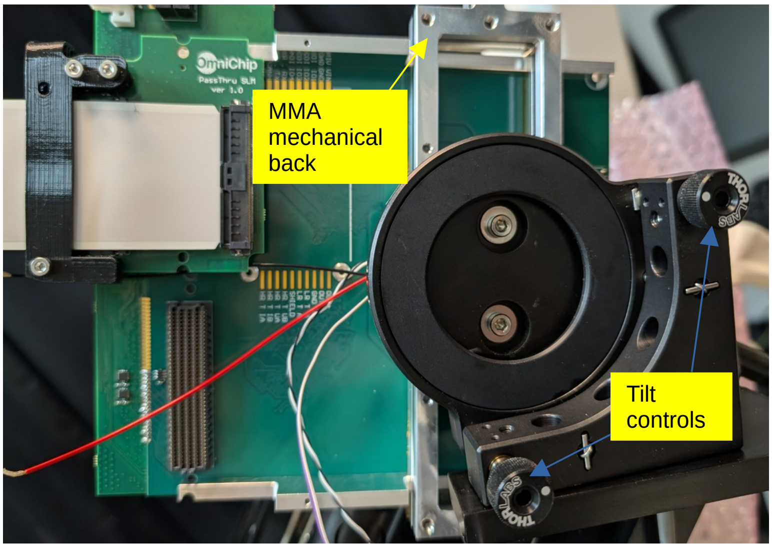


Figure 13: MEMS-SLM system mount assembly. MEMS-SLM electronics board and mechanical chip mount supplied by OmniChip and the consortium.

4.2.3 Beam splitter and folding mirror assembly

Figures 14 and 15 show the sub-assemblies and their integration into the optical path. The proximity of the BS to the SLM is evident and is the result of the necessity to keep the SLM at the designed distance from the first optical element, in order to preserve optical performance.

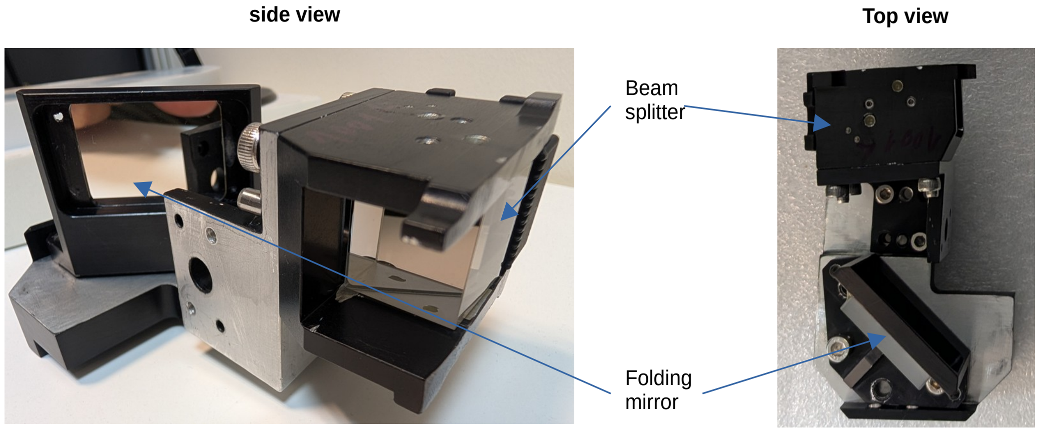


Figure 14: Beam splitter and folding mirror sub assembly

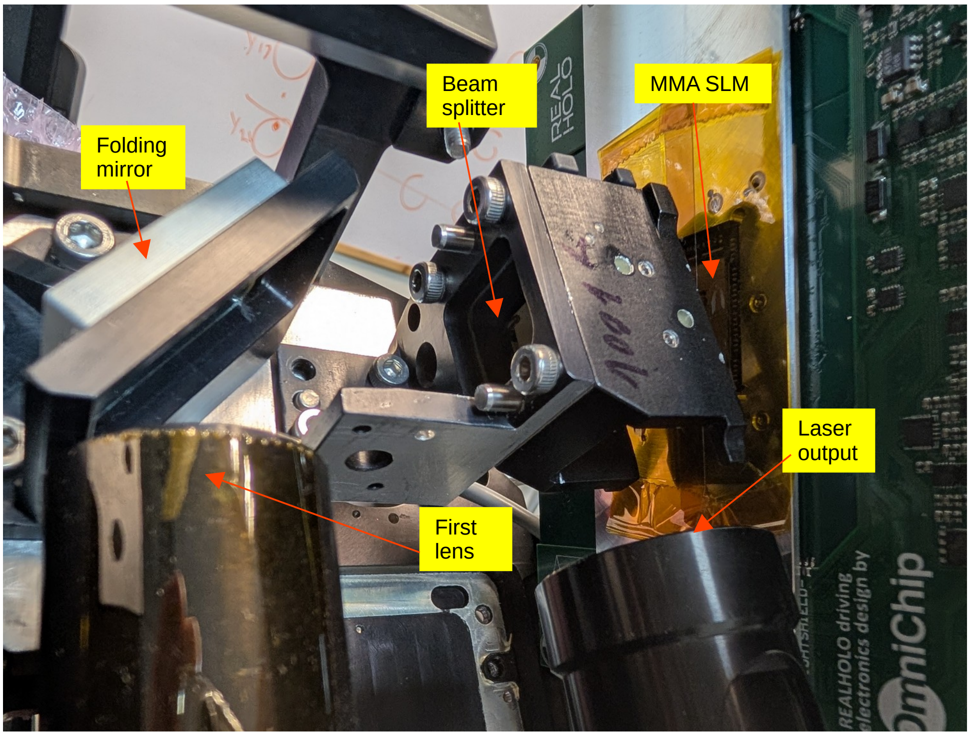


Figure 15: BS and folding mirror assembled in optical path

4.2.4 FPGA and PSU assembly

The MMA-SLM driving FPGA and PSU assembly is shown in figure 16.

4.2.5 Full assembly of single eye channel

The first eye to be assembled was arbitrarily selected to be the left eye. Figure 17 presents the full assembly of the left eye on the HOLOSCOPE-i holographic system.

Figure 16: FGPA and PSU assembled

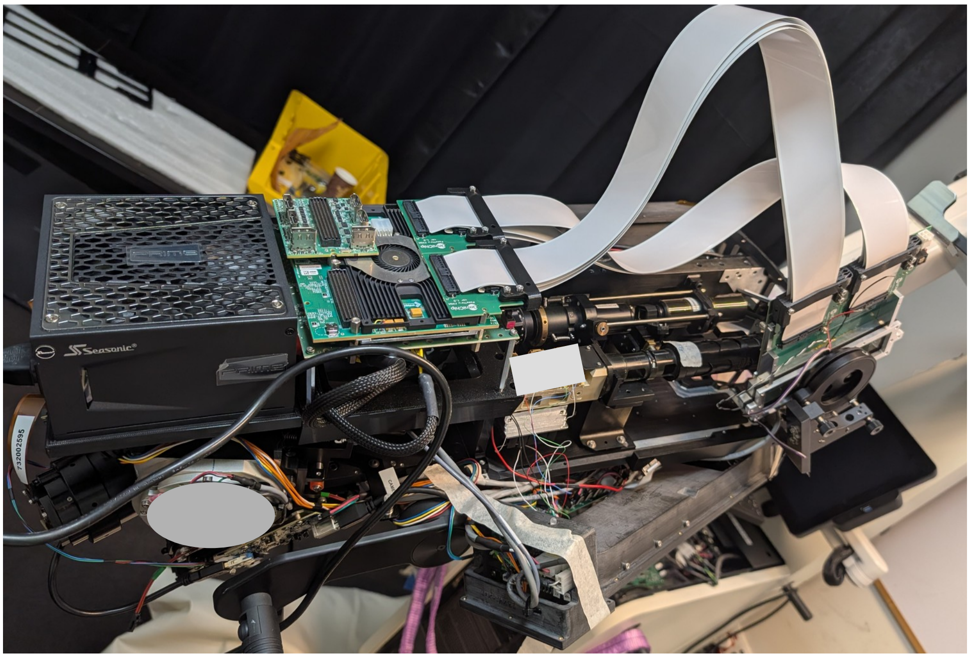


Figure 17: Left eye full assembly

Chapter 5 Calibrations and bench testing

In this chapter the plan for bench testing of the MEMS-SLM prior to system integration and the calibration procedure for integrating it is described. Since no active chips have been delivered to date, no results will be presented. Another requirement for proper system calibration is 60Hz real time SLM operation which is currently not available since it has not been implemented to date.

5.1 Bench testing

Prior to integrating a SLM into the system, it is imperative to test it on a test bench to verify it is working as expected and to perform phase linearization.

5.1.1 Basic operation

This includes powering up the MMA apparatus, connecting it to a computer via Ethernet and performing basic operations such as sending images to the SLM and observing the phase response. As a second stage Display Port (DP) operation will be tested.

The test bench setup will be the same as for phase linearization and will be described in the next paragraph.

5.1.2 Phase linearization

Phase linearization is the process of generating a Look-Up Table (LUT) between the gray level value of a pixel sent to the SLM in a projected frame (or voltage value) and the resulting phase modulation value. This is a necessary stage since linear phase response between 0 and 2π is essential for image quality, especially in the context of ghosts images. We use a phase linearization setup as illustrated in Figure 18. This setup is a phase scanning apparatus which enables the measurement of phase response to gray level values as follows [1]:

- SLM is thermally stabilized using a Peltier element.
- A collimated beam is directed to the SLM.
- The SLM is uploaded with a frame divided in half into two Gray Level (GL) values: one side is a reference value (usually GL=0) and the other half is updated with the GL to be measured (GL = 0 to 255).
- Beam reflected by the SLM is modulated such that there is a phase retardation between the two sides of the modulated beam.
- A double aperture plate is situated such that each aperture transmits a clean part of the reference and modulated beams.
- A lens is focusing the two beams to overlap at its focal plane. An interference pattern is formed in the shape of vertical stripes.
- Camera having an objective lens if focused to the interference pattern.
- Analysis software analyzes the progression of the stripes (phase shift) as a function of GL.
- The result is a response curve of phase shift vs. GL.

After an initial response curve is formed the voltage level is corrected per GL to a new LUT. The new LUT is then tested by performing a phase scan. This process may need to be performed several times until a satisfactory LUT is generated and verified.

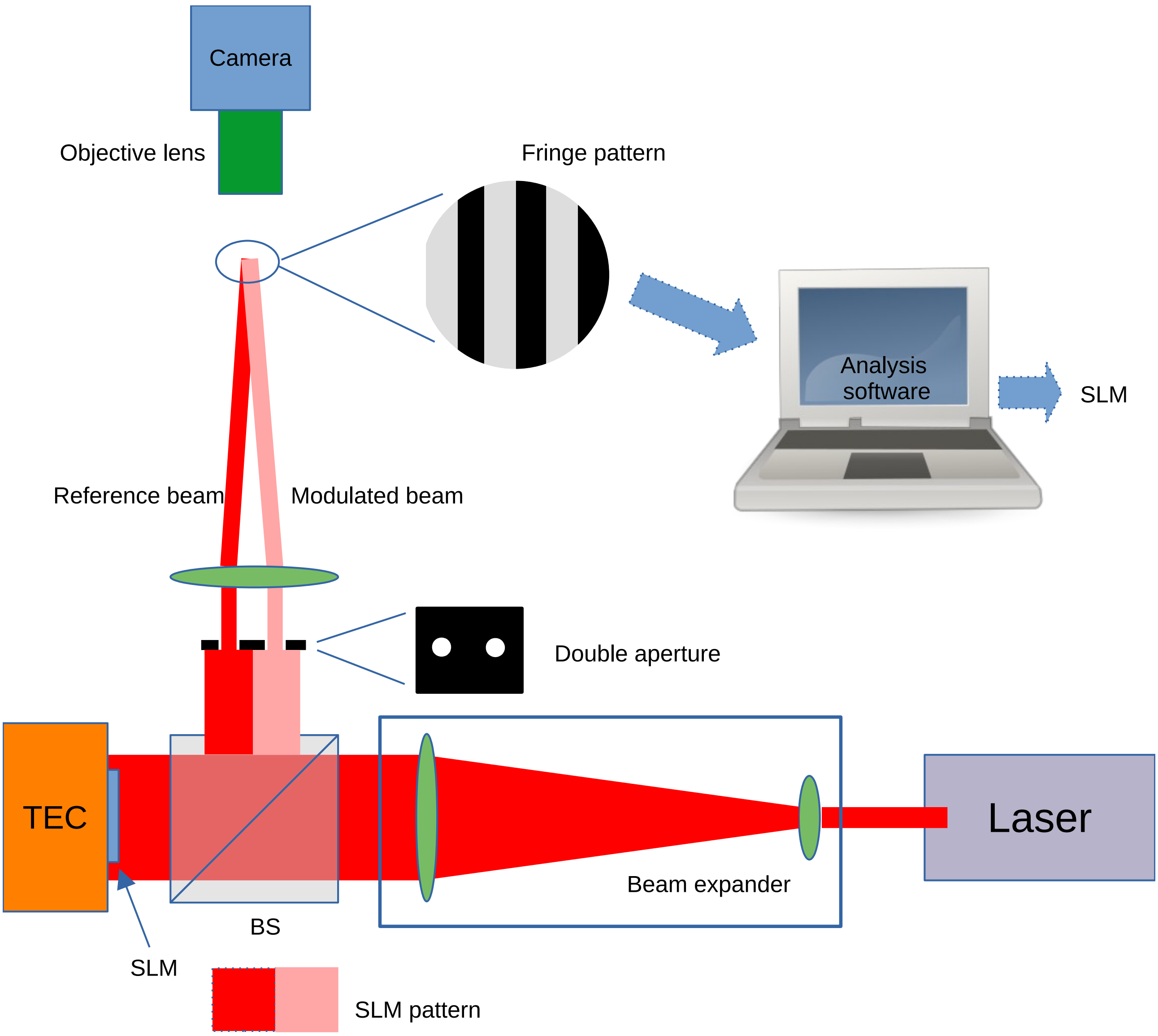


Figure 18: Phase linearization setup

5.2 System calibration

Mounting the SLM on the optical head is preceded by a calibration procedure which ensures that the optical elements and modules are aligned as designed.

The SLM calibration is part of the system calibration and as such the procedure is partly managed by the system computer and the results are stored in calibration files. The procedure requires that the system software updates the SLM at a rate of 60Hz which requires the DP interface to be operational. This requirement is currently not met, and as previously mentioned, no active chips are currently available. For this reason the calibration procedure will only be outlined in general.

5.2.1 Calibration goals

Viewing a hologram through the system with both eyes in an effortless and natural manner with no fatigue requires that both eye channels are properly aligned to each other, and that the hologram is projected to all depths correctly and all with the adequate vergence. It also requires correct 3D geometrical fidelity and integrity. SLM calibration is an important part of achieving the above especially regarding hologram position in space.

5.2.2 Calibration procedure

Calibration procedure is basically divided to two main categories:

- *Physical alignment*: manipulating the SLM angular position.
- *Phase manipulation*: training the software to apply phase correction at various operation states and cases for the purpose of fine 3D geometrical corrections and wavefront compensation to mitigate some optical aberrations within the system.

Every calibration needs a reference. Both eye channels and projected holograms must be co-located in space at the designed effective “hologram volume” which is a physical (mechanical) reference points/plains relative to the optical head. A mechanical jig is used to define these points/plains and allows for various target mounting according to the calibration task. The mechanical jig is mounted on the optical head at the beginning of the calibration process and is kept in place throughout the procedure. In addition to the mechanical jig, various camera setups are used to “view” the hologram and supply feedback to the calibration process. The camera is mounted at the nominal eye position.

Calibration procedure is as follow:

1. SLM tilt alignment: adjusting the SLM reflection orientation.
2. Depth calibration: Adjusting the phase so the hologram is projected to the correct depth.
3. Roll alignment: Adjusting the hologram roll angle.
4. 3D geometrical alignment: lateral and depths alignment of the holograms.

Chapter 6 Evaluation plan

6.1 background

The HOLOSCOPE-i True-Holography system is a medical volumetric holography display system capable of providing real-time video rate interference-based 3D/4D holograms within hands reach, while allowing for a wide range of interactions with and within the hologram as illustrated in Figure 19.

Figure 19: HOLOSCOPE-i usage illustration.

Optical head unit is hovering above the physician (boom-mounted), which has the ability to view the hologram through the transparent HUD eyepieces or push it up when not using the system. A patient is lying below and the physician is manipulating the catheter (Figure 20). The HOLOSCOPE-i system receives volumetric stream of medical information in real-time intra-operatively and presents true volumetric holograms of the treated area during the actual procedure while the holograms are above the patient and in front of the treating physician. In addition, the system is able to receive voice commands and/or hand interactions as appropriate in the context of the procedure (Figure 21).

Applicability of the system requires a wide range of conditions to be met which includes, among others: Usable image quality, Ergonomic considerations, Application software, System build etc. MEMS-SLM system integration needed to be such that it does not interfere with the ability to freely view and interact with the holograms, and provide good image quality. Integration result as presented in Figure 22 accomplishes the system-level mechanical implementation of the entire MEMS-SLM device, mechanics and related driving electronics integrated on the HOLOSCOPE-I holographic system. Image quality has not been demonstrated to date.

Figure 20: HOLOSCOPE-i operation environment and demonstration. Taken from an actual procedure.

Figure 21: Hologram interaction in actual procedure

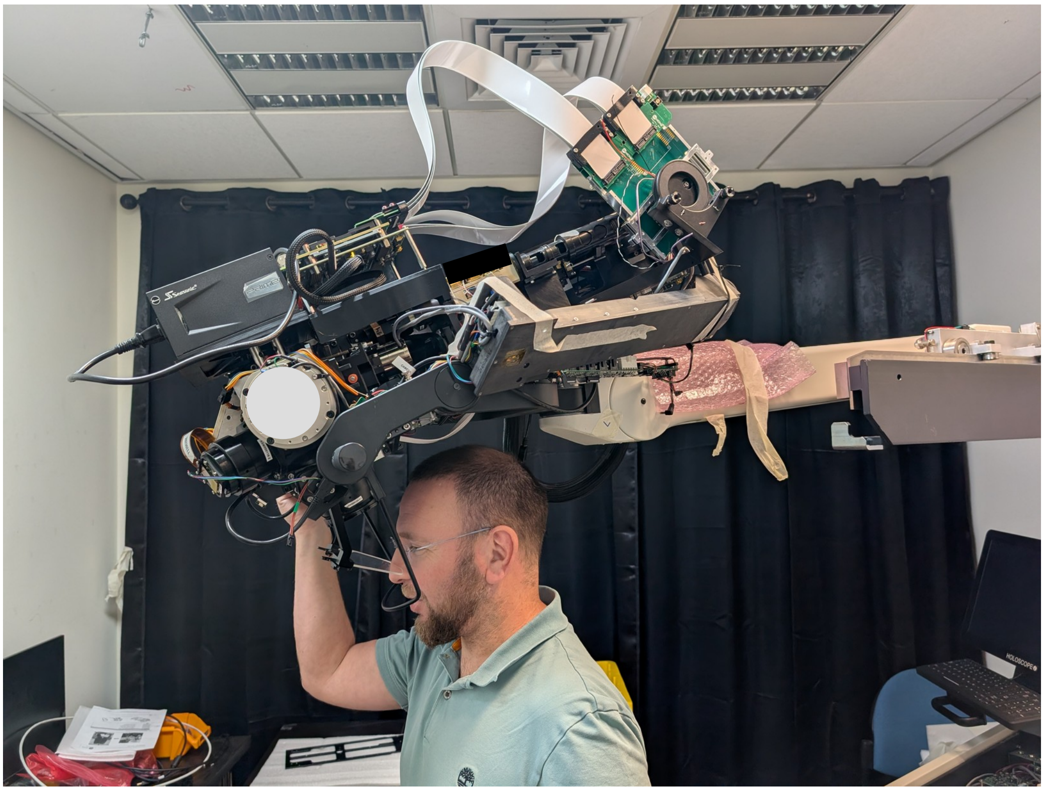


Figure 22: MEMS-SLM integrated on HOLOSCOPE-i system. User is able to view with no obstructions.

6.2 Evaluation plan

User experience is in general subjective and can have both physical and psychological drivers. Keeping that in mind, evaluation will be divided into subjective impression and objective tests.

Objective tests are required for referencing. Comparison between technologies require objective metrics. Since comparison of MEMS-SLM with LC SLM is desired, two basic tests that target the main expected performance gains derived from the technological differences between devices shall be performed: luminance ratio (background noise) and ghost images analysis. This is planed to be performed using a camera directed at the hologram and analysis software.

Eventually the system is intended for humans, and the subjective experience of a user is the end point of the system. It integrates all the variables influencing the visual usability of the system which are not always quantifiable. For that reason a subjective evaluation based on professional and non professional viewers is planed.

Chapter 7 Objective image quality evaluation

7.1 Methodology

Image quality is influenced by multiple factors such as background level, noise, color representation and other visual cues. Some of the metrics used to quantify image quality such as Point Spread Function (PSF) and Modulation Transfer Function (MTF) overlap, and the metric to be measured is chosen based on context, ease of measurability and other factors. Different metrics often target different dominant parameters according to the use case, for example an optical system targeting the human visual system will emphasize different parameters than one intended for camera detection. In this project it is of interest to compare current LC SLM to the developed MEMS-SLM and for that purpose two metrics have been chosen: luminance ratio (background noise) and ghosts formation. These metrics have been selected since they directly target technology differences between LC SLM and MEMS-SLM. Other image quality parameters such as resolution are not good candidates for comparison since the optical system is not optimized for the MEMS-SLM.

7.2 Luminance ratio – background noise

In what follows photometric rather than radiometric units will be used to quantify light, and specifically luminance. Luminance is a measure of light power in lumen per unit area per solid angle (NIT or cd/m^2). This unit is more relevant when addressing the human visual system than the radiometric unit $W/m^2/str$ and is commonly used in this context.

Background noise will be defined as the average luminance at dark image areas, meaning areas that would have zero luminance in an ideal system.

Background noise is a limiting factor of contrast. The main drivers of background noise in the system are:

- Scattered light from optical interfaces.
- Hologram calculation artifacts.
- SLM scattering: in LC based SLMs scattering occurs from liquid crystal molecules, as opposed to MEMS-SLM where it might be generated by micro mirror edges.
- SLM modulation fluctuations, which are the result of pulse code modulation (relevant to LC SLMs) or micro mirrors vibration for MEMS-SLM.

Luminance ratio (r') is defined as the ratio between maximal (L'_{max}) and minimal (L'_{min}) luminance [2]:

$$r' = L'_{max} / L'_{min}$$
$$L'_{max} = L_{max} + L_{amb}$$
$$L'_{min} = L_{min} + L_{amb}$$

Subscript 'amb' stands for ambient and L_{amb} is ambient luminance.

Since in a mixed reality system the background includes ambient light which passes through the eyepieces (HUD transparent optics) by background objects, it is helpful to simplify the measurement conditions to total darkness, discard the ambient term and reduce the parameters to:

- L'_{min} – average luminance at dark areas of the image where no light is expected (Gray Level 0).
- L'_{max} – average luminance at a maximal brightest area (Gray Level 255).

This approach focuses on the performance of light modulation with minimal confounding factors.

The luminance ratio is a measure of low spatial frequency contrast and its inverse in the reduced form is a measure of relative background noise.

7.2.1 Measurement procedure

1. Camera is assembled at the eye pupil location directed at the hologram. A physical target is placed at a selected distance and camera is focused to the target. The camera in conjugation with the measurement software is calibrated to measure luminance at the relevant wavelengths.
2. Target hologram is projected to the selected depth.
3. Hologram frame is captured individually per color.
4. Average luminance values at the signal (L'_{max}) and background (L'_{min}) zones are calculated per color.
5. Luminance ratio is calculated per color:

$$r'^{Red} = \frac{L'^{Red}_{max}}{L'^{Red}_{min}}$$

$$r'^{Green} = \frac{L'^{Green}_{max}}{L'^{Green}_{min}}$$

$$r'^{Blue} = \frac{L'^{Blue}_{max}}{L'^{Blue}_{min}}$$

7.3 Ghosts

Ghost images are undesired duplicates of the projected image. Ghost images of a hologram can be classified as follows:

- *Optical ghosts*: optical surfaces are usually AR coated which reduces the amount of light reflected back. Sometimes a situation is created where the position of one or more optical elements in the system is such that multiple reflections reach the viewer and the intensity is high enough to be noticeable. These ghost images usually manifest themselves as blurred duplicates of the original image and can be arbitrarily located within the viewable space.
- *Complex conjugate ghosts*: this type of ghost is unique to holography. Imperfections in hologram creation such as deviation from 2π modulation and non-linear phase response results in a duplicate image which is mirrored in all dimensions as illustrated in Figure 23
- *Color memory ghosts*: Projecting RGB images in field sequential mode where colors are projected using the same SLM in a serial manner (R→G→B→R→G…) may exhibit crosstalk between colors (Figure 23). Information decoded in one color may persist to the

next color frame due to hysteresis or other effects. It is common to observe memory effects in LC modulation.

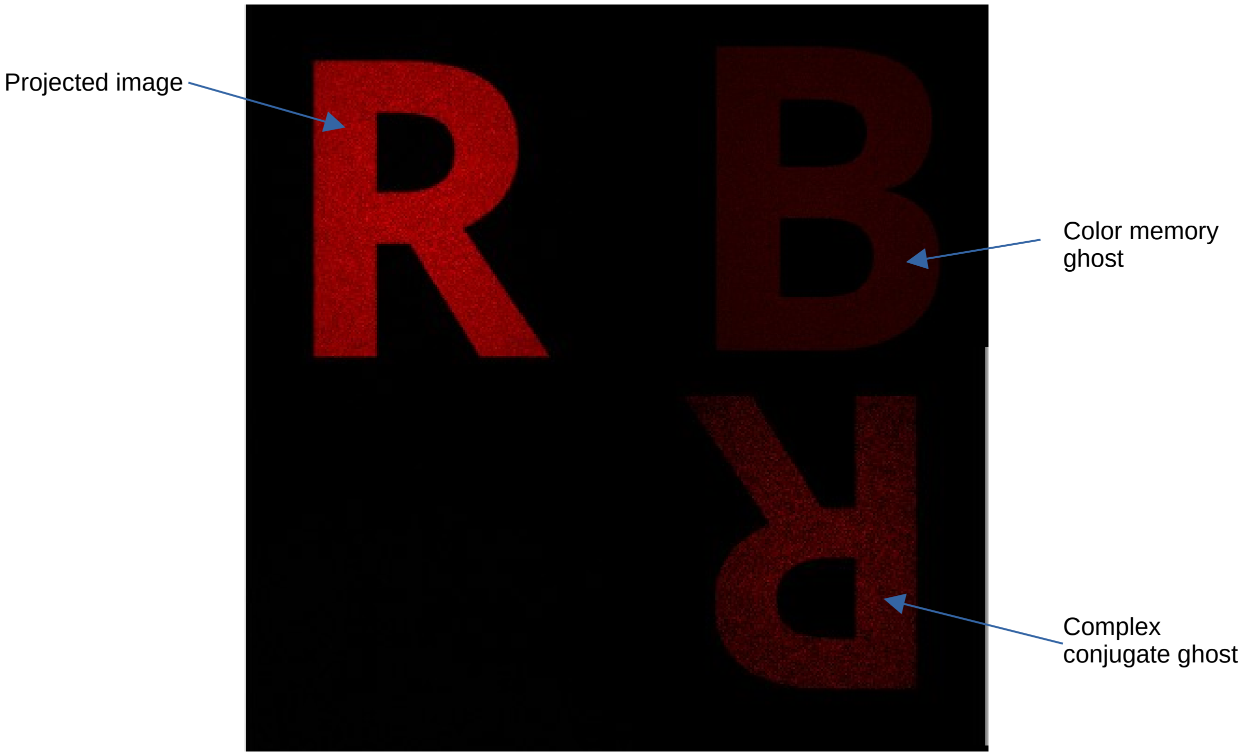


Figure 23: Ghost types illustration

7.3.1 Ghost measurement

Ghost measurement is performed by projecting an image as presented in Figure 24. The target is divided into four quadrants, three of them are occupied with images of the color letter (R, G, B) and one quadrant is empty. In the presented target the complex conjugate ghost of the red will manifest in the empty quadrant, and memory ghost images, each will appear in its place out of intended color time slot. A dedicated software algorithm searches each quadrant in context for the ghost image and measures the average light power of the ghost relative to the principle image average light power.

The metric to be used for ghost intensity (r_G) is the ratio between average ghost luminance (L_G) and average image luminance (L_I): $r_G = \langle L_G \rangle / \langle L_I \rangle$. For a measurement value to be significant, it should rise above the background noise level (n_B) which is the ratio between average background luminance (L_B) and average image luminance (L_I): $n_B = \langle L_B \rangle / \langle L_I \rangle$

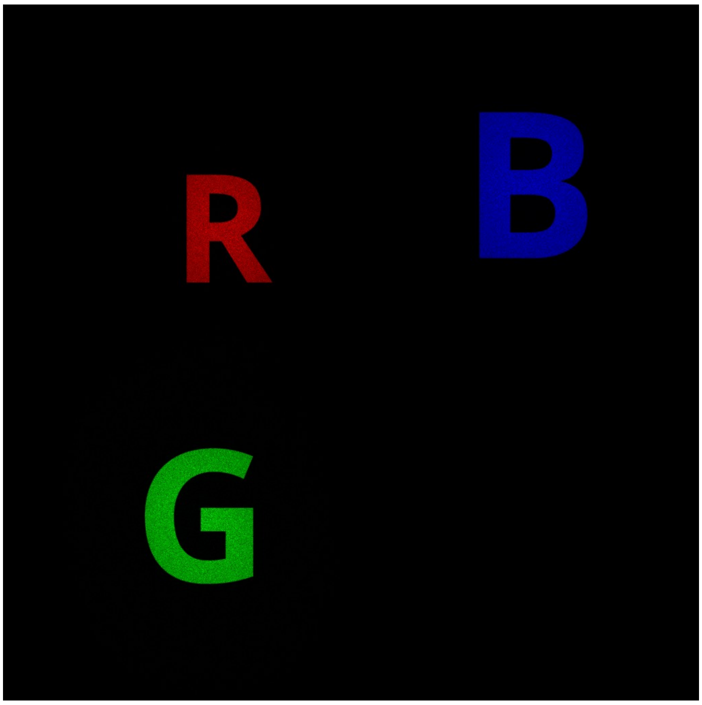


Figure 24: Ghost measurement projected target

Chapter 8 Subjective evaluation

8.1 Methodology

8.1.1 Background

The HOLOSCOPE-i system is intended for medical professional personnel and as such it is judged by its ability to deliver its intended use and added value for clinical applications. As such the subjective experience of a physician may be totally different than the experience of a layperson in this field of work, since a physician perspective is directed at the value for performing procedures, while a consumers point of reference are entertainment displays.

Quantifying a subjective experience is by its nature a challenging task and prone to a large variety of biases. In what follows there is an attempt to perform a modest subjective evaluation within the scope of the current project funding and timeline.

8.1.2 Evaluation goal

It is the goal of this evaluation to compare LC SLMs with MEMS-SLMs by comparing the subjective experience of viewing the hologram between two HOLOSCOPE-i systems, one using LC SLM and the other MEMS-SLM. This is both within the context of the intended use and audience of the system, and naive viewers. It is not within the scope of this evaluation to reach statistical significance, but to serve as an initial base for further future studies, and future MEMS-SLM development.

8.1.3 Evaluation plan

- *Participants*
- A minimum of 10 people of which 5 are experienced in viewing holographic content on the HOLOSCOPE-i and are familiar with 3D medical data. The other 5 are naive to viewing medical data and have little to no experience in using the HOLOSCOPE-i system.
- *Equipment*
- Two HOLOSCOPE-i systems will be situated side by side in the same room. One is a standard system with LC SLM and the other is a system fitted with MEMS-SLM.
- *Evaluation conditions*
- Room lighting conditions will be maintained the same for all participants at all times. Both systems will be facing the same background.
- *Projected holograms*
- List of projected objects will include: 1 static test cube, 4 Ultrasound (US) 3D video streams, 4 static 3D mesh objects and 1 static 3D CT object. A possible factor which might influence the results is viewing the same hologram on both systems. The “experience” of watching it first on one system and then on another may introduce bias. To try and control for that, the Ultrasoundand mesh holograms will be divided to 2 of each per system in a randomized fashion. For each participant the images will be reshuffled. CT and test cube will be present for both systems and serve as an anchor. The viewing order of holograms will be randomized as well, per system per participant.
- *Procedure*

  Each participant will start with a system selected by a coin flip. A hologram will be projected for 1 minute. In that period the participant will perform 2 basic hologram interactions:

hologram rotation and zooming in/out. At the end of the projection the participant will be asked to fill in a short questionnaire (Figure 25) summarizing the viewing experience. This will be repeated for all holograms on both systems. The entire procedure is expected to be completed in about 20 minutes.

Realholo MEMS-SLM subjective evaluation form

System: MEMS-SLM / LC-SLM

Clinical professional: YES / NO

Hologram #	perceived quality (1-5)	noise performance (1-5)	Contrast (1-5)	Clinical usability (1-5)	Notes

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System: MEMS-SLM / LC-SLM

Clinical professional: YES / NO

Hologram #	perceived quality (1-5)	noise performance (1-5)	Contrast (1-5)	Clinical usability (1-5)	Notes

Figure 25: Evaluation questionnaire

- *Analysis*
- Rigorous statistical analysis is not feasible due to the low number of participants. Data will be sliced per system according to the following:
  - Viewing experience parameter score averaging over all holograms (4 values per system).
  - Average score over all viewing experience parameters per hologram (6 values per system).
  - Total average over all holograms and viewing experience parameters (1 value per system).
- Based on the data slicing, a comparison between systems will be performed. In addition, comparison between professional and naive participants will be explored.

8.1.4 Confounding factors

In order to maximize the validity of the evaluation it is important to acknowledge confounding factors which may influence the outcome of the evaluation as follows:

- *Operational context* – HOLOSCOPE-i system is intended for medical professionals and in a cardiac catheterization lab setting. Evaluation is planned to be performed in a demonstration room setting (Cath-lab simulator/mockup) due to ethical and logistical limitations.
- *Calibration differences* – there may be some calibration quality differences between systems due to the fact that calibrating a system based on MEMS-SLM is new.
- *Number and pool of participants* – small number of participants with limited diversity are not a representative cohort, which may bias results.
- *HOLOSCOPE-i system not optimized for MEMS-SLM* – naturally a non optimized system will not exploit the MEMS-SLM device to its full potential.
- *Aesthetics* – as seen in Figure 22, MEMS-SLM system optical head is not as aesthetic as the original. This may induce a bias as looks has influence over subjective experience. In addition, the pronounced difference in appearance makes it impossible to blind the participant to which system is currently viewed.

Chapter 9 Conclusion and discussion

MEMS-SLM holds great potential to break current barriers in hologram quality while not compromising resolution and speed. This report presents the integration of the MEMS-SLM into the HOLOSCOPE-i system and the evaluation plan. Originally a full integration which includes optical calibrations and alignments of both eye channels was planned, but unexpected development issues, in spite of the tremendous effort by the consortium, caused delays in active chips supply and DP implementation. DP is required for full integration since it is the physical layer by which the system transmits phase images to the SLM in real time. This is essential for some calibration steps which generate phase corrections in response to feedback from a camera. Some calibrations might have been possible using the Ethernet interface, but this would require modifying the calibration application, an effort which is out of scope of this project.

From an application standpoint this report demonstrates that the MEMS-SLM can be successfully integrated to the HOLOSCOPE-i system for the purpose of viewing holograms in a similar way to the commercial system with minor compromises of image size. Dedicated optical and system design to take advantage of the unique characteristics of the MEMS-SLM can enable expansion of the medical applications range for such a system. Integrating the MEMS-SLM into an existing design was a decision made to keep within the project scope of work, funding and challenging timelines. Although the optical head seems cumbersome it shows that both eyes can be integrated and it does not affect the ability of the user to view the hologram comfortably.

Objective evaluation plan targeting the technological differences between MEMS-SLM and LC SLM has been presented and results for LC SLM performed (not disclosed in this report). Speculating, the results of the MEMS-SLM are expected be significantly better in both luminance ratio and ghosts formation for the following reasons:

1. No LC molecules to scatter light → less background noise.
2. Micro mirrors are stable which translate to less phase fluctuations → less background noise.
3. MMA design minimizes pixels crosstalk, which helps to preserve phase linearity → less complex conjugate ghosts.
4. Fast stabilization and low hysteresis reduce color memory effect for color field sequential projection → less color memory ghosts.

Subjective evaluation and comparison plans have not been executed. Although in principle the MEMS-SLM is expected to perform better than the LC SLM it is hard to predict the outcome due to the confounding variables discussed above and especially the fact that the HOLOSCOPE-i system is not optimized for the MEMS-SLM mainly in its optical design. Reduced image dimension might also have negative impact on viewing experience.

In the future, developing and building a dedicated HOLOSCOPE-i system for MEMS-SLM is expected to yield a system with significantly superior image quality. Performing a comparative study between two optimized systems, one based on MEMS-SLM and the other on LC SLM, is a desired milestone for establishing MEMS-SLM superiority over LC technology and boosting its further development towards a mature industrial device.

Chapter 10 List of Abbreviations

Abbreviation	Translation
FPGA	Field-Programmable Gate Array
PSU	Power Supply Unit
DP	Display Port
LC	Liquid Crystals
AR	Anti Reflection
LUT	Lookup Table
TEC	Thermo Electric Cooler
PSF	Point Spread Function
MTF	Modulation Transfer Function
US	Ultra Sound
CT	Coherent Tomography
CGH	Computer Generated Hologram
FFC	Flat Flexible Cable
HUD	Head Up Display
MEMS	Micro-Electromechanical Systems
MMA	Micromirror Array
SLM	Spatial Light Modulator
BS	Beam Splitter
RGB	Red Green Blue

Chapter 11 Bibliography

1: Holoeye, Application note SLM, , https://holoeye.com/products/spatial-light-modulators/leto-3-phase-only/

2: IEC-62563, Medical electrical equipment – Medical image display systems –, 2009