Glass versus Film Mirrors for Wide FOV Collimated Visual Displays

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ABSTRACT

The development and deployment of wide field-of-view collimated visual display systems for simulators poses many challenges. Optical performance is the primary factor used when evaluating the display solutions, but other factors such as size, weight, strength, adjustability, reliability and maintainability are also critical for providing an integrated, compliant and sustainable system. Mechanical and electrical compatibility with the simulator, motion system and facility must also be taken into account. The industry has offered two major technical approaches for fielding these systems: Segmented Glass-Mirrors and Vacuum-Drawn Continuous Film Mirrors. Each of these approaches has its own strengths and weaknesses along with unique integration issues.

This paper reports on the developmental progress of two similar U. S. Navy Operational Flight Trainers: one using a Segmented Glass-Mirror and the other using a Continuous Film Mirror. It discusses the strengths and weaknesses of each, relative to the optical performance factors and other evaluation criteria mentioned above. Further, the mechanical and electrical integration challenges encountered with both approaches will be reviewed. Both quantitative and qualitative assessments are offered using currently available information. The paper concludes with a discussion of lessons learned and suggested areas for research.

ABOUT THE AUTHORS

Marty Quire is a Lead Project Engineer at CAE USA in Tampa, Florida. He is currently leading the development and deployment of the Navy’s new MH-60R Tactical Operational Flight Trainers, which incorporate the visual display technologies discussed in this paper. He is a 33 year veteran of the simulation industry, specializing in graphical and video display systems for simulated cockpits, sensor simulations, instructor stations and visual systems. He received a Bachelor of Electrical Engineering degree from Georgia Tech in 1979.

Andrew Fernie is currently Manager, Visual Systems Engineering at CAE in Montreal. He is responsible for display engineering, system architecture, and product management for visual systems. Prior to that, he held a variety of positions at CAE involving display system design and other areas associated with flight and visual simulation. He received a Bachelor of Applied Science degree from Queen’s University in Kingston, Ontario in 1983.

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BACKGROUND

Fielding Wide Field-Of-View (WFOV) collimated Visual Display Systems (VDSs) for full-flight simulators is one of the more challenging aspects of simulation and training. Although optical performance is the primary factor used when evaluating the VDS, other factors are also important. In order to ensure a compliant and sustainable system is delivered, factors such as size, weight, strength, adjustability, reliability and maintainability must also be reviewed. The physical interface between the VDS and the simulator, motion system and facility from a mechanical and electrical standpoint must also be taken into account. These interfaces can vary greatly based on the VDS technology chosen.

This paper reports on the developmental progress of two similar U. S. Navy Operational Flight Trainers with respect to their VDS mirror technology and implementation. Due to various technical and programmatic factors, the MH-60R team selected a Segmented Glass-Mirror approach and the MH-60S team selected a Continuous Film Mirror. We discuss the strengths and weaknesses of both approaches, citing the optical performance as well as the other criteria mentioned above. In addition, the mechanical and electrical installation and integration issues encountered are reviewed. These additional factors are presented in order to illustrate the complexities that will be encountered when choosing a given technology.

Two Mirror Types

Two major technical approaches for the VDS collimator reflective display surface (i.e. mirror) have been offered by the industry. These are: 1) Segmented Glass Mirrors and 2) Vacuum-Drawn Continuous Film Mirrors. Each of these two technologies has its own pros and cons, strengths and weaknesses, along with its own unique set of integration issues. However, both approaches owe their origin to the invention of the wide angle collimated display.

The basic optical configuration of the wide-angle collimated display for flight simulation was presented in the 1977 report, “Wide-Angle, Multiviewer Infinity Display Design”, prepared by McDonnell Douglas Electronics Company (MDEC) (Rhinehart, 1977). As shown in Figure 1, it described a system with a large curved mirror, overhead curved rear projection screen, and multiple video projectors. While glass was not explicitly stated as being the technology envisioned for the production of the mirror, it was expected to “be made in sections for ease of manufacturing”, implying a rigid design.

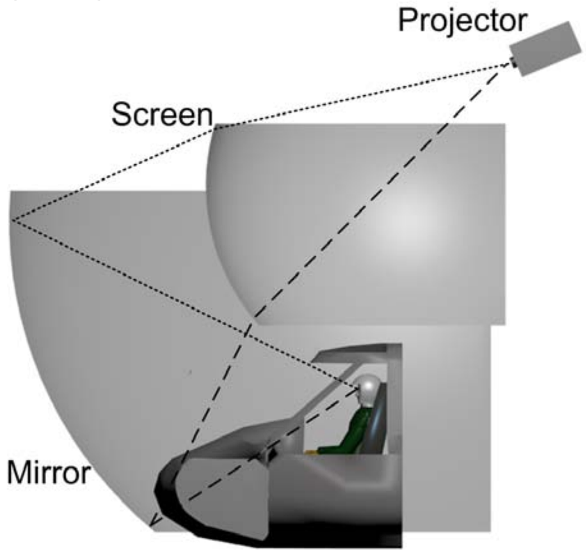


Figure 1. Wide Angle Collimated VDS

In practice, early displays using the approach described in MDEC’s report were based on the use of large glass mirrors, and acceptance of these wide FOV displays was initially limited due to the complexity of dealing with the glass. Production of the simpler and smaller FOV, Wide-Angle-Collimated (WAC) displays using a spherical mirror and beamsplitter to produce an image for a single pilot, continued and remained the standard approach, shared with the occasional use of direct-view domes primarily for military applications. The introduction of the wide film mirror caused an expansion of the use of the wide-angle collimated display.

Glass Mirror Training Device

The MH-60R Tactical Operation Flight Trainer (TOFT), device 2F195, serial number 8 (henceforth called Romeo 8), is currently being integrated and tested for use by the U.S. Navy training squadron at Naval Station Mayport, Florida. Romeo 8 will be used to train pilots in all aspects of flying and operating the MH-60R helicopter. Romeo 8 employs electric motion/vibration seats and is not mounted on a large full-motion base. Instead, the cockpit and instructor area (or "Hut") are mounted on a small baseframe which is anchored to the concrete floor of the training facility. This is often called a fixed-base device. Romeo 8 will be installed in a legacy "high-bay" building that previously hosted an SH-60B mission simulator with full hydraulic motion.

Romeo 8 requires a VDS capable of displaying a 200º horizontal by 60º vertical Field-Of-View (FOV) image. The designers have chosen to employ a Segmented Glass-Mirror for the VDS. See Figure 2.

Figure 2. Romeo 8 Glass-Mirror Segment Install

Glass Mirror Technology

The Glass Mirror technology currently employed is in many ways similar to traditional optical concave mirror production (e.g. for large reflecting telescopes). A large piece of high quality glass is draped over a spherical dome and baked in an oven to produce a "slumped" segment of glass that has a near spherical shape. This substrate is then carefully ground and polished on a specialized machine to a nearly perfect concave spherical surface. This surface is then aluminized to provide a reflective surface. A thin layer of quartz is then baked on to protect the reflective surface. Finally the back of the mirror receives layers of backing material where ultimately mounting provisions are attached. The large concave mirror would change shape, due to its own weight, however the mounting frame can be designed to compensate and hold the mirror in its optimum spherical shape.

There are practical limitations on how large a mirror segment can be. Already, the largest commercially available raw glass sheets are being used. So, for very large mirror applications, multiple segments can be mounted edge-to-edge to effectively form a much larger mirror. Suppliers have strived to push the state-of-the-art to a point where the segments are as large as possible, while still maintaining high optical performance from edge-to-edge. Innovations were introduced to increase strength, reduce weight and minimize the gap between segments. In addition, a reduction of production cost was needed to return glass mirrors to a viable position in simulation.

Film Mirror Training Device

The MH-60S Operation Flight Trainer (OFT), device 2F189 Update, serial number 1 (henceforth called Sierra 1), is currently being integrated and tested for use by the U.S. Navy training squadron at Naval Air Station North Island, California. Sierra 1 will be used to train pilots in all aspects of flying and operating the MH-60S helicopter. Sierra 1 is also a fixed-base device which employs electric motion/vibration seats. Sierra 1 is installed in a legacy building that previously hosted a very early version of this same trainer.

Sierra 1 also requires a VDS capable of displaying a 200º horizontal by 60º vertical Field-Of-View (FOV) image. The designers have chosen to employ a Vacuum-Drawn Continuous Film Mirror for the VDS. See Figure 3.

Film Mirror Technology

The introduction of the film mirror design by Rediffusion in the early 1980's was an elegant solution to the cost, weight, and handling issues of glass in the type of display described in the MDEC report, and resulted in the near universal adoption of this type of display for flight simulators for aircraft with side by side crew seat configurations.

The film mirror is formed by stretching a large sheet of thin, flexible, metalized material, typically polyester film (often referred to as Mylar™, a Dupont product), over a set of “retainer” supports to which the edges of the film are attached.

Figure 3. Sierra 1 Film-Mirror Install

The retainers are designed such that, to a first approximation, they follow the intersection of a sphere and a cone. The conical attribute allows the flat sheet of film to be “unrolled” onto the retainers, stretched to remove wrinkles, then attached. This process is often call “skinning” the mirror. A sealed chamber is formed behind the film and a partial vacuum is applied to the chamber. The resulting difference in air pressure between the chamber and the ambient environment forces the film back into the chamber. The film is constrained by the retainers (now viewed as defining the surface of a section of a sphere) at the edges, and stretches such that it forms an approximately spherical shape.

The elegance of the solution is apparent: the large pieces of glass, and the entire process of slumping, grinding, polishing and coating them to form mirrors, have been replaced by a sheet of film that is produced in large quantities, at low cost, for applications such as food packaging.

Anyone that has designed, purchased, or used a display system will be familiar with the tradeoffs that inevitably interject a healthy dose of reality on a promising design, and film mirrors are no exception. The issues that arise include both fabrication and performance. The core of the performance issue is the deviation from the desired spherical mirror shape. Some of the deviation may be smoothly distributed over the entire mirror surface, in which case, and assuming the shape is repeatable, its impact may be minimized through design and/or alignment. More problematic are the localized deviations that typically occur along the edges of the mirror. These deviations can result in rapid changes in system geometry for small changes in viewing position which cannot be corrected. The result observed by the pilots is that objects in the scene shrink and grow as they traverse the problematic areas, and as a function of natural movements of the head.

Localized distortions have been features of film mirror displays ever since their introduction, Initial attempts to resolving them involved both design strategies and assembly techniques. The brute force design approach is to make the mirror significantly larger than needed, and thus allow the problematic areas towards the edge to be masked. Given that the standard FOV of the initial systems was generally 150º or 180º (horizontal) by 40º (vertical), there was plenty of scope for allowing large masked areas. On a system by system basis, however, the greatest impacts on performance were a result of the techniques used to install the film on the retainers, with each company providing the systems making use of their own proprietary techniques. Even within a company, there were apparent variations in quality dependent on the person, or team, responsible for the assembly of a specific system. Depending on one’s perspective, the situation could be viewed as being dependent on either craftsmanship or “black art”.

The trend towards display systems with larger FOV has been driven by both a general recognition that 180º x 40º is insufficient to perform many helicopter and military fixed wing training tasks (Simons & Fernie, 2005) as well as civil regulatory requirements (e.g. FAA document AC120-63, Level D). In general, a larger FOV requires a physically larger display, and this makes it more difficult to provide an oversized mirror with large masked areas. The basic problem is the size of the available film. The material is produced for the packaging industry, with a maximum available width of about 12’. While it is technically feasible to produce in widths greater than 12’, suitable machinery does not exist and production for simulation is at best seen as an undesirable interruption to an established production line. The film is produced in rolls so there is no effective limit in length, but as a result of the mirror using a section of a sphere that is not centered along the equator, increasing either the horizontal or vertical FOV of the display requires additional film length and width. The unrolled flat pattern of typical film mirror is shown in Figure 4. Given that the width of the mirror is fixed, and that a larger active mirror area is needed for a larger FOV, the size of the masked area must be reduced. A smaller mask area implies that the mirror quality must be improved, if acceptable performance is to be achieved. This need for improved mirror quality over the past years has driven the industry to take a more scientific approach to the problem, starting with better analysis of the behavior of the film under the stresses produced by the partial vacuum.

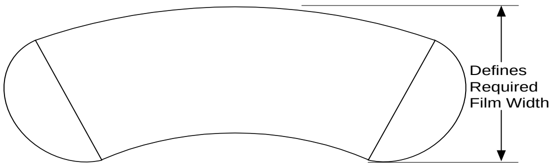


Figure 4. Typical Flat Film Mirror Pattern

The analysis shows that because the mirror is restrained along an axis parallel to the retainers towards the edges of the mirror, the film can stretch only in the orthogonal axis. As areas closer towards the center of the mirror are considered, they are less impacted by the edge effects and can stretch equally in both axes. This shows that there is a theoretical basis for at least part of the non-linear behavior of the mirror. Solutions involve the application of forces to the mirror in localized areas, and, more recently, system design processes that incorporate the actual (rather than ideal) shape of the mirror. The result has been a steady improvement of the performance of film mirror based display systems over the past few years.

Performance Metrics

The performance of the display system is determined by both the theoretical design, assuming "perfect" components, as well as by the finite tolerances that apply to each component. While both the glass and film mirror displays were designed to the same basic FOV standard, their optical designs (screen and mirror configurations relative to the design eye point) differ, and it is generally more difficult to control the shape of a film mirror than it is a glass mirror. Both of these issues directly impact the optical performance as determined by distortion, collimation, and dipvergence. Other performance metrics, such as resolution, brightness, and contrast, must be validated, but can generally be expected to be consistent with predictions from the design analysis and are less dependent on the differences in design between the two systems.

Image distortion in a display is the angular difference between the computed elevation and azimuth of a point in the scene and the position of that point measured by an instrument such as a theodolite. Starting from a nominal projector calibration, it is generally possible to introduce additional calibration terms so as to result in arbitrarily small image distortion from a single (normally center) eye point. The difficulties arise when the eye point is displaced from the center to the nominal pilot eye points, and then to a range of positions representing typical pilot head movements. The theoretical behavior of a typical system is shown in Figure 5, where the difference between the distorted grid and background grid is the distortion seen be the pilot in the right seat. The worst case combined horizontal and vertical error is approximately 2.5°, but this occurs in the low inboard area where it will normally be masked by cockpit structures. The worst case within the normal viewing error is limited to approximately 1.5°. Additional errors are introduced by component tolerances, with the result that the maximum allowable error from the pilot and copilot eye points (PEP and CPEP) is typically specified as a maximum of 3°.

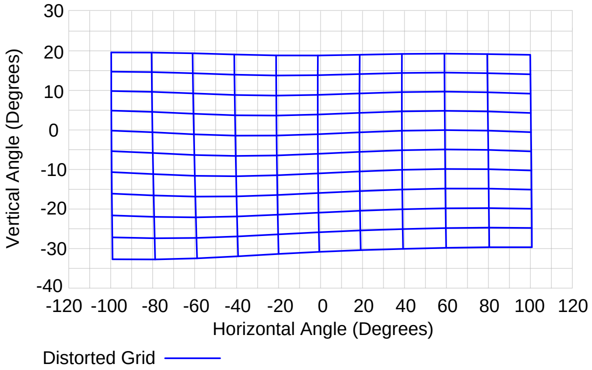


Figure 5. Typical System Distortion Example

Collimation refers to the degree to which light rays are parallel, which in turn determines the apparent distance to an image (parallel rays indicating a distant object), and defines the angle by which the eyes must be rotated along the horizontal plane to converge the image for the two eyes. Collimation is generally specified in diopters, representing the reciprocal of the distance to the image in meters. Given that objects exist in nature over a wide range of distances, humans have developed the ability to handle objects located anywhere from a few tens of centimeters distant to, effectively, infinity. Apart from ensuring that any negative collimation (implying that the eyes must be toed out) is controlled, specification of collimation in simulator displays is primarily a decision related to the image distance desired to represent a training situation, rather than a need to respect a limitation of the viewer's vision.

Typical collimation requirements for simulator displays are: not greater than 0.1 diopters (i.e. not closer than 10m), and not less than -0.05 diopters (i.e. not closer than -20m). Even from a theoretical point of view, there are significant variations in collimation across the FOV, so these figures are worst case, with much of the display exhibiting significantly greater performance. As system vertical FOVs have grown from the initial 40° to the newer, higher performance 60° designs, it has proved to be more challenging to meet the +0.1/-0.05 diopter requirements.

Dipvergence represents the difference in the vertical angles to which the eyes must be oriented to align the images from both eyes. Dipvergence does not occur in nature and humans have a limited ability to accommodate it. As the amount of dipvergence increases it can cause discomfort, and beyond a certain point it will be impossible for the viewer to fuse the images for the two eyes. A typical design limit for dipvergence in a simulator display is no greater than 7 milliradians. There is no effective difference between the left eye being oriented a given angle higher than the right eye and the right eye being oriented higher than the left, so it is the absolute value of the angle that is significant.

Common Design Considerations

Both VDS solutions described herein were designed to meet the current need for a 60º x 220º FOV for Navy helicopter training. However, in both cases the trainer specification only required a horizontal FOV of 200º. It should be noted that we have found that the 220º systems force the vertical wall further aft of the Design Eye Point (DEP) than the numerous 200º devices previously deployed. This can cause conflicts with preexisting instructor station / Hut designs and can move the instructor undesirably aft of the student stations.

To compensate, the designers may well consider modifying the Hut, Back Projection Screen (BPS), instructor station, or some combination of these. On the glass mirror trainer, Romeo 8, the 220º-capable BPS was cut back on its aft lower corners so as not to conflict with the existing Hut design. However, on the film mirror trainer, Sierra-1, we decided to cut back the front-upper corners of the Hut so as not to conflict with the 220º-capable BPS. In both cases, the customer was advised that the VDS would meet the 200º requirement, but not necessarily the desirable (but not required) 220º width.

GLASS-MIRROR DISCUSSION

Design

In order to achieve the required FOV the Supplier proposed its current 220º x 60º glass mirror solution. It uses 5 segments each supplying approximately 44º degrees horizontally and 60º vertically. Each of the mirror segments is held in its own large metal frame which rests on the facility floor. The frame holds the mirror by its back using multiple adjustable pressure pads that have been cemented to the back coating.

The 5 frames are bolted to the floor and to each other in a ring configuration. Each of the 5 mirror/frame assemblies weighs approximately 600 pounds making the whole glass mirror and support frame weigh about 3000 pounds, not including any cover panels. This comparably high weight and mass is not of much concern for the fixed based trainers, but it must be carefully considered for motion-based trainers. Our preliminary analysis indicates that it is feasible that current hydraulic and electric motion bases can handle the increased load. However, a detailed analysis should be performed during the proposal phase of each project. The additional load in the nose may cause additional or asymmetrical stress on the motion system and base frame. The Return-To-Home (RTH) abort sequence is of particular concern, since the extra weight will no doubt move the Center of Gravity (CG) toward the nose. In a hydraulic motion system, the RTH is accomplished passively by gravity only. In an electric motion system, the RTH is accomplished actively under limited battery-only power. For both cases, early testing with a dummy load may be warranted. The Romeo 8 glass mirror Supplier is currently fielding a similar segmented glass mirror solution on an electric motion base on an S-76D simulator for West Palm Beach, Florida.

In order to meet the Romeo 8 program resolution requirement of 5.5 arc-minutes/OLP in the central area and 6.5 arc-min/OLP towards the corners, five QXGA (2048x1536) format projectors are provided and are oriented in portrait mode.

Fabrication

The projector deck, its support structure and access stairs were custom designed for this application and provide easy access to the projectors, mechanical edge blend mechanisms and interface electronics. A front vertical wall and mirror cover panels are also fabricated.

The mirrors are produced by the Supplier and its optical coating subcontractors. They are mounted to their individual support frames and then tested and tuned using the adjustable mounting pads. Once the mirrors are tuned and tested, the mirror/frame assemblies are packed in individual crates for shipping to the installation site. Mirror floor mount segments are also fabricated. These form the ring upon which the mirror support frames rest.

Installation

Once all the components are received and unpacked, installation begins. First the floor is carefully surveyed and marked for the DEP. The projector deck and support frame are erected over the planned location of the cockpit and instructor Hut and then bolted to the floor. The vertical wall is mounted to the structure and the BPS is mounted to the vertical wall. The stairs are added and the projectors, blend mechanisms and interface electronics are then installed.

The 5 mirror assemblies are then lifted into place one by one forming a ring on the floor below the BPS. For the 11-foot radius glass mirror, the floor mount ring is approximately 8-foot in radius. Although the whole glass mirror is quite heavy, since it is handled in 5 segments, it is in some ways easier to install than a whole film mirror would be. The segments are bolted to the floor using threaded anchors and the segments are bolted together as well, forming a rigid assembly. During this process, a theodolite and other laser sighting tools are used to ensure all components are aligned properly relative to the design center, DEP and centerline. If the floor is uneven or has holes or deckplate (as is often the case with legacy training buildings) shims and other adaptations may be required.

Mechanical adjusters built into the frame allow each mirror to be moved into its final position. The adjusters are carefully tightened and loosened to bring each of the 5 mirrors together, edge-to-edge. A small gap or seam of approximately .06 inches is left between the mirror segments to allow for thermal expansion (Knaplund, 2012). Although this is a small gap/seam, it is immediately apparent when viewing the mirror or a visual scene from the cockpit. Projector and Image Generator test patterns are used to aid the installer in aligning the mirrors to minimize adjacent segment alignment errors. Care must be taken to ensure the mirror edges do not come into contact as mirror damage may occur. During Romeo 8 initial installation, this did occur, causing a small chip of mirror to be dislodged. Fortunately the chip was on a bottom corner and should not fall within the students FOV.

After mirror alignment is completed, the outer cover panels and overhead panels can be attached. These, along with the vertical wall, create a basic light-tight enclosure for the mirrors, BPS and projectors.

Integration

The cockpit and Hut are mounted on a small baseframe that has rollers to allow easy placement on the facility floor. However, in each installation, space is usually at a premium, with equipment and raised flooring usually preventing free movement. Therefore for the installation sites we have attempted to plan ahead and provide no less than 6-feet of unoccupied space behind each cockpit/Hut assembly. This allows the cockpit/Hut to be rolled back, to allow clear access to the completed 5-segment mirror. A theodolite is set up in the center of the mirror, the tripod resting about 2-feet in front of the cockpit nose. This allows final tuning of the mirror segments and a chance for data gathering of the VDS performance metrics without interference from the cockpit and windscreens.

The glass mirror system requires no electrical power and the mechanical interface to the facility consists of bolting the assemblies to the concrete floor as previously described. The IG interfaces to the projector system via dual-link DVI and fiber-optic extenders.
Notably, the projectors and IG are virtually identical for both the Romeo 8 and Sierra 1 programs. This allows the integrated testing to be very similar on both devices.

Performance

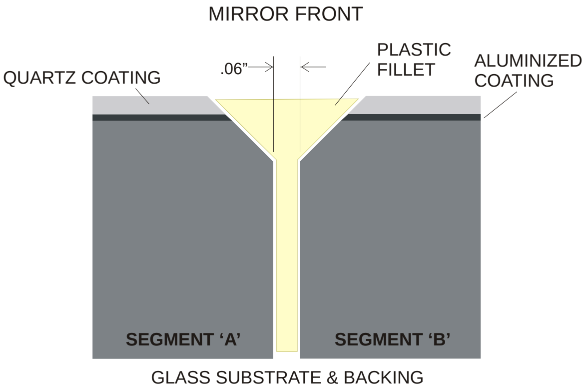
CAE’s standard test methodologies and procedures have been developed over the last several years in collaboration with visual engineers from NAWC-TSD Orlando. We are in the process of collaborating with these VDS subcontractors to reuse these methods and procedures to the extent possible. Both subcontractors have been extremely cooperative and we have been able to collect preliminary performance data for the two systems.

Preliminary measurements on the Romeo 8 system indicate that the distortion is low, having been measured at less than 0.5° from the DEP, and less than 2° from the PEP throughout the FOV. Note that the data for this system was collected with the VDS installed on the trainer, with cockpit installed, and so only those points not occluded by cockpit structure are included. It is likely that larger errors would have been measured in the low/inboard area if the cockpit had not been present, but this is not typically an issue for deliverable systems.

Collimation was very good, ranging from +0.044 diopters (convergent) to -0.051 diopters (divergent) across the FOV when measured from both the PEP and CPEP. Dipvergence was also good, ranging from approximately +5 to -7 milliradians across the FOV when measured from both the PEP and CPEP.

The overall performance is especially attractive when one realizes that it is essentially consistent from edge-to-edge for each mirror segment. Further, the performance of the 5 segments delivered for Romeo 8 appears to be consistent from segment to segment. The gaps/seams appear to be the primary detractors from the overall performance. The gaps/seams, although very small, are still quite noticeable (especially to those used to a continuous FOV). Customers should be aware that current glass mirror technology will present seams. Many VDS specifications require a continuous FOV and the segmented approach does not meet a literal interpretation of that requirement.

During the design phase of the Romeo 8 program, we suggested that the glass mirror Supplier investigate ways to reduce the detraction of the black gap between mirror segments using some sort of filling material. The Supplier researched available materials and their appearance under various lighting conditions. Currently, the best results have been obtained with a gray colored plastic extruded fillet material. Although the material only reflects the general lighting conditions, it does reduce the black gap effect somewhat and has the added benefit of providing a protective layer between adjacent mirror segments. See Figure 6 for a diagram illustrating a typical gap between glass mirror segments.



Information & concept, courtesy FSI, 2011

Figure 6. Typical Glass-Mirror Gap (not to scale)

Of the few pilots we have surveyed who have flown simulators with these segmented glass mirrors, the consensus appears to be that they forget about the gap after a few minutes of flying.

Maintenance

Although the glass mirrors are rather robust, they are not indestructible. As previously mentioned, during Romeo 8 installation one of the mirrors experienced a small chip in the lower corner by contacting the adjacent mirror. On Romeo 9, all 5 mirror segments suffered water damage during shipping from the Supplier. It was not the water itself, but rather some wet packing material rubbing on the protective coating that caused the damage. Recoating the mirrors can take a few weeks to accomplish, but this is much better than having to replace the mirror. If a segment of the mirror is damaged, that single segment can be moved out and back in without changing the other segments.

There appears to be no need for periodic adjustments, except perhaps in the projectors, however the use of digital projectors has minimized that as well. There is good access to the mirror cell via maintenance doors in the vertical wall, but no frequent need identified. Since there is no vacuum pump or controller, there is no maintenance or failures possible in that area.

The mirrors can be cleaned; but again, there is no real need for frequent cleaning unless there is an abnormal amount of dust being circulated through the facility. A particular type of dust mop can be used, after a significant amount of dust collects. In the unlikely event that some foreign material is spilled on the glass, it can be cleaned by using standard optics cleaning methods.

FILM MIRROR DISCUSSION

Design

Sierra 1 uses a new design film mirror display optimized by its Supplier for the +20° (up) to -40° (down) vertical FOV distribution, typically required for helicopter flight simulators. While this program requires only a 200° horizontal FOV, and the projector layout and mirror masking have been configured accordingly, the display design can potentially support up to 220° for future applications. The Sierra 1 program resolution requirements are 6 arc-minutes/OLP in the central area and 7 arc-min/OLP towards the corners. The same quantity, model and orientation of QXGA projectors are being used on both devices.

Fabrication

The projector deck, support structure and access ladder design for Sierra 1 was based on previous configurations provided by this Supplier. However, previous designs all featured a 10-foot mirror; so the overall size of this VDS is larger, to accommodate the required 11-foot radius 220º mirror. Again, in this design the projector deck and ladder provides easy access to the projectors, optical blend plate mechanisms and interface electronics.

In the case of the film mirror VDS, the mirror cover bowl forms an integral part of the mirror support structure. Unlike the glass mirror design, there is no metal mirror support frame present. The bowl also provides a vacuum cell for drawing the film into the mirror shape. The raw film is paid out from a roll and carefully inspected for flaws and defects. The selected film is then manually stretched across the retaining frame and attached using various types of tapes and fasteners. The exact process and method of adjusting the film is usually considered intellectual property by the Supplier. In particular, ways of compensating for distortion on the edges and near the corners is of particular interest, but carefully protected. Once the film has been pulled into place, the vacuum pump system can be activated to draw the film into the mirror shape and preliminary mirror performance testing can begin. The top cover panels (or petals) and the vertical wall will be used to close out the light-tight chamber.

Installation

The projector deck and support frame are erected over the cockpit and instructor Hut and the vertical wall is mated to the structure, with the BPS mounted to the vertical wall. The ladder is added and the projectors, optical blend plates and interface electronics are also installed. Again, a theodolite is used to mark the floor to aid in mechanically positioning all components. It is important for the deck, mirror bowl, cockpit, etc to all be aligned on the centerline.

In this design, uneven flooring can be compensated for conveniently using large adjustable "feet", strategically located at the bottom of all VDS elements. At each foot, one or more brackets are used to bolt the section to the floor, but the brackets use slotted holes to allow for adjustment. Once the feet have been adjusted, the bracket bolts are tightened to ensure everything is secured to the floor. If leveling the VDS causes an overall increase in height, then the cockpit baseframe will have to be leveled-up to match. This can be accomplished using shims or off-the-shelf leveling blocks. For sites with limited space, the film mirror system may pose additional challenges. If the film mirror is damaged it will be very difficult to re-skin it in a small room.

Integration

The film mirror system requires reliable electrical power to ensure that vacuum pump and controller run continuously and reliably. The vacuum pump controller monitors and controls the depth of draw using a sensor and control valve. In some installations the user requests that the pump system be supported by an Uninterruptable Power Supply (UPS), however if the UPS removes power during an Emergency Power Off (EPO), then the pump would lose power.

There is still some debate in the industry as to whether multiple relaxation-drawing of the film mirror reduces its life. However, recent data we have collected indicates the film mirror geometry may change slightly after each of the first few cycles. In fact, we recommend that the film mirror is cycled a few times prior to gathering geometry data.

Performance

Given that this is a new display configuration for the selected Supplier, validation checks were performed during the design phase on test mirrors and screen segments with various shapes. The test data supported optimization of the design, and only once the measured performance demonstrated that the system would meet the program requirements was the design finalized. Given the cost and time required to produce some of the tooling, this approach helped to manage risks for both the program and the Supplier.

The preliminary performance of the Sierra 1 film mirror VDS was measured in the factory acceptance tests at the Supplier's facilities, and it is the results from these tests that are presented in the following sections. The tests were performed without any cockpit being present, which allowed the evaluation of areas of the FOV that will not be visible once the cockpit is installed. This provides useful information as to how closely the performance of the as-designed system matches that of the as-built system. Integrated tests with the Image Generator (IG) will be conducted once the display has been installed on the simulator.

Gross geometry distortion behavior was typical of this type of display, reaching a maximum of approximately 1° from the DEP. Distortion reached greater than 3.5 degrees across the full set of measured data from the PEP. However, this was measured without a cockpit in place, and the greatest deviations were located primarily in the lower inboard (cross cockpit) area as expected from the theoretical behavior of this type of system. Once the errors in the area that will be masked by the cockpit are excluded, the maximum deviation was approximately 2°. Localized visible errors were in the upper corners of the display, and are a function of limitations in the mirror shape rather than of the theoretical optical design. This is typically a problematic region in film mirror displays. With the exception of the corners, the behavior along the top edge of the FOV near the mirror edge was generally good.

Preliminary collimation tests showed a range of ±0.05 diopters, with the areas showing negative values located low inboard, where they are masked by cockpit structures. The VDS generally showed dipvergence of less than 4 milliradians with worst case performance in limited areas of 6 milliradians. Both the collimation and dipvergence values for the VDS appeared to be generally good for a 60° vertical configuration.

Maintenance

Given that the Sierra 1 display is similar in concept to that of earlier film mirror based displays, it is expected that any maintenance related issues will also be similar. The principle maintenance task for the overall display will be related to the alignment of the projectors, and is independent of the mirror technology. Maintenance of the mirror itself is limited to keeping it clean, and protected from wayward falling objects. The mirror is somewhat fragile, and this must be considered over the lifetime of the system.

A secondary task is to ensure that the vacuum pump is reliably doing its job, which is to maintain the pull on the film mirror. A feedback system monitors the pull of the mirror and controls the amount of vacuum applied. A failure of this system makes the film mirror unusable and could possibly cause permanent damage to the mirror.

It is inevitable that some amount of dust will collect on the mirror. Removing the dust is at best a delicate operation, with the potential of making the situation worse if the contamination is smeared across the mirror. Generally, gentle air pressure to blow off the dust is the safest approach. Any operation around the mirror risks the possibility of destroying it if any tool, or other object, is dropped on the mirror. The cost of the material for a new mirror skin is not high, but both the amount of labor required to perform the replacement, as well as the disruption to training until the work is done, mean that the mirror must be protected. Cleaning should therefore be avoided, unless absolutely necessary. If there is a downtime period scheduled for major work on the simulator for any reason (e.g. an update), it is worthwhile to inspect the mirror when the work is planned, to decide whether or not cleaning or replacement is required.

GLASS AND FILM COMPARISON

The good news is that both of these technologies can be used to provide an excellent VDS for a wide range of applications. However, as previously discussed, there are a number of pros and cons with these technologies that should be considered when designing the VDS for a given training device. Please see Table 1 for a high-level summary.

Table 1. Mirror Technology Pros and Cons

Segmented Glass Mirror – Romeo 8		Continuous Film Mirror – Sierra 1	
+	Good optical geometry from edge to edge	-	Geometry errors increase at edges
+	Mirror surface resistant to damage	-	Mirror surface delicate & easily damaged
+	Requires no moving parts or electronics	-	Requires vacuum pump & electronic controller
+	Additional segments added would increase HFOV	-	No increased HFOV design path clear
+	Mirrors can be cut away for custom fits	-	No similar capability exists for film mirrors
-	Mirror segments & support structures are massive	+	Mirror & support structure is comparably lightweight
-	Mirror has noticeable gaps at segment boundaries	+	Mirror FOV is continuous, no segment boundaries
-	Mirror fabrication & major repairs are long-lead	+	Skinning a film mirror takes 1-2 weeks
-	Very few systems fielded on full-motion	+	Multiple film mirror units fielded on full-motion
-	Floor mirror interface 8’ radius & requires shims	+	Floor mirror interface 6.5’ & built-in adjustment feet

Glass Mirror Advantages

Both technologies can produce compliant geometry; however the glass mirror appears to provide slightly improved performance, especially near the upper and lower edges. The glass mirror is very resistant to damage, that is, minor scratches can be buffed out and the mirror surface can be periodically cleaned if desired. Conversely, contact with film mirrors should be avoided. The glass mirror requires no moving parts or electronics; whereas the film mirror requires the constant service of an electric vacuum pump with an electronic controller and may complicate EPO provisions. The glass mirror horizontal FOV can be increased by adding more mirror segments. It is unclear whether compliant film mirrors can be produced reliably at horizontal FOVs much larger than 220º. Further, glass mirrors can be cut away to allow for custom fits with obstructions such as instructor Huts, or other display elements such as chin-window screens. There is no similar capability for film mirrors.

Film Mirror Advantages

The film mirror and its support structure are relatively lightweight when compared to the massive glass mirrors and their required support structures. The film mirror provides a continuous wide FOV, while the glass mirror remains segmented with obvious gaps between mirror segments. Skinning a film mirror generally takes 1 to 2 weeks. For glass mirrors, fabrication generally takes months and major repairs can take several weeks. Multiple successful film mirror installations on both hydraulic and electric full motion systems have been fielded for many years. Conversely, very few glass mirror systems have been fielded on full motion systems. The floor interface ring for the film mirror bowl is approximately 6.5’ in radius and features adjustable feet throughout, to compensate for uneven flooring. By contrast, the glass mirror floor interface ring designed for Romeo 8 is approximately 8’ in radius and provides no adjustability for uneven flooring (i.e. metal shims must be used). This is a minor point, but could be very important if dealing with a legacy building with uneven or limited flat floor space.

LESSONS LEARNED

At any installation site there can be irregularities in the floor where the training device is intended to be installed. The designers should attack the problem from both sides, i.e. provide the truest section of floor possible and design into the mounting structures suitable adjustment provisions, especially for height. Similar adjustment provisions need to be made for the cockpit section in order to match the VDS.

For these training devices, the designers incorporated marking plates showing the location of the DEP (waterline, station and butt-line). These plates are securely fastened to the exterior of the cockpit to allow simple and confident alignment of the cockpit and the VDS DEPs. This was particularly useful since these cockpit/Hut assemblies can actually be rolled in and out of their home position during installation and test.

There is always a certain element of risk or concern when shipping optical components. The Supplier of the glass mirrors has totally redesigned their packaging process to minimize the possibility of future water damage. In a similar vein, the Suppliers of film mirrors have shown that, with care, an 11-foot radius, fully-skinned film mirror assembly can be shipped to a distant site and installed without having to re-skin. However, re-skinning on site is the typical approach.

AREAS FOR RESEARCH

The slight improvement in the appearance of the glass mirror gaps due to the fillet being inserted, leaves one to wonder whether a special reflective coating on the front of the fillet might make the gap “invisible”.

Since the mass of the glass mirror seems to be its main disadvantage, perhaps further research into the effect of the additional weight and CG shift on a full-motion base in terms of reliability would be of value, as well as the long term effect of motion and vibration on the glass segments. Now that the new glass mirror technology is being fielded on full-motion systems, actual measurements can be taken.

Because installed glass mirrors are rather robust and can be cleaned, the industry and users should consider whether the actual or simulated windscreens could be eliminated from the simulator cockpits. While this reduces some realism, it has the potential to increase brightness and quality of the VDS image as seen by the trainees.

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