Liquid Mirrors: A new technology for optical designers  
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I. Introduction

It has been known for centuries that the surface of a spinning liquid will take the shape of a paraboloid. Originally, this concept was considered for astronomical applications, yet initial attempts to make liquid mirrors were only partially successful. Due to advances in technology, there has been a revived interest in liquid mirrors as a viable replacement for glass particularly in primary mirrors for large telescopes. There are several advantages to using a liquid mirror including low cost, large size, excellent surface quality and low scattering. Liquid mirrors up to 2.5 meters in diameter have been extensively tested and shown to be diffraction limited1. However, liquid mirrors have interesting applications in areas other than astronomy. A brief analysis of a telecentric f-θ scanner is presented.

II. Liquid Mirrors

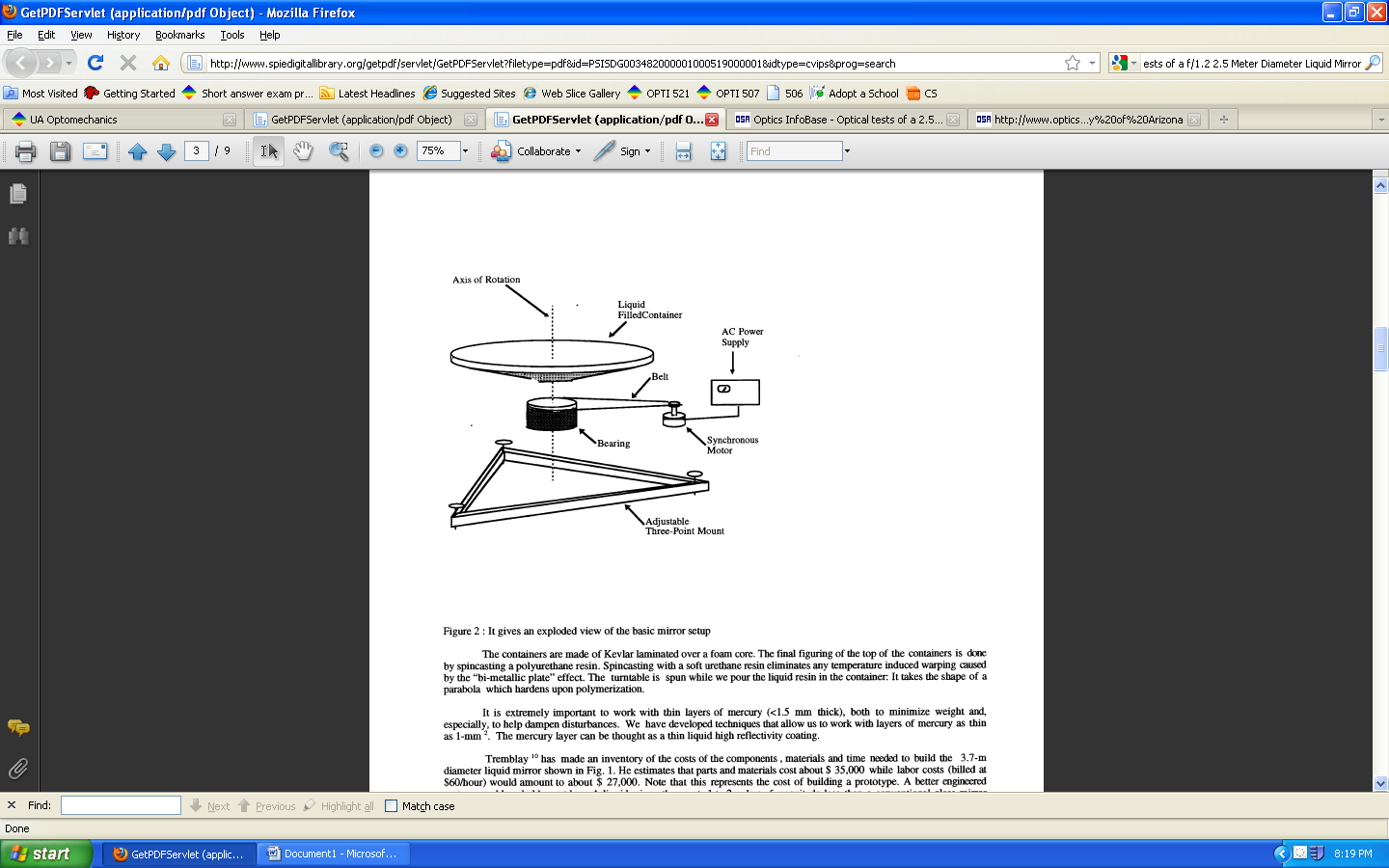
Adding the vectors for gravitational and centripetal acceleration at the surface of a liquid results in a parabolic shape. The focal length of a mirror (f) is related to the acceleration of gravity (g) and the angular velocity of the turntable (ω) by the following equation

[1]

For astronomical mirrors, the angular velocity is on the order of a few seconds per rotation. Smaller mirrors are mounted on air bearings because they are commercially available and have very low friction. Larger mirrors are mounted on oil lubricated bearings because they are stiffer and can support larger masses. The bearing used can limit system performance due to coning error and vibration. For many less demanding applications, ball bearings are sufficient but better bearing designs are certainly possible if needed.

Figure 1 shows an exploded view of the setup for a 3.7 meter mirror. The three-point mount is used to align the axis of rotation to the Earth’s gravitational field. Using a spirit level, this can be accomplished to within one arcsecond, though greater precision is possible using optical methods. The turntable is driven by a synchronous motor coupled to the table by a Mylar belt made from magnetic tape. A more robust design uses a direct drive controlled by a variable frequency AC power supply which can be adjusted to set the focal length of the mirror. The container which holds the liquid is constructed from Kevlar laminated foam. Experiments have shown that thin layers of mercury (<1.5 mm) reduce the mirror’s weight and provide better damping for vibrations. However, a thinner layer requires a higher quality cell and can

Figure 1. An exploded view of the mirror setup

result in more scattered light2. A cost study was conducted for the 3.7 meter mirror and the parts and labor totaled almost $70,000. This is at least one to two orders of magnitude less than the cost of a traditional glass mirror of comparable size.

III. Optical Tests

Interferometric measurements are made with a Shack cube and a scatter plate interferometer. The interferograms are captured with 1/60 second exposure times so that rapid liquid movements can be detected but also makes the measurement sensitive to the effects of seeing. Fortunately, these effects are small. Many hours of data have been videotaped to ensure that the interferograms presented are representative of the mirror’s long term performance. In the videotaped data the diffraction pattern is always visible, though the intensity and symmetry of the rings can vary. There is also a change in the position of the centroid consistent with coning error due to the bearing.

Perfect liquid mirrors should be possible. Liquid mirrors are fairly insensitive to vibrations. The authors have found that vibration effects are negligible when testing is performed in the basement of their building. The main effects of vibration are concentric rings on the mirror surface which have very small amplitudes (~λ/100) for thin layers of mercury. Vibration is only likely to be a problem for small mirrors operating in noisy environments. In general, the small departures from ideal wavefronts may be caused by instability in the bearing leading to small errors in focus. Computer simulations show that these small variations in focus are magnified by null lenses and the data reduction procedures increase wavefront degradation. It is important to note that the aberrations are due to misalignment and are not errors on the mirror surface. A better drive and bearing will significantly improve the mirror’s performance.

IV. Technological and Practical Considerations

Though metallic mercury is less toxic than other forms, the vapors can have adverse health effects. However, mercury evaporates very slowly and proper ventilation is sufficient to mitigate the danger. Measurements made a few centimeters above the surface of a freshly cleaned mirror detected mercury vapors but the concentration decreased to a safe level after a few hours. Any dangers from spilling can be controlled using a plastic lined container placed below the mirror because the quantity of mercury used is small (about 10 liters for a 3 meter mirror). Pouring mercury directly into the container produces a thickness of about 4 mm. This can be reduced to 2 mm with improved pouring techniques. The layer thickness can be further reduced by siphoning off excess mercury. Spinning the mirror evens out the surface.

The reflectivity of the mercury mirror has 90% of the reflectivity of a traditional aluminum mirror. The wavelength dependence of the reflectivity is well-behaved and is similar to that of aluminum. The reflectivity does not significantly vary over the course of a few weeks and the mirror is easy to clean by skimming.

While the liquid surface effectively damps vibrational effects, it is very sensitive to turbulent winds. Sheltering the mirror from environmental winds is easy to accomplish with an enclosure. The effect of winds due to mirror rotation are more complicated to deal with and may eventually limit the practical size of liquid mirrors. A plastic cover can protect the surface from winds but also degrades the mirror quality. A study of multiple plastic films has revealed some with very good optical quality that do not significantly impair the mirror’s performance. The combined effect is comparable to the quality of a conventional glass mirror.

While most work with liquid mirrors has been conducted using mercury, other reflective liquids are possible. A supercooled gallium-indium alloy is very stable. A simple Ronchi test of a 1 meter Ga-In mirror indicates a parabolic shape and good surface quality. The main problem with Ga-In is that it oxidizes almost instantly. The authors have been developing a technique to remove the oxidized layer but more work is needed on this topic.

The technologies are still fairly new and there is much room for improvement. Better mechanical engineering is needed to support larger mirrors and mercury is likely not the best liquid to use.

V. Applications

In Astronomy, the high cost of conventional telescope requires sharing among many experiments. Getting time on a telescope is very competitive and a given project may only have a few nights a year on 4 meter telescope. A low cost liquid mirror could allow the construction of more telescopes and thus give astronomers more observation time. This would be particularly useful in conducting deep sky surveys and other cosmological studies. A common criticism of liquid mirrors is that they have small fields of view due to the fact that they can’t be tilted. However, innovations in corrector design can allow observation of much wider portions of the sky.

In atmospheric science, liquid mirror are being put into use for LIDAR systems3. The lower cost for a larger diameter mirror increases the aperture-power product for the system and improves performance. In this application, the low scattering of the liquid mirror is an important feature.

Liquid mirrors have also been used as low cost, high quality reference surfaces for interferometry.

VI. A Telecentric F-θ Scanner that Uses a Liquid Mirror

Automated 3D inspection systems are commonly used in industry yet most systems have small working volumes. Large volume inspection is usually performed with a coordinate measuring machine with camera attachment but requires a long acquisition time. Faster measurements can be made if the scale of the camera is increased.

An F- θ scanner deflects a focused beam with constant speed over a surface. The telecentricity ensures that the direction and size of the beam remain constant regardless of the shape of the surface being inspected. This requires an aperture larger than the object being scanned. The low cost of liquid mirrors allows construction of larger scanners which would be prohibitively expensive with conventional optics.

While concentric rings from vibration have little effect in astronomical applications, for laser beam delivery systems they could deviate the beam and thus change its position in the volume being scanned. In the prototype system built by the authors, the worst deviations were 5-10 arcseconds which corresponds to the 0.05-0.1 mm in the working volume. In general, the deviation is five times less which is acceptable for this application.

VII. Conclusions

Liquid mirrors have many properties that make them well-suited for a variety of optical systems – their low cost, large size, good surface quality and low scattering. High numerical apertures can also be achieved. They are particularly suited for applications where a large diameter optic is needed but a traditional glass mirror would be prohibitively expensive. A prototype of an F- θ scanner is analyzed to show that liquid mirrors can replace aluminum coated glass optics. While there are still many improvements to be made to the existing technologies, liquid mirrors provide a versatile tool for the optical designer.

VIII. References

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