Liquid mirrors: A new technology for optical designers

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ABSTRACT

The surface of a spinning liquid takes the shape of a paraboloid that can be used as a reflecting mirror. Liquid mirrors have many characteristics that make them useful for optical applications: low costs, large sizes, excellent optical qualities, possibility of very high or very low numerical apertures, low scattered light, etc... The largest mirror built so far has a diameter of 3.7 meters. The largest mirror that has been extensively tested has a diameter of 2.5 meters. Interferometric tests show that it is diffraction limited. We discuss several technical issues related to liquid mirrors. A handful of liquid mirrors have now been built that are used for scientific work. We briefly discuss a practical application of liquid mirrors: We built and tested a telecentric f-θ 3-D scanner that uses a liquid mirror as its objective. The prototype has a stand-off distance of 1.5 meters, a scan length up to 1 meter (telecentric), a depth of view of 1 meter and a relative depth resolution of 1 mm or less. The design is based on the auto-synchronized scanner and is f-θ corrected for field scanning distortion. We therefore claim that the liquid mirror technology gives a new tool to the optical designer.

Keywords : optical design , mirrors, 3D sensing, liquid optics.

1. INTRODUCTION

That the surface of a spinning liquid takes the shape of a paraboloid has been known for centuries. The concept however was never taken seriously because early attempts to make such mirrors were only partially successful, giving a bad reputation to the concept. Also, liquid mirrors were only considered for astronomical applications where they have a major limitation since they cannot be tilted and hence cannot be pointed and track like conventional telescopes do. A revival of the concept was triggered by an article [1] that pointed out that modern technology gives alternate tracking techniques that render liquid mirrors useful to astronomy.

Following the early suggestion, modern testing facilities have been built and we have engaged, at Laval University, in a R&D program to develop the technology. Tests on a 1.5-m diameter liquid mirror showed that it was diffraction-limited [2]. This was followed by tests of a 2.5-m mirror [3]). Independent tests of a liquid mirror at the Centre Spatial de Liége [4] have confirmed that a properly tuned LM is diffraction limited. Astronomical imagery with a liquid mirror telescope has been demonstrated [5] At the time of this writing, a large number of astronomical observations have been taken and published [6,7].

Liquid mirrors are interesting in other areas of science besides Astronomy. For example, atmospheric scientists have expressed great interest for these inexpensive large mirrors for Lidar applications: The University of Western Ontario has built a Lidar facility that houses a 2.65-m diameter liquid mirror as receiver [8].

Liquid mirrors promise two main advantages over conventional glass mirrors: They are considerably cheaper and it should be possible to build them to much larger diameters. They also have, or promise, other interesting properties for many optical applications: very high surface quality, very low or very high numerical apertures, variable focus that can be controlled with a very high precision, low scattered light.

More information on liquid mirrors and their applications can be found at http://wood.phy.ulaval.ca/lmt/home.html.

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This article describes briefly a telecentric f-θ scanner that uses a liquid mirror as its main optical element. This is a good example of a system that uses one of the major advantages of using a liquid mirror: its low cost. Since the objective of a telecentric scanner must be larger than the object to be scanned, the optics of telecentric scanners for objects larger than a few centimeters become prohibitively expensive with conventional optics but are affordable if one uses a liquid mirror.

2. LIQUID MIRRORS

Adding the vectors of the centripetal and gravitational accelerations at the surface of a rotating liquid gives a parabola . Using a reflecting liquid one therefore gets a reflecting parabola. The focal length of the mirror L is related to the acceleration of gravity g and the angular velocity of the turntable ω by

$$L = g/(2\omega^2). \quad (1)$$

For mirrors of practical interest the periods of rotation are of the order of a few seconds and the linear velocities at the rims are of the order of a few km/h. Figure 1 shows a liquid mirror having a diameter of 3.7-m meters and a focal length of 4.44 meters that we have built in our laboratory at Laval and are currently testing.

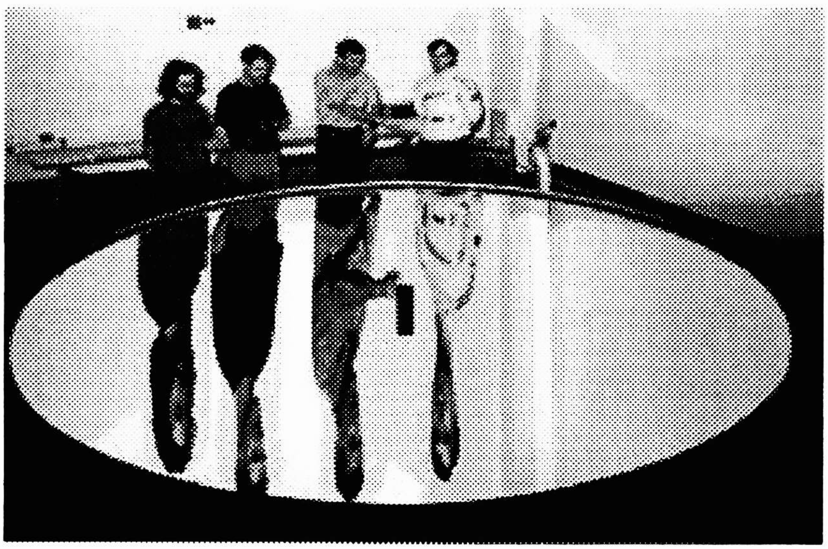

Figure 1: It shows a liquid mirror having a diameter of 3.7-m meters and a focal length of 4.44 meters.

The mirrors that have been extensively tested, as well as those used in applications, have all used airbearings because they are convenient for small systems and commercially available units have the required precision and low friction. For larger mirrors it will be preferable to use oil-lubricated bearings as they are more robust, have greater stiffness and can support substantially higher masses for a given bearing size. The 3.7-m shown in Fig. 1 uses two ball bearings. Their performance is not quite good enough for diffraction-limited performance as the coning error is about 1 arcsecond and they induce a fair amount of vibrations; but it is adequate for less demanding applications (e.g. Lidar work). However, better bearings are available and a better bearing mount design is certainly possible.

Figure 2 gives an exploded view of the basic mirror setup. The mirror and bearing rest on a three-point mount that aligns the axis of rotation parallel to the gravitational field of the Earth. Alignment is done with a spirit level to within one arcsecond, sufficient for many applications. There are optical methods that can align it to a greater accuracy [3]. The turntable is driven by a synchronous motor coupled to it via pulleys and a thin mylar belt made from a discarded magnetic tape. The belt drive is adequate but not sufficiently robust for practical applications. A direct drive used with a 3-m LM built and operated by NASA [9] is far more robust. The motor is controlled by a variable-frequency AC power supply stabilized with a crystal oscillator. We control the rotational velocity of the table and thus the focal length of the mirror with the frequency of the power supply.

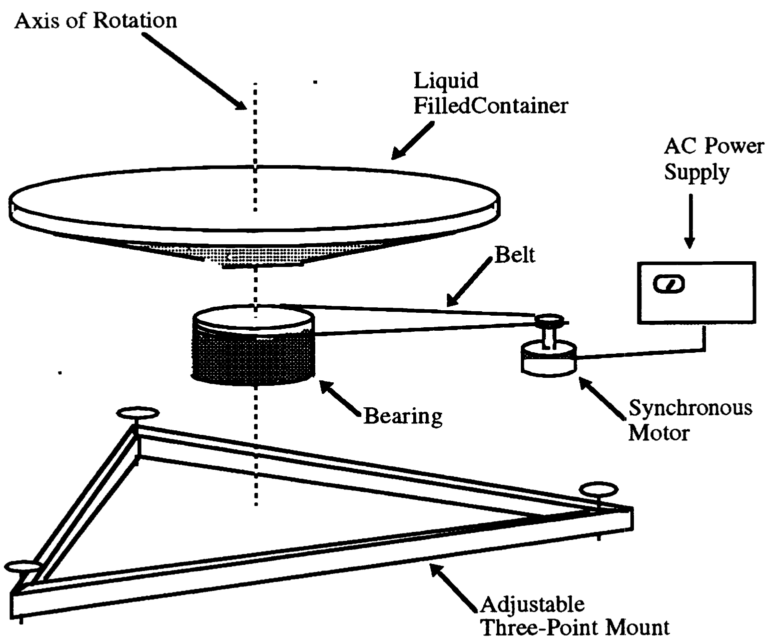

Figure 2 : It gives an exploded view of the basic mirror setup

The containers are made of Kevlar laminated over a foam core. The final figuring of the top of the containers is done by spincasting a polyurethane resin. Spincasting with a soft urethane resin eliminates any temperature induced warping caused by the "bi-metallic plate" effect. The turntable is spun while we pour the liquid resin in the container: It takes the shape of a parabola which hardens upon polymerization.

It is extremely important to work with thin layers of mercury (<1.5 mm thick), both to minimize weight and, especially, to help dampen disturbances. We have developed techniques that allow us to work with layers of mercury as thin as 1-mm [2]. The mercury layer can be thought as a thin liquid high reflectivity coating.

Tremblay [10] has made an inventory of the costs of the components , materials and time needed to build the 3.7-m diameter liquid mirror shown in Fig. 1. He estimates that parts and materials cost about $ 35,000 while labor costs (billed at $60/hour) would amount to about $ 27,000. Note that this represents the cost of building a prototype. A better engineered system would probably cost less. A liquid mirror thus costs 1 to 2 orders of magnitude less than a conventional glass mirror and its cell.

3. OPTICAL TESTS

We carry out interferometric measurements with either a Shack cube or a scatter plate interferometer. The interferograms are captured with 1/60 second exposure times by a 512X480 CCD detector connected to an 8-bit framegrabber interfaced to a microcomputer. The 1/60 second capture times are sufficiently short that we can detect rapid liquid movements, but they also render the interferometry sensitive to seeing effects in the air in the optical path which, fortunately, are small. Because the mirror is liquid and can shift shape, a few interferograms are not necessarily representative of its optical quality. Interferometric tests of well-tuned mirrors typically give Strehl ratios of about 0.8. We have analyzed numerous interferograms [2,3] and have videotaped hours of interferogram data that satisfy us that the interferograms analyzed are representative. We also have observed the diffraction pattern of the 1.5-m and the 2.5-m mirrors. We have videotaped hours of data and find that the diffraction pattern is always visible, although the intensity and symmetry of the rings vary a little. The centroid of the PSF moves, describing a curve having an amplitude of image motion compatible with the coning error expected from the bearing and is obviously caused by the coning error of the bearing.

Liquid mirrors are reasonably insensitive to vibrations. We find that vibration effects are negligible for mirrors located in the basement of the large building we work in. The main effect of vibrations consists in the generation of concentric rings on the surface of the mirror. We find that the amplitudes of the rings are very small (~/100 λ) for thin mercury layers (<1.5-mm). Vibrations may be a problem for small mirrors operating in a very noisy environment or in the upper floors of buildings. One should work with as thin a layer of liquid as possible to dampen all disturbances. More detailed discussions of effects that degrade the optical qualities of liquid mirrors are given in [2,3].

Essentially perfect liquid mirrors should be possible. Our investigations indicate that our small departures from a perfect wavefronts are mostly caused by the fact that rotational velocities of the turntables are not perfectly stable, causing tiny periodical variations of the focus. Computer simulations show that those focus variations greatly magnified by the presence of the null lenses and our reduction procedures are responsible for much the degradation of the wavefront. A better drive will correct this. Note that the aberrations we are talking about are introduced by the effect of small variations in focal length on the alignments with respect to the null lenses and are not on the mirror surfaces.

4. TECHNOLOGICAL AND PRACTICAL CONSIDERATIONS

Although metallic mercury is far less toxic than some of its compounds, mercury vapors can be detrimental to health if inhaled massively over long periods of time. However, in practice mercury evaporates very slowly so that a proper ventilation eliminates all danger. We find that a polyethylene enclosure having a weak ventilation system adequately controls the mercury vapors that are present at mirror start up. Furthermore, a transparent oxide skin develops in a few hours and cuts the evaporation to negligible levels. Measurements of vapor concentration taken a few centimeters above the surface of a 50 cm mirror [2] detect mercury vapors after starting a freshly cleaned mirror but the concentration decreases after a few hours below 0.05 mg/m^3, the legal limit used in most countries that allows a human to work an 8-hour workshift without protective mask. The quantities of mercury involved are small (a 3-m mirror needs about 10 liters) and a simple plastic-lined pool can handle catastrophic spills. In practice, the health and environmental impacts of mercury are insignificant, provided simple precautions are taken.

We have compared the reflectivities of mercury and aluminum mirrors in our laboratory and find that mercury has 90% of the reflectivity of an aluminum coated mirror. The wavelength dependence of the reflectivity curve is well-behaved and similar in shape to the curve of aluminum. The reflectivity of mercury does not vary noticeably over several weeks. A mercury mirror is very easy to clean: It is stopped and then skimmed. It takes about 1/2 hour to clean a 3.7-m mirror and a few hours for its surface to stabilize.

We have dedicated considerable effort to find ways to minimize the thickness of the layer of liquid we work with. There are two main advantages to thin layers. First, because disturbances (wind, vibrations) are dampened more effectively. Second because cost is dominated by the bearing and the container, the cost of which increase with weight and therefore the depth of the liquid.

Simply pouring mercury in a container necessitates a minimum thickness of about 4 mm. After considerable experimenting we found that it is possible to start a mirror with a layer as thin as 2 mm. The container needs a groove along its circumference so that the layer is more than 4 millimeters thick in a circular region a few centimeters wide extending along the rim. We pour a quantity of mercury sufficient to fill the container to the desired thickness. The turntable is then repeatedly spun and then slowed down by hand until the layer closes. We can make even thinner layers (< 1 mm) by removing the unwanted excess liquid [2]. This may seem pointless as one must first start with a large quantity of mercury that overloads the container and bearing anyway; however, it is quite important since thin layers dampen waves and disturbances.

The surface of a liquid mirror is sensitive to turbulent winds. Sheltering a liquid mirror from environmental winds is easily done with an enclosure. The effects of winds induced by the rotation of the mirror are more worrisome and may eventually limit the size of liquid mirrors. Fortunately, there are solutions to the wind problem. A transparent plastic cover gives a brute force approach that works but degrades the mirror quality. We have examined samples of numerous plastic films finding that some have surprisingly good optical qualities that degrade somewhat the mirrors but that the overall qualities are comparable to the one of a typical conventional glass mirror [11]. Thin layers are also very effective at dampening wind-induced disturbances.

So far, most of our work has involved mercury but other reflecting liquids are possible. We are investigating mirrors that use a gallium-indium eutectic alloy. Its nominal melting temperature is 17 degrees C but it is easy to supercool and very stable in the supercooled state. A simple Ronchi test of a 1-m Ga-In mirror shows the signature of a parabola and a reasonable surface quality [12]. The main problem that we are facing with gallium is that it oxidizes almost instantaneously. Like its oxide does for aluminum, gallium oxide is transparent and protects the underlying metal from oxidization; however if the liquid is stirred, as occurs during startup, there forms a thick oxide crust that hopelessly degrades reflectivity and surface quality. We have developed a skimming technique that removes the oxide layer, but we are still perfecting techniques to deal with this problem.

This is a very young technology and there is much room for improvement. Clearly our mechanical setups should be better engineered, particularly if one wants to build much larger mirrors. Mercury liquid mirrors work but mercury is not an ideal liquid and efforts should be made to find other reflecting liquids

5. APPLICATIONS

At the time of this writing, several liquid mirrors are used for various applications..

a) Astronomy

In Astronomy, liquid mirrors promise major advances for deep surveys of the sky and, in particular, cosmological studies. This can be understood by considering that conventional telescopes are very expensive and can only be justified by sharing them among many investigators. Obtaining telescope time is a very competitive process so that only a few astronomers manage to get even a few nights per year on a 4-m class telescope. On the other hand, large inexpensive LMTs can be dedicated to a specific project. Over 100 nights of astronomical observations have been taken with the NASA Orbiting Debris Observatory 3-m [9]. Figure 3 shows an image of a cluster of galaxies taken with that telescope. Figure 4 shows an image of the same region taken with a conventional telescope.

Figure 3: It shows an image of a cluster of galaxies taken with the NASA 3-m liquid mirror telescope (courtesy of NASA and Mark Mulrooney). The vertical lines on the bright images are caused by CCD bleeding due to well overflow and not by the mirror. They are not present in Fig. 4 because the detector was a photographic plate.

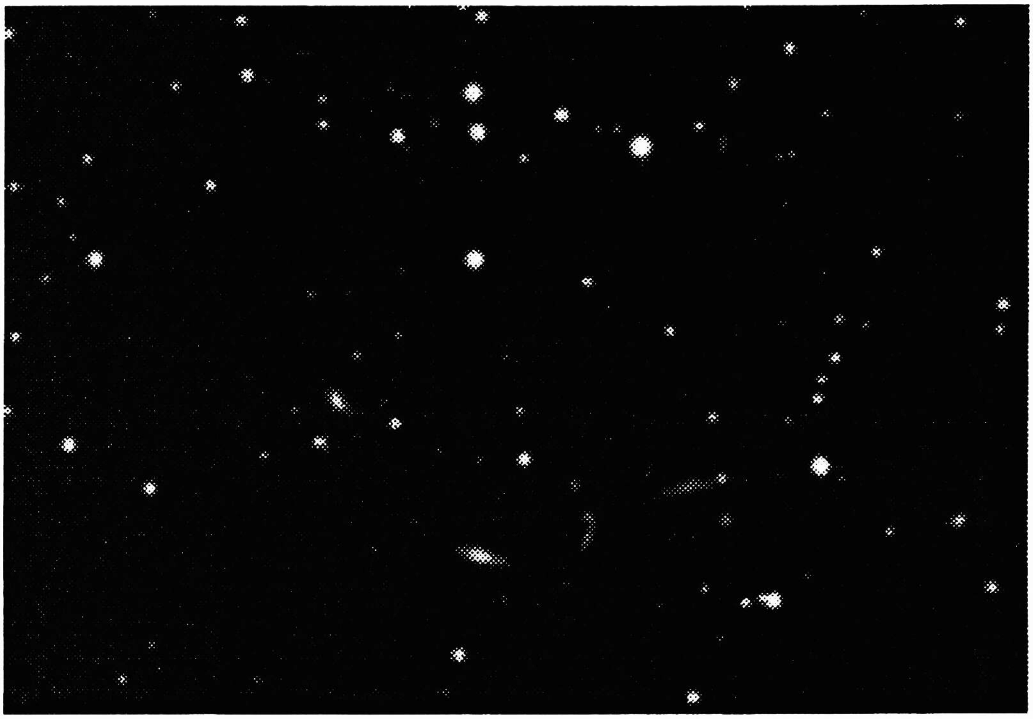

Figure 4: It shows an image of the same region taken with a conventional telescope (Palomar Sky survey). The detector is a photographic plates; hence the bright images do not show the vertical lines due to the CCD detector used for Fig. 3.

One of the often cited limitations of astronomical liquid mirrors addresses the small regions of sky that they can observe. However, this criticism implicitly assumes the corrector designs presently used in astronomical telescopes. Recent optical design work [13] and some laboratory experiments [14] show that much larger regions of sky can be observed with innovative correctors. A 6-m diameter LMT is presently under construction near Vancouver, Canada [15]).

b) atmospheric science

Atmospheric scientists have recognized that LMTs would allow a significant increase in the power-aperture product of LIght Detection And Ranging (lidar) systems. The University of Western has built a lidar system that uses a 2.7-m liquid mirror as its receiver [8] . The observatory has now operated for over 5 years in the harsh Canadian climate. A lidar system, using a 2.7-m LM receiver has also been built by UCLA in Alaska [16].

c) other applications

At the NASA Lyndon B. Johnson center in Houston, a team led by D. Potter has built a 3-m diameter LMT [9] that is used to observe for space debris. It has operated satisfactorily for 4 years. It also has been used to gather a large quantity of astronomical observations: over 100 nights of astronomical observations have been taken at the time of this writing. At the Centre Spatial de Liége, Ninane & Jamar [4] have built a 1.4-m diameter LM that has been as a reference surface in optical applications. Their independent optical tests confirm diffraction limited performance.

6. A TELECENTRIC F-Θ SCANNER THAT USES A LIQUID MIRROR.

Automatic 3-D measurements and inspection systems are widely used in industry; however, the sensors of most industrial vision systems only provide small working volumes. Large volume inspection is done generally with a coordinate measuring machine (CMM) enhanced with a small volume camera. Unfortunately this system requires long acquisition times because of the mechanical movements of the sensor and the need to fuse several image for full body reconstruction. To achieve faster 3D measurements in a large volume, we have to scan this volume with the same approach as a smaller scanner system. Therefore we have to scale up the small camera to increase the working volume. This can be done readily but the resolution must be scaled as well and the power of the laser source must be increased to conserve the signal-to-noise ratio in the detection channel. It is also possible to increase the size of the collecting optics to conserve the same solid collection angle but the cost then increases rapidly with size.

F-θ telecentric 3-D scanners are particularly interesting. By respecting the f-θ condition, a focused beam deflected at a constant angular speed moves the focused spot over a surface linearly and at a constant speed. The telecentric configuration insures that, while the beam scans the surface of interest, the direction of the beam and the size of the spot remain constant. Unfortunately, the design of a telecentric sensor is more complex and, furthermore, requires an optical aperture even larger than the object itself. This is therefore a good example of a system that uses one of the major advantages of using a liquid mirror: its low cost. The optics of telecentric scanners for objects larger than a few centimeters become prohibitively expensive with conventional optics.

The scanner's design and its performance has been described in a previous article [17]. We shall therefore only present her short summary of the measured performance of the prototype that we have built.

Table 1: Desired parameters of the design

Design wavelength	632.8 nm (visible)
Beam quality	Single mode
Stand-off distance (to the centre of the volume of scan)	1.5 m
Scan length (telecentric)	up to 1 m
Total scan angle (mechanical)	11.8 degrees
Depth of view	1 m
Transverse resolution	0.8 - 1 mm
Depth resolution	1 mm
Detector length	1 5 mm
RMS spot size on detector	120-200 mm

The objective of the scanner is a 1.3 meter diameter liquid mirror that has a focal length of 1 meter. We have tested it, finding that its surface quality is adequate for our purpose. We were particularly concerned by the effect of mechanical vibrations on the surface of the liquid. Vibrations induce concentric waves on the liquid surface. Those waves have minimum impact for astronomical use but for laser beam delivery systems they could deviate the illumination beam which could then change the position of the beam in the working volume. For a 1 mm resolution, the maximal deviation must be less than 0.1 mm. We measured the local slope of those waves by measuring the pointing stability of a laser beam reflected by the liquid surface. We find that the worst local beam deviation is about 5-10 arcseconds which corresponds to 0.05-0.1 mm of deviation at the end of the working volume (at 2 m). In general the deviation is five times less. The deviations observed are acceptable for this kind of application.

We have studied the optical performance of our prototype: We mean by this the f-θ and telecentricity conditions as well as spot size in the working volume and on the detector. Table 2 gives the experimental data for the departure from the f-θ condition in the illumination channel. We can see that the f-θ condition obtains with an excellent accuracy (<0.1 %).

Table 2. Departure from f-θ condition

Scan angle (degrees)	Departure (%)
1.5	0 (reference)
3.0	0.05
4.5	0.06
6.0	0.02
7.5	0.05
9.0	0.02
10.5	-0.03
12.0	0.09

To respect the telecentricity condition, the inclination of the chief ray with respect to the planar surface should be constant during the scan. The accuracy with which this criterion holds for the illumination channel is shown in Table 3.

Table 3. Departure from ideal telecentricity

Scan position	α(ideal) - α(real) (minutes)
Center	5.2
Edge	5.1
Corner	5.1

We have a constant angle of 5 arcminutes which indicates that the distance between the primary and the secondary is a little bit shorter than the optimal. The entire working volume is inclined.

Our experiments show typical beam shapes for the illumination channel that are slightly elliptical with the maximum dimension in the working volume being about 1 mm X 1.2 mm (1.20:1 ratio). For the detection channel, the results show an excellent agreement with the theoretical predictions. For example, the beam at the beginning of the working volume in the center has dimensions of 0.940 X 0.795 mm with a roundness of 0.85. In the ideal case, the beam waist diameter, in the centre of the scanning volume, should be 0.8 mm, and on the edges should go up to 1 mm. The departure from the ideal case comes from astigmatism. This astigmatism come from a tilted surface or misalignment but it is not critical and can be corrected. If we consider the beam profile on the detector for the central position in the working volume, a typical example, we find that the beam has a roundness of 0.98 with dimensions 156 X 159 mm. There are no speckles because of the size of the entrance pupil (50 mm diameter). The shape is very smooth and there should be no problem for the peak detection by the software.

In conclusion, we find that reflective optics offer interesting properties for the laser scanning of large bodies. The combination of a primary parabolic liquid mirror and an aspheric secondary mirror achieves telecentric diffraction-limited performance in a large working volume. Experimental results shown excellent agreement with the predicted performances. While the present system is not overly demanding, these experiments clearly demonstrate that reflective surfaces and liquid mirrors can play important roles in the design of large optical systems.

7. CONCLUSIONS

Liquid mirrors have many characteristics that make them useful for optical applications: low costs, large sizes, excellent optical qualities, possibility of very high or very low numerical apertures, low scattered LIght, etc... They open interesting possibilities to the optical designer. For example, in optical instrumentation, a large mirror can be a necessary optical element for various applications. However the high cost of large optics discourages applications where cost is a consideration. This is not the case for inexpensive liquid mirrors so that a cost-prohibitive application becomes practical. We briefly discuss such a practical application of liquid mirrors: We built and tested a telecentric f-θ 3-D scanner that uses a liquid mirror as its objective. The prototype has a stand-off distance of 1.5 meters, a scan length up to 1 meter (telecentric), a depth of view of 1 meter and a relative depth resolution of 1 mm or less. The design is based on the auto-synchronized scanner and is f-θ corrected for field scanning distortion. Experimental results show excellent agreement with the predicted performances.

We find that reflective optics offer interesting properties for the laser scanning of large bodies. Our current work is concerned with applications where large optics is needed.

In conclusion, we propose to use the liquid mirror technology in applications that require large size elements, diffraction limited performance, low scattering, low effective cost and high numerical aperture possibilities (attainable short period of rotation). We therefore claim that the liquid mirror technology gives a new tool to the optical designer.

8. ACKNOWLEDGMENTS

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