A Low-Cost Defocus Blur Module
for Video Rate Quantified 3D Imaging

by

Leeway Ho

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

Existing three-dimensional surface imaging systems are expensive, difficult to use, time consuming, and do not always provide the best accuracy or resolution. By using an offset aperture on a rotating disc, the 3D Monocular Imaging System provides a fast, portable, accurate, and cheap method of 3D surface imaging by relating the differences in images generated by the aperture at different positions to the depth of the features on the target surface. A cheaper and simpler alternative to the Monocular System was designed such that two offset fixed apertures would replace the rotating aperture. Rhombic prisms and a light-blocking mask ensured that the images would be generated properly on the camera's imaging surface. The new prototype was never completed, but the purchasing of the parts suggested that the cost of production would not drop enough to consider the module a popular purchase for home electronics usage. In addition, the requirement of precision-machined parts increased the time, effort, and cost to produce the module. However, the design for this new system is a viable alternative to the original 3D Monocular System since it is smaller, simpler, and cheaper.

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1 Introduction

Existing technologies for three-dimensional surface imaging, such as laser scanning systems, structured light systems, and stereoscopic 3D imaging systems, all have flaws that detract from their effectiveness and prevent widespread commercial usage. These systems are expensive and difficult to setup, maintain, and operate. Some of them take a long time to acquire the 3D surface image, while others have poor accuracy and/or resolution.

The 3D Monocular Imaging System is a new surface imaging system being developed by the Hatsopoulos Microfluid Mechanics Laboratory. Using an offset aperture on a rotating, opaque disc, called a Defocus Blur Sampling Module (DBSM), mounted to a digital camera, researchers created a system for imaging three-dimensional surfaces quickly, accurately, with high resolution, and for cheaper than other 3D imaging systems currently on the market. The DBSM is also modular, designed to be used in conjunction with existing photographic equipment.

The purpose of this thesis project was to develop a low-cost version of the Monocular System, creating a device that would be cheap enough so that everyday consumers could purchase the module and attach it to their photographic equipment, effectively turning any 2D imaging device into one that could perform 3D imaging. This new, low-cost, module would be designed to interface with the most common consumer digital cameras and camcorders on the market. Instead of using one offset aperture on a rotating disc, the new version would use two fixed, offset apertures, in conjunction with a pair of rhombic prisms, to eliminate the cost of the moving components.

The successful creation of a fast, accurate, and low-cost 3D surface imaging system has several implications for commercial applications. By eliminating previous problems that plagued 3D imaging technologies, such as accuracy, resolution, and processing speed issues, 3D imaging based on the Monocular System will drastically improve any applications already requiring the use of three-dimensional imaging. In addition, the benefits of low-cost and compatibility with existing photographic equipment will open new doors for possible 3D surface imaging applications. The 3D Monocular Imaging System could be used for facial recognition, medical procedures such as visualizing surgical sites, and teleconferencing. If a very low-cost version can be created that is within the price range of an everyday electronics consumer, people would be able to transform their home digital cameras and camcorders into 3D imaging devices by simply attaching a module to the camera lens.

2 Background

Photography is the process of capturing an image by focusing light through an aperture onto an imaging surface. Photographs, however, are two-dimensional images. They cannot convey depth or provide an idea of what the object being photographed actually looks like in 3-space.

2.1 Existing Technology

There are several available technologies on the market that can be used to resolve three-dimensional surfaces. These systems all have flaws, however, that prevent them from being used more commonly in commercial applications, such as high costs, slow processing speed, poor resolution, and difficult hardware operation. Laser scanning systems are among the most popular 3D surface imaging systems because of their high accuracy, but they are expensive, cumbersome, and can have lengthy scanning times, meaning the surface being imaged must remain still for several seconds while it is being scanned. Stereoscopic 3D imaging systems often suffer from camera misalignment, while the generated images can have low resolutions and high computational costs. Structured light systems, which measure the deformation of a grid when optically projected onto the target surface, have poor accuracy and resolution, and suffer from lengthy processing times.

2.2 3D Monocular Imaging System

A 3D Monocular Imaging System was developed by researchers at the Hatsopoulos Microfluid Mechanics Laboratory. The system is a modular and compact package that operates with existing cameras and lenses. Using relatively inexpensive hardware, when compared to other 3D imaging systems on the market, the Monocular System provides accurate and fast surface imaging, leading to the capability of real-time surface imaging[1]. The main component of the imaging system is the Defocus Blur Sampling Module (DBSM), which when used in conjunction with a digital camera, yields a device which can perform 3D surface imaging. The aperture of the DBSM, which sits off-axis on a rotating opaque disc, creates a defocused blur of the target surface on the imaging CCD of a digital camera. Figure 1 shows two positions of the rotating aperture and the corresponding images that are generated on the image plane. If a continuous image is recorded as the opaque disc, and thus aperture, is rotated, a circular image would be recorded by the camera, with the diameter of the generated image proportional to the distance between the feature and its focal reference plane. A continuous, circular image is never needed, however, since the blur circle diameter can be extrapolated from the distance between the two images generated by two consecutive frames. Thus, only two images of the target surface are needed to map out the three-dimensional surface characteristics, with the rotating aperture stopping at two positions for image sampling.

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[1] Hart, Douglas P., et al. *High Speed 3-D Surface Imaging*. Massachusetts Institute of Technology: Cambridge.

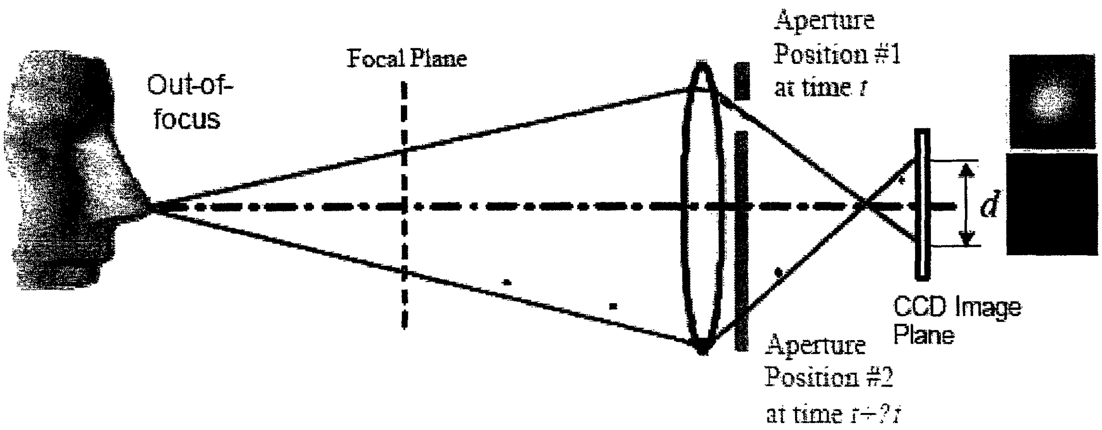

Figure 1: The rotating aperture generates two blurs on the image plane (lower box). Replacing the rotating aperture with an open iris leaves a defocused blur (upper box).[2]

The Defocus Blur Sampling Module has several advantages over the similar and more common two camera stereoscopic system for 3D imaging. The DBSM is simple, inexpensive, and features better accuracy, resolution, and sensitivity than stereoscopic systems. The precision of the system is determined by the grinding of the optics and not the optical alignment of components, unlike triangulation-based devices. The active rotating aperture allows for system feedback from the processing algorithm, increasing performance. Finally, because the DBSM can be used in conjunction with almost any optical system, instruments such as microscopes and camcorders can all be easily and inexpensively converted into 3D imaging systems.

Although the Defocus Blur Sampling Module is already much cheaper than other 3D surface imaging systems, at over $1000 per unit, it is still much more expensive than what can be afforded by most household consumers. In order to lower the cost of the DBSM and make it more accessible to consumers who may wish to turn their digital cameras and camcorders into 3D imaging-capable devices, a design change to the DBSM was proposed. The new, low-cost Defocus Blur Sampling Module would be cheaper to make, easier to use, and have little trade-off in terms of image quality.

2.3 Impact and Applications

This new method for 3D surface imaging with the Defocus Blur Sampling Module has the potential for tremendous impact in both consumer and industrial markets. The DBSM is a low-cost, robust, and modular system that interfaces with existing photographic and optical equipment to provide video rate 3D imaging. The module does not require any modifications to hardware or instrumentation, and it does not interfere with the normal operation of the device. 2D instruments can be transformed into 3D devices with the capability of producing results with high speed and accuracy, meaning applications that once shunned 3D measurement information due to performance and/or cost limitations

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[2] Hart, Douglas P., et al. *High Speed 3-D Surface Imaging*. Massachusetts Institute of Technology: Cambridge.

can now benefit from the technology.

2.3.1 Face Recognition

One possible application for the 3D monocular imaging technology is face recognition, used for surveillance and security measures at airports, police stations, government installations, banks, and any areas requiring high levels of security. Current facial recognition systems compare two-dimensional images from the field, such as an airport security camera, with a computer database of 2D images. Under ideal conditions, the 2D system of matching pictures and facial characteristics is only 80-90% accurate. This recognition rate drops significantly with poor lighting conditions or situations where the person's head is in a different orientation from the image stored on file. By switching to a 3D imaging and recognition system, the accuracy of facial recognition will increase because the process no longer relies upon comparing two flat images. Rather, 3D imaging will allow for the examination of the actual contours of the face, providing more data for facial comparisons and eliminating system dependence on lighting and subject orientation and scaling.

2.3.2 Manufacturing Inspection and Quality Control

Another promising field that the monocular imaging system may be used for is manufacturing inspection and quality control. The 3D surface imaging technology can be used to analyze parts coming off of an assembly line. Much like facial recognition, parts and assemblies can be scanned and compared to the image of an ideal part in memory to ensure proper shape and dimensions as the pieces are being produced. The high accuracy of the imaging technology means that devices that need to be manufactured to close tolerances can be analyzed. In addition, the robustness and portability of the modular device allows it to be easily taken on-the-go for field inspections.

2.3.3 Medicine

There is also a large market for 3D imaging in the medical field. The monocular imager could be used to locate certain areas inside a person's body with respect to a 3D surface scan, such as the location of a tumor. Thus, as a patient returns to the hospital multiple times for radiation treatment to kill the tumor, there is no need to undergo an MRI to relocate the tumor's position, saving time and money. If attached to a microscope, researchers can observe cells and tissue samples and their structure without having to constantly move the sample. A monocular attachment at the end of a endoscope could help surgeons better evaluate the area where they plan on operating, observing exact tissue shape, size, and 3D structure in real-time without moving the endoscope tip around constantly.

2.3.4 Other Uses

Those were only three examples of possible applications for the 3D monocular imaging system. There are many more possibilities; too many to list. 3D imaging could be used in teleconferencing to allow participants to see each other, their reactions, and even demonstration props they may be using. The imaging system could also be used as a feedback system for industrial and medical robots, helping the machines perform precision movements and adapt to objects that are not uniform in shape or size. The low-cost, fast, and accurate 3D monocular surface imaging system has many possible uses, including some innovative applications that do not currently apply any 3D imaging technology. The possibility of making this device cheaper and more available to everyday consumers will only serve to broaden the coverage of this emerging technology and open new doors to possible applications.

3 Design

The low-cost Defocus Blur Sampling Module was designed to mimic what the original DBSM did, but for a lower cost. This meant simplifying the design so that there were no moving parts, and shrinking the size to make a more convenient and compact package to transport. Instead of having an offset aperture on a rotating opaque disc, the disc was fixed in place and two vertical parallel slots were inserted, centered in the middle of the disc. This arrangement simulated the offset aperture and its 180-degree rotated counterpart, simultaneously imaging the two defocused blurs through the dual apertures. To prevent overlapping of the blurs on the imaging CMOS surface, two rhombic prisms were used, one at each aperture, to shift the image horizontally away from the center of the CMOS chip by 1/4 of its width. The shifting of the two defocus blurs away from each other, each by 1/4 CMOS chip width, lets each of the blurs image half of the chip, wasting as little sensor area as possible. A light-blocking mask, consisting of a disc with a single slot milled out of the center and positioned such that the slot was parallel to the aperture slots, was mounted to the prisms on the side opposite to the aperture. The mask blocked excess light from exiting the prisms, preventing any defocus blur overlap that may occur at the center of the CMOS sensor. Because the addition of the prisms, aperture, and mask in front of the CMOS sensor would extend the focal length of the camera's imaging system, a concave lens was added to the front of the optics system, before the light entered the aperture, to extend the focal length back to the CMOS chip and ensure proper focus.

3.1 Design Parameters

The design of the 3D imaging module was dictated chiefly by two design parameters: adaptability and cost. The module had to be a product that everyday consumers could use, meaning that it would have to be able to easily attach to and operate properly with popular consumer cameras and camcorders. This new, low-cost module would also have to be made as inexpensively as possible, lowering the price point and allowing household electronics consumers to purchase it as an accessory for their home photography equipment.

3.1.1 Adaptability

It was decided that the interface between module and camera would use a Nikon C-mount system, a standardized lens mounting system that dictated the dimensions and specifications of the interface. Not only would the C-mount interface allow the module to easily attach to existing camera systems, but there are lens-mount converters on the market that can adapt a C-mount to other mounting specifications, such as F-mount. This complement of lens-mount adapters means that a C-mount based module will be able to interface with most cameras.

Another major design consideration was ensuring that the images generated by the 3D imaging module would be transmitted properly to the imaging surface inside the camera. The two most popular existing technologies used for imaging surfaces in photographic equipment are CCD and CMOS. CMOS used to be less common, but due to better quality images and refined CMOS wafer production processes that are causing a reduction in prices, CMOS is rapidly gaining popularity as the imaging surface technology of choice. The most widely used CMOS chip size in digital cameras is 2/3 inch (measured diagonally). It was thus decided that the 3D module would be designed to project its two images onto a total surface size of 8.8 mm x 6.6 mm, which corresponds to the dimensions of the 2/3 inch CMOS chip, with each individual image projected on half of the CMOS surface (4.4 mm x 6.6 mm). This meant that each individual image would have to be shifted by the rhombic prism a distance of 2.2 mm.

3.1.2 Cost

After deciding upon the best method of interfacing the 3D imaging module with digital cameras and camcorders to ensure the broadest possibility of camera support, the next objective was to ensure that the design was made as low-cost as possible, since the goal was to have a 3D module that an everyday consumer can buy at an electronics store and attach to their own home equipment. To achieve a low cost, the number of pre-manufactured parts that could be ordered from suppliers was maximized. Pre-manufactured prisms were ordered from Optarius. Two C-mount extension tubes were purchased from Edmund Optics to serve as the module's interface and rotational adjustment. A concave lens, used to extend the focal length of the optical system, was bought from Sunex Optics. Aluminum stock was used to manufacture the remaining parts, ensuring a lightweight and cost-effective construction.

3.2 Components

Knowing that one of the key requirements for the 3D imaging module was a low cost, the design was made to accommodate as many pre-manufactured components as possible. Thus, approximate sizes and dimensions for required parts were first determined by examining the package size that would be necessary to house all the components and still be convenient to transport and install, modular package. The components that could be ordered from suppliers, which had similar specifications to what was required, were purchased, and the remaining parts were manufactured from stock material.

3.2.1 C-Mount Extension Tubes

Two 5 mm C-mount extension tubes were bought from Edmund Optics, part # NT54-628. The specifications of the tubes are shown in Figure 2. The external threads on one of the extension tubes were machined off, allowing the tube to rotate freely inside the other stock tube without axial translation. Figure 3 shows the machined and stock extension tubes. The prism sub-module, discussed later, was permanently attached to the inside of the machined tube. By using a set screw, the machined tube, and thus the attached prism sub-module, could be rotated with respect to the stock extension tube and fixed in place. This ensured that once the stock C-mount extension tube was fixed to the camera, the prisms could be rotated so that they were oriented to properly project their dual images side-by-side horizontally on the CMOS imaging surface. Figure 4 shows the machined tube assembled with the stock tube.

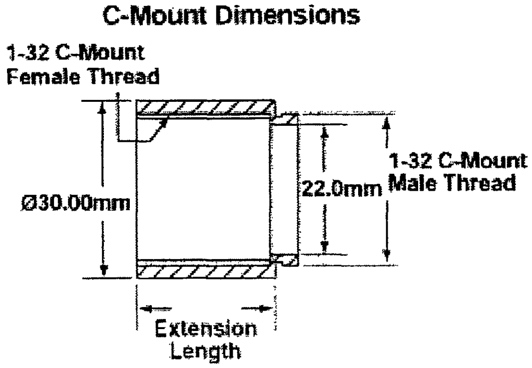

Figure 2: The specifications for the C-mount extension tube are shown here. The extension length is 5 mm.[3]

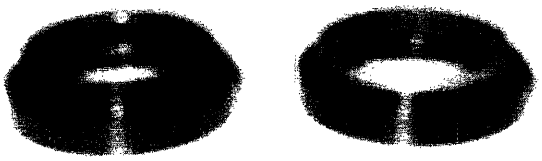

Figure 3: Stock tube is on the left; right tube has had the threads machined off.

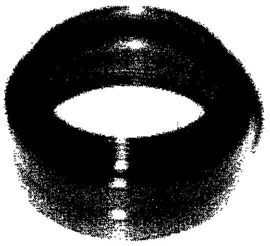

Figure 4: The tubes have been placed together, with the stock tube fitting over the top of the removed threads of the machined tube.

3.2.2 Bi-Concave Lens

Also included in the prism sub-module was a bi-concave lens, purchased from Sunex Optics, part # DVS013, shown in Figure 5. The bi-concave lens was used to increase the focal length of the system, since using the two 5 mm extension tubes for the 3D imaging

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[3] Picture from Edmund Optics website.
http://www.edmundoptics.com/IOD/DisplayProduct.cfm?productid=1510

module extended the distance between the camera lens and CMOS imaging surface. The lens had an outer diameter of 20 mm, and a focal length of 30 mm.

Figure 5: The bi-concave lens was supplied by Sunex Optics.

3.2.3 Prisms

Rhombic prisms, which shift light by a fixed distance without changing the direction, were needed to shift the two defocused blurs after light had entered through the two aperture slots. The light beams entering and exiting a rhombic prism are parallel to each other, but translated by a distance equal to the prism's critical dimension. Without the prisms, the blurs would have overlapped each other in the middle of the CMOS, creating a jumbled image. By shifting the images away from each other by 1/4 of the CMOS surface width, the surface of the sensor could be optimally used, with 1/2 of the surface being devoted to each image. The most common CMOS sensor size is 2/3 inch diagonal, which translates into a usable sensor area of width 8.8 mm. Thus, the rhombic prisms needed to have a critical dimension of 2.2 mm. Two rhombic prisms were ordered from Optarius, part # 11-6811, with a light shift of 2.12 mm. The dimensions of the rhombic prisms are shown in Figure 6, while the actual prisms received from the company are shown in Figure 7.

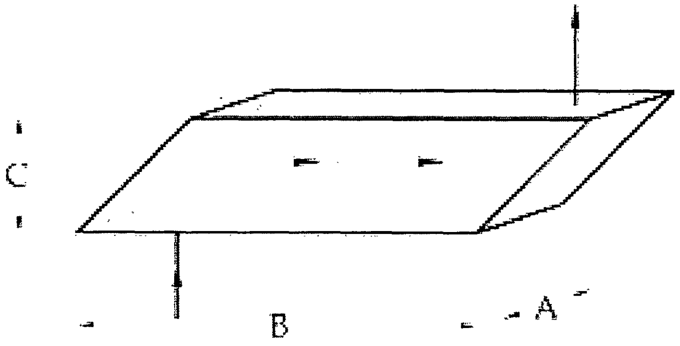

Figure 6: The arrows show how light is translated in a rhombic prism a certain distance, B, parallel to where it entered the prism from. In the prism purchased from Optarius, B, the critical dimension, is 2.12 mm, while A and C are both 1.5 mm.[4]

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[4] Picture from Lambda Research Optics website. http://www.lambda.cc/PAGE127.htm

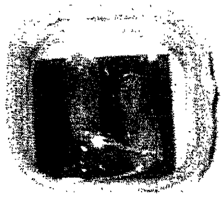


Figure 7: The two rhombic prisms in their storage container.

3.2.4 Prism Sub-Module

The prism sub-module and blocking mask were machined from aluminum. The sub-module consisted of the bi-concave lens, the two rhombic prisms, and a sleeve with integrated dual-aperture to which everything else was affixed. The combination sleeve and aperture component was machined from a piece of aluminum rod, 8.016 mm long. The external dimension of the rod was first machined to a 22 mm diameter, allowing it to fit snugly inside the C-mount extension tubes. The rod was then hollowed out from one end to a depth of 5 mm, leaving a tube wall thickness of 1 mm. The rod was hollowed out from the other end to a depth of 2 mm, again leaving a wall thickness of 1 mm. Two parallel slots, used as apertures, were then machined into the remaining 1.016 mm thickness of material in the middle of the rod. The slots were 1.14 mm wide, 6 mm long, and 4.96 mm apart (measured from the inside edge of one slot to the inside edge of the other), centered in the middle of the aluminum sleeve. This aluminum sleeve and aperture combination is shown in Figure 8.

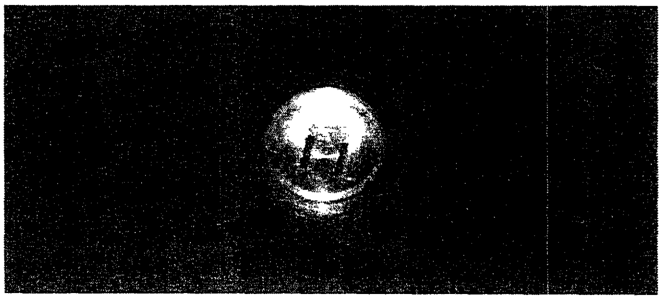


Figure 8: The combination sleeve and aperture can be seen in this picture, with the two machined slots, used as apertures, visible.

The bi-concave lens fit right up against the aperture inside the 2 mm deep side of the sleeve. On the other side of the aperture, where the rod was machined out to a depth of 5 mm, the two prisms were arranged such that they rested against the aluminum surface from which the apertures had been cut. The prisms were oriented so that each prism would take the light coming through one aperture and shift the image toward the middle of the tube by 2.12 mm.

3.2.5 Blocking Mask

The blocking mask was the other main component machined from stock material. A disc 20 mm in diameter was machined from 1.016 mm thick sheet aluminum. A slot was cut into the center of the disc, 6 mm long and 2.23 mm wide. The completed blocking mask can be seen in Figure 9. This disc fit into the 5 mm deep side of the aluminum sleeve, resting up against the prisms, oriented such that its slot ran parallel to the slots of the aperture. The entire prism sub-module, consisting of the sleeve and aperture combination, concave lens, rhombic prisms, and blocking mask were then fixed to the inside of the rotating C-mount extension tube.

Figure 9: The blocking mask can be seen here with the single machined slot.

3.3 Design Calculations

The location and dimensions of the components, most importantly aperture and blocking mask slots, of the 3D imaging module were developed based on a combination of desired optical behavior, such as an image shift distance of 2.2 mm to accommodate the CMOS chip size, and specifications of the pre-manufactured parts, such as the focal length of 30 mm of the concave lens. Also, the default focal length of a C-mount lens, 17.526 mm, was a crucial value.

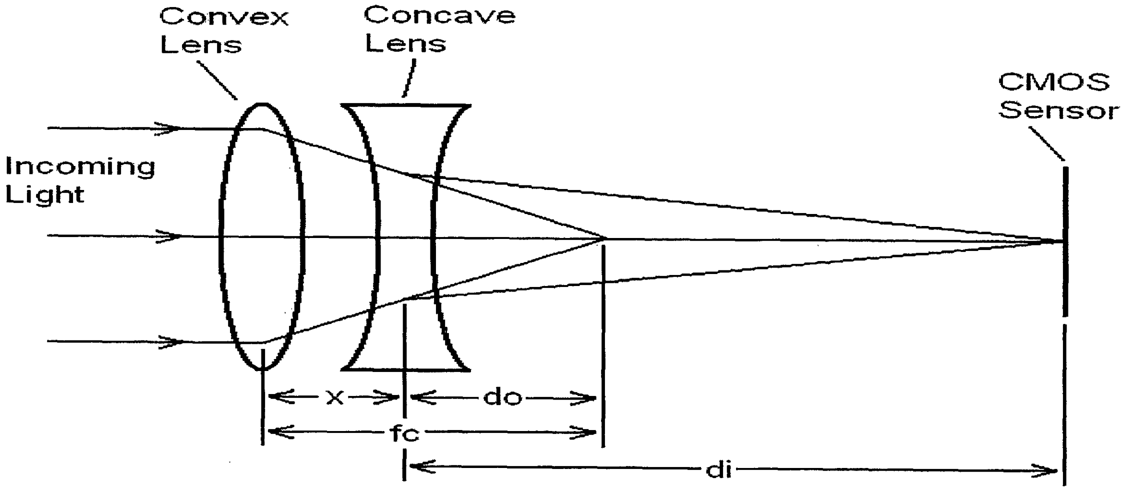


Figure 10: This diagram shows how the concave lens extends the focus length of the system.

Figure 10 describes how the bi-concave lens was used to extend the focal length of the camera system after insertion of the 3D imaging module caused the original C-mount convex lens to focus light too far in front of the CMOS imaging surface. In the diagram, fc is the original focal length, 17.526 mm, x is the distance between the convex lens and concave lens of the system, and di is the position of the concave lens relative to the CMOS sensor in the camera. Since the insertion of the 3D imaging module between the convex lens and the CMOS sensor added an extra length to the system equivalent to the module's length, the new distance from the convex lens to the CMOS surface, x plus di, is the sum of the original focal length, 17.526 mm, and the length of the 2 extension tubes that make up the module, or 10 mm total.

Using equation 1, an optics equation analyzing the result of placing a concave lens next to a convex lens,

$$1/fd = 1/do + 1/di, \qquad \text{(Eq. 1)}$$

where fd is the focal length of the concave lens, in this case 30 mm, the result yields a distance between lenses, x, of 4.5 mm. This equation also shows that the distance between the concave lens and the CMOS sensor, di, is 23.026 mm.

The two distances calculated with equation 1 were then used in conjunction with Figure 11 to determine the location and gap sizes for the aperture slots. The location of the apertures was determined by where the images needed to be placed on the CMOS imaging surface, after being shifted by the rhombic prisms. The aperture size was limited by the need to ensure that all light entering through the apertures was shifted by the prisms. Thus, the apertures had to be small enough to restrict the light entering at an angle from missing the reflective surfaces of the prisms. Any light not reflected by the prism surfaces would not have been shifted, leading to corrupt images on the CMOS sensor that would have been partially shifted in some areas and untouched in others.

Equations 2 and 3 were used to ensure that all light entering the apertures, regardless of the incidence angle, would be shifted by the rhombic prisms.

$$(1.5 - a)/1.5 = (y + 2.12)/D. \qquad \text{(Eq. 2)}$$

$$y = 2.12 + (1.5 - a). \qquad \text{(Eq. 3)}$$

The values a, y, and D correspond to the dimensions labeled in Figure 11. The distance, D, between the back side of the aperture plate and the CMOS imaging surface was found by subtracting the plate thickness and half of the concave lens thickness from the distance between the concave lens and CMOS surface, first found from equation 1 as di. The aperture width, a, was calculated to be 1.14 mm, and the distance from the centerline to the edge of the aperture slot closest to the centerline, y, was found to be 2.48 mm.

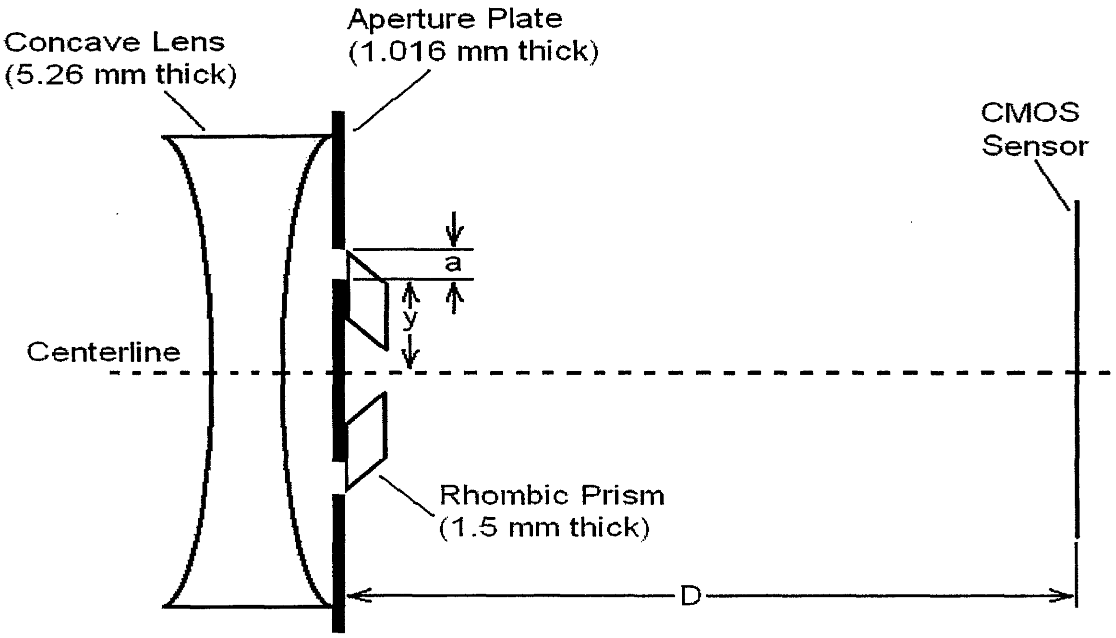


Figure 11: This diagram shows the setup involving the concave lens, aperture, and prisms. If the gap size, a, is too large, not all light entering the aperture will be reflected by the slanted surface of the prism.

The process for determining the slot size required for the blocking mask was similar to that of finding the aperture size. The mask had to prevent light from the two apertures from overlapping in the middle of the CMOS sensor. The smaller the width of the mask's slot, the larger the gap between the two images projected onto the CMOS surface. Having too small of a slot, however, would be wasting CMOS surface area that could have been put to use for imaging. Thus, the angle and location of light from each aperture, after being shifted by the prisms, were determined in the same fashion as it had been for the aperture slot widths. It was calculated that a mask slot size of 2.23 mm in width would be sufficient to ensure that there would be no image overlap in the middle of the CMOS sensor.

Please see Appendix A to view all of the technical drawings for the parts that were machined.

4 Results

The design phase of the low-cost Defocus Blur Sampling Module was completed before any parts were ordered or machined. The design, however, was created around the specifications of parts that could be ordered pre-manufactured. The pieces that needed to be machined were created as parts started to arrive. However, there was a 5 week lag time on the prisms as they were manufactured and shipped from Great Britain. Thus, the prisms were not received until over one month later. By that time, this thesis report was already due to the department. The low-cost Defocus Blur Sampler Module was never fully-assembled, though its parts have all been acquired and the schematic diagrams have been put on file. However, based on observations made during the design process, the prospect of this low-cost 3D imaging system does not look promising, mainly because production costs and machining requirements will push the costs of the system beyond what everyday consumers will probably be willing to pay for an attachment for their cameras. There is nothing wrong with the design itself. The two independent apertures simulate the one offset aperture rotating to two distinct positions, while the rhombic prisms ensure that the light entering from the two apertures for two distinct images on the CMOS chip surface.

The first and foremost issue that makes the design for this low-cost Defocus Blur Sampling Module implausible is that it will not be low cost, at least not low enough such that everyday consumers, who this device will be targeted towards, would want to purchase. This prototype, in just materials alone, cost over $200. The biggest single cost-factor in the device were the rhombic prisms. Those specialized optics pieces were $70 each. This high price was due to the requirement that the prisms have extraordinarily small dimensions to fit within the C-mount extension tubes and displacement images the proper distance. Even at mass quantities, the tiny prisms cost $40-$50 per piece. With digital camera prices as low as $200, it is doubtful consumers would be willing to purchase an accessory that could cost as much as half of the camera itself. Since the CMOS surface dimensions are all on the scale of 10 mm, the light shift that is required of the rhombic prisms will always be 1/4 of that dimension. That required light shift property of the rhombic prism therefore dictates that the prisms must be very small, making them hard to manufacture and expensive.

The second major issue encountered during the design and manufacture of the low-cost prototype was the machining of parts on a small scale such as 5-10 mm. The sleeve and blocking mask were all machined with dimensions such as 2 mm or 5 mm. Because of the small scale machining, both the setup and machining times were very long. This time requirement would once again translate into high costs if the device was ever manufactured in production. The time and effort required to machine the small dimensions were compounded by the needed precision to ensure the optics of the system would work out. Besides being time-consuming, some of the small-scale machining that was required was difficult to perform with common machine shop equipment. For example, the slots that were to be used as apertures were designed to be 1.14 mm wide, but the smallest available end mill that could have been used to machine the slots was 1.5875 mm wide. Thus, the aperture slots were machined wider than the design called for, and the extra space had to be partially covered with an opaque tape to narrow the slots. Machining everything that is required for the low-cost Defocus Blur Sampler Module will require specialty equipment and tooling to achieve the small-scale details and precision that is necessary for the module to function correctly.

As previously mentioned, production of this design for a 3D surface imager is difficult in part because of the high precision machining that is needed. When slots are being milled on the order of magnitude of 1 mm, being off by 0.1 mm means a 10% error. The precision of the pre-manufactured parts also poses additional problems. The bi-concave lens and rhombic prisms were both manufactured with tolerances of +/- 0.2 mm. This is a very significant variation in dimensions, especially since a difference of 0.05 mm could mean overlapping images or light not being completely shifted by the prisms. Dimensions are already very small, and if specifications, such as the aperture size and mask slot size, need to be made smaller to compensate for possible variations in pre-manufactured parts, there is a risk of losing image quality and possibly even the image itself since most light would be blocked out.

5 Conclusion

Three-dimensional surface imaging is a powerful technology that is currently underutilized. Existing 3D imaging systems on the market, including laser scanning, stereoscopic, and structured light systems, each have flaws that make them impractical to use unless there are no other alternatives. These systems are expensive, difficult to manage and execute, require lengthy processing times, and often yield poor accuracy and resolution.

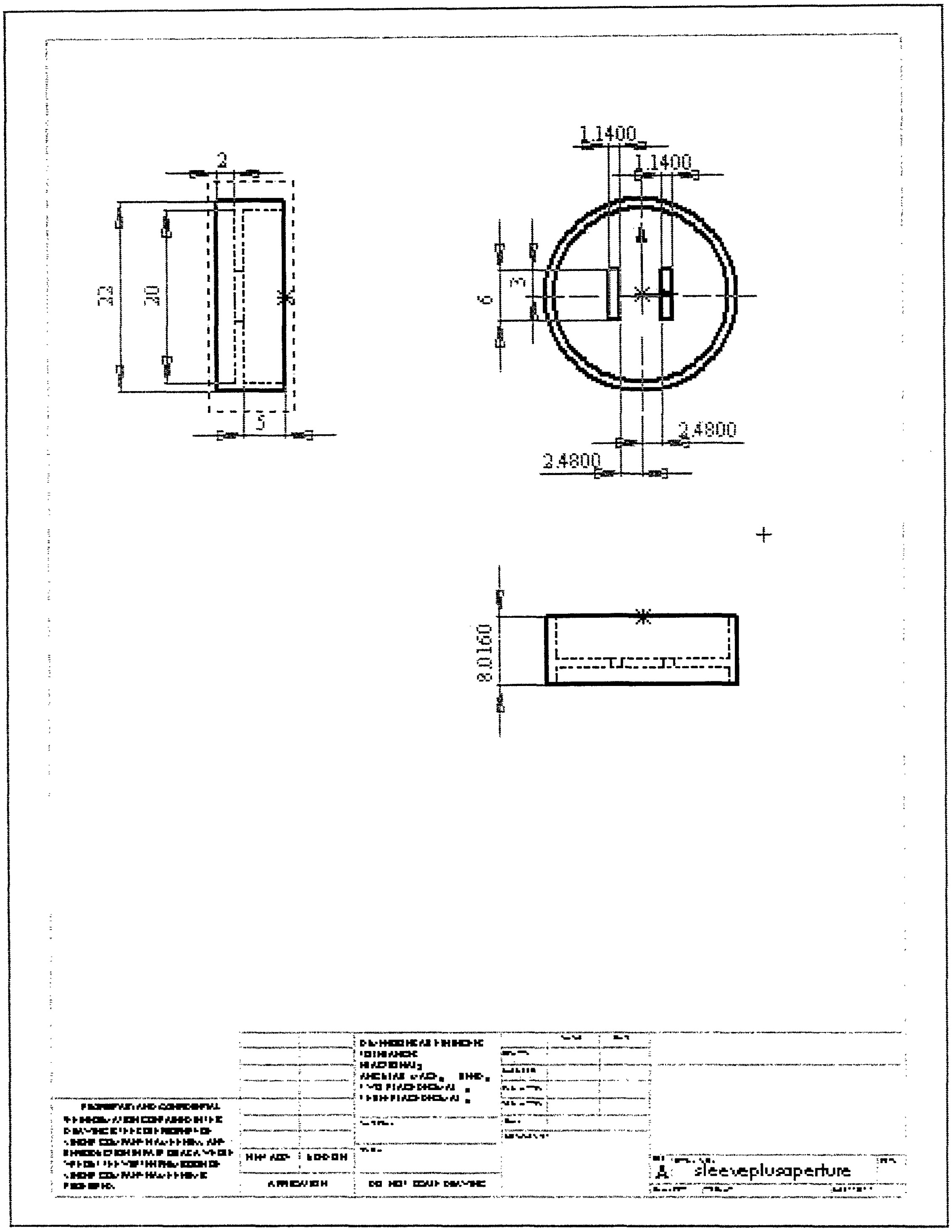
The Monocular 3D Imaging System solves many of these problems by providing a fast, accurate, high resolution solution for 3D surface imaging, all for a much lower price than the other systems currently on the market. By using an offset aperture on a rotating, opaque disc, the Monocular System projects images of the target object onto a digital camera's CCD from different aperture locations. An algorithm can then determine the target object's depth based on variations in the images corresponding to the different aperture locations.

The goal of this thesis was to design a simplified Monocular System that could be manufactured for even less money. This low-cost device, targeted towards home electronics consumers, would be able to attach to popular digital cameras and camcorders, effectively turning most photographic equipment into 3D surface imagers. To simplify the module, the rotating aperture was scrapped in favor of dual offset fixed apertures. Rhombic prisms were used to offset the images as they passed through the apertures, ensuring they would not overlap on the CMOS sensor surface. Due to the addition of the prisms and other components, a concave lens was inserted at the beginning of the module to extend the focal length of the system. The entire module was packaged in two short C-mount extension tubes, making it easy to carry around and install.

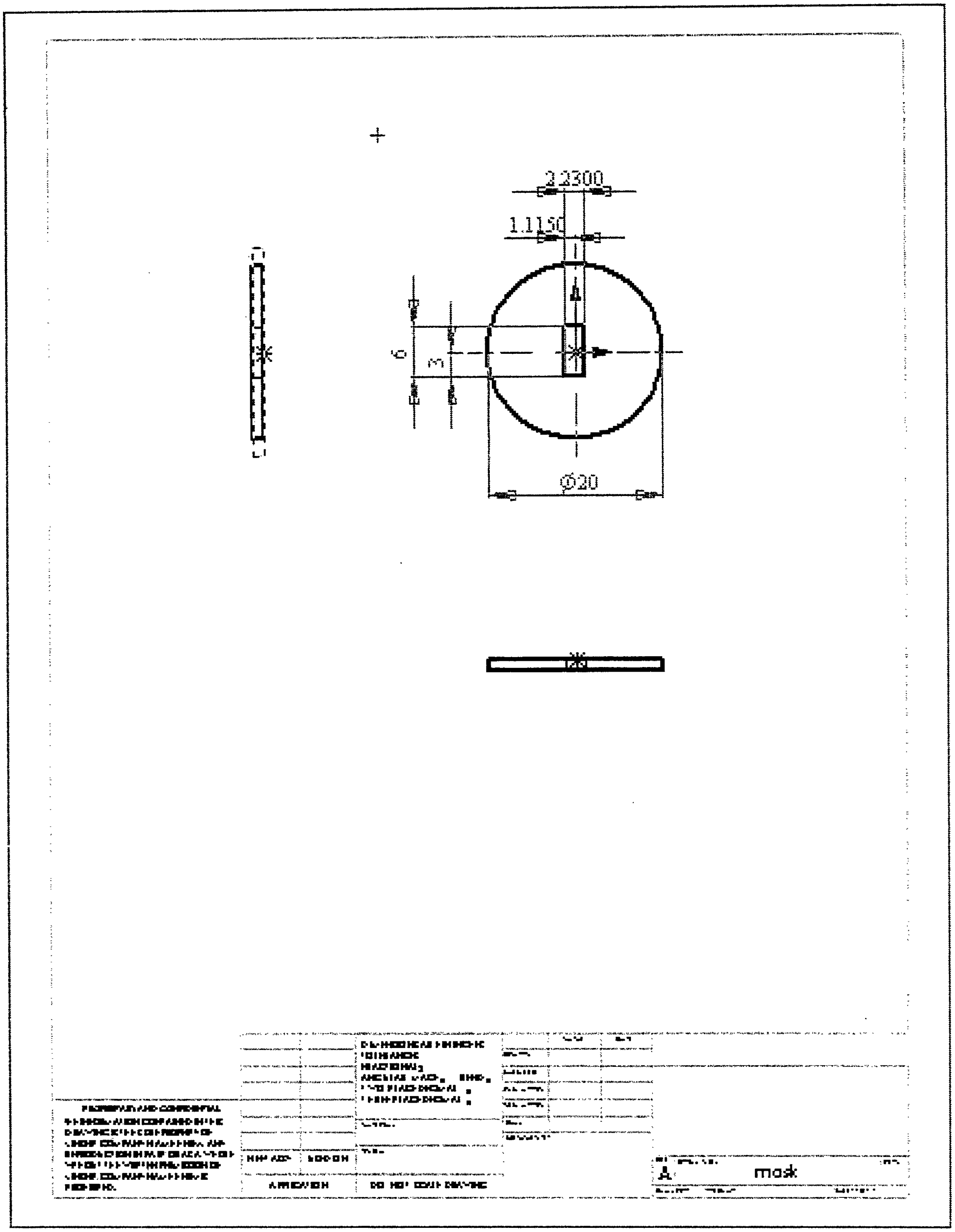
Because the prisms did not arrive until one week prior to this thesis being due, the module was not fully assembled or tested. If the theory behind replacing the rotating aperture with the dual, fixed apertures is correct, however, the low-cost Monocular System should perform similarly to its higher-cost sibling. Based on observations made during the manufacturing process, the low-cost version of the module may not be that desirable to take into production. The first problem is cost. If this low-cost version is targeted toward home electronics consumers, they may not be willing to pay for a camera attachment that costs half the price of a digital camera. The reasons why the cost for the module is so high are that the small prisms are difficult to make, and thus expensive, and the parts require precision machining that takes time and specialized tools. In addition, the tolerances in the prism and lens are around 0.2 mm, which is quite large considering everything is made on a scale of 1 mm. Thus, because of the imprecision of the pre-manufactured parts from suppliers, it may be difficult to obtain desired accuracy and results.

There are a few possible solutions to these problems. The entire size of the 3D imaging module could be scaled larger, making the tolerances less significant, and also removing the high costs associated with manufacturing everything on such a small scale. There could also be a way of decreasing the costs if rhombic prisms were not required. This would mean that the optics of the 3D module would somehow have to be manipulated to yield the same results as when there were prisms integrated in the system. Much of this discussion about cost would be a moot point, however, if people would be willing to pay the price to have a novel and useful attachment for their photographic equipment. That having been said, this low-cost version of the Monocular System could be a viable replacement for the original prototype with the rotating aperture. It may not be able to penetrate the market for home electronics consumers, but this design does pose a simpler and cheaper design than the original prototype.

Appendix A



Prism Sub-Module: Aluminum sleeve and aperture combination



Aluminum Blocking Mask: Cut from 0.040” sheet aluminum