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VARIABLE FOCUS THREE-DIMENSIONAL LASER DIGITIZING SYSTEM

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ABSTRACT

This paper describes a new three-dimensional scanning technology which is being developed at Colorado State University. Unlike other laser-based scanners which use active or passive triangulation to obtain surface range data, the new variable focus laser digitizing system (VFLDS) uses the principles of optical focal length to measure surface range data. This system should represent a significant step forward in speed and simplicity over current laser-based single point digitizing systems while retaining all of their advantages. The goal of the initial research presented here is to produce preliminary results which will prove the viability of this new approach.

INTRODUCTION AND PROBLEM STATEMENT

Three-dimensional surface digitizing, a method of building computer based models of real world objects using measurements obtained from the object itself, provides a direct link between physical design models and computer aided design and manufacturing (CAD/CAM) systems. A digitizing system measures range data for discrete points on an object's surface. Next, using advanced computer algorithms, these surface points are linked together and "built" into a three-dimensional computer model of the object which can be manipulated and modified digitally. 3D surface digitizing plays a major role in many wide-ranging applications including commercial design and manufacturing, inspection and quality control, surgical planning and simulation (especially cranial and facial reconstruction), biomedical prototyping and manufacturing of prosthetics and implants, and Hollywood special effects, where imagination can be turned into big-screen reality (Ashley, 1993).

Systems which perform three-dimensional surface digitizing have assumed a wide variety of forms suited to specific digitizing tasks. 3D scanner technology can be broken down into two distinct classifications: contact and non-contact sensing. Contact digitizers include both manual and automated sensing, while non-contact methods include automatic laser based triangulation, Moiré interferometry, and others (Skifstad).

Manual systems generally use a hand held probe operated by a skilled technician. As the probe is moved along the object's surface, the orientation of the probe's tip and corresponding surface coordinates are collected by optical, magnetic, acoustic, or jointed arm means. These devices offer advantages of low cost and portability, however they are limited by low speed data acquisition and human interaction requirements.

Similarly, Coordinate Measuring Machines (CMM) make use of a mechanical probe making direct physical contact with the object. Unlike manual systems, however, the CMM probe is manipulated mechanically, often by a robotic arm, moving in a predetermined pattern.

Moiré interferometry utilizes field of view acquisition of distorted Moiré fringe patterns ("ripples" of light) to extract surface details (Skifstad). These systems require complex and sometimes unreliable data processing. Also, the small field of view of Moiré projectors and CCD cameras can require multiple sensing arrays and it is often difficult to reliably fuse the results of the independent overlapping data sets.

The majority of non-contact measurement systems use some form of laser light to capture surface information. The laser may be employed as a collimated beam, collecting single data points, or projected as a plane of light, often collecting thousands of data points at a time (Wohlers 1992, 1993). In either case, the surface range data is determined using the triangulation principle illustrated in Figure 1. While laser plane methods represent an advantage in scan speed, point methods still have the upper hand in cavity probing situations. Also, point methods do not demand the complex optics and image processing power required by line technologies making their design more simple and less expensive.

Unfortunately, laser point scans are often limited by their triangulation methods. In passive triangulation, a linear CCD array is used to determine object range via similar triangles (see Figure 2). Limited range due to the size of the CCD array as well as well as the necessity of CCD image processing techniques make this method less include both manual and automated sensing, while non-contact methods include automatic laser based triangulation, Moiré

used to determine object range via similar triangles (see Figure 2). Limited range due to the size of the CCD array as well as well as the necessity of CCD image processing techniques make this method less than ideal. Active triangulation uses mobile sensors searching at fixed angles, to locate the illuminated laser reflection and determine range by simple triangulation (see Figure 3). This method is used by several commercial scanners including Digibotics' Digibot, a scanner whose prototype was developed here at Colorado State University seven years ago (Koch). Because of its separate left and right sensors, Digibot scans can become time consuming as the complexity of the surface increases and the system is forced to perform search-and-switch operations around object corners and cavities.

With variable focus laser digitizing, the problems associated with other laser point scan technologies, specifically those related to system complexity and range limitations (passive triangulation) and search-and-switch operations (active triangulation), will be eliminated by a system which retains the simplicity and low cost of a single photo-diode sensor acting on the laser's line of sight.

Variable Focus Laser Digitizer

A focused beam of light converges in a cone shape from the source lens to a point (focal point) of minimum cross-section, then diverges away from that point in increasing diameter as distance from the source increases (see Figure 4). Total energy of any cross section at any distance is constant and equal to the energy through the source lens. As the beam is focused down, however, the energy per unit area increases as the cross-section decreases. Using laser techniques we hope to use this optical property to develop a 3D surface digitizing system which has the potential to outperform current active triangulation systems in the areas of speed, simplicity, and cost.

Experimental Procedure and Preliminary Data

For initial proof-of-concept testing we developed a crude experimental design utilizing a helium-neon laser mated to an off-axis vertical aperture photo-diode sensor aimed at spot center (see Figure 5). The photo-diode sensor receives a thin strip of laser light reflected from the target's surface through the vertical aperture. The laser beam's focus is held constant while the target/sensor position is varied, resulting in a varying diameter spot of laser light projected onto the target. Total energy projected by the laser remains constant, while reflected energy per unit area varies with focus. Accordingly, the vertical aperture strip area, a percentage of total spot area, yields a varying energy per unit area when received by the photo-diode (see Figure 6 a.). The output of the photo-diode, a voltage proportional to the incident light energy, is measured to determine the maximum energy per unit area as focal distance is varied (see Figure 6 b.). This maximum should correspond to the laser's focal length when focused on the object (i.e. the smallest spot corresponds to the highest energy per unit area). The known focal length can then be converted to a range value which can in turn be used to determine surface point coordinates for three-dimensional digitizing.

In the initial runs using the experimental set-up, several curves like figure 7 were obtained. As anticipated, the voltage rises as the distance from the converging lens approaches the minimum spot size located near 38.5cm, then decreases as the spot size increases away from the focal point. Do to limits in sensor and laser alignment of our initial design, we chose to keep the step size large (on the order of 1 cm.) as a demonstration of the principle. We anticipate smoother curves and better resolution especially near the minimum spot region with a more accurate experimental test-bed which allows for precise lens, sensor, and laser alignment.

Future Work

The next step in the VFLDS project is to characterize the accuracy of the design. This will entail precise aperture evaluation and lens control as well as defining accuracy limiting factors such as beam alignment. The current off-axis design will be tested for its potential as will an on-axis design which could allow true line-of-sight ranging. The on-axis design might take the form of figure 8, where complex optics would allow for precise focal length control and an in-line mirror, blocking a small percentage of the incident energy, would direct the spot image from the optical axis to the photo-sensor.

Once we have established experimental results that achieve a desired accuracy comparable with other digitizing systems, we would like to continue development towards a complete digitizing system. This may entail interfacing the new technology with the department's prototype Digibot scanner, which could form a ready-made platform for software development, including a closed-loop feedback control algorithm for real time scanning. Because of the design's simplicity we anticipate a complete scanner package to be far less costly than current laser-based scanners. This alone should open up more applications of surface digitizing technology where cost was previously prohibitive.

Conclusions

This work to date has shown that the variable focus laser concept has potential for surface digitization. The distinct change in voltage corresponding to focal length in these simple test runs suggests the power of the technology. To match the capabilities of current commercial digitizer designs, however, more tests will need to be conducted to fine-tune the overall ranging accuracy of the system. Our next step is to develop a precise experimental platform to test aperture and sensor combinations and the accompanying electronics, and optimize the overall design for accuracy and reliability.

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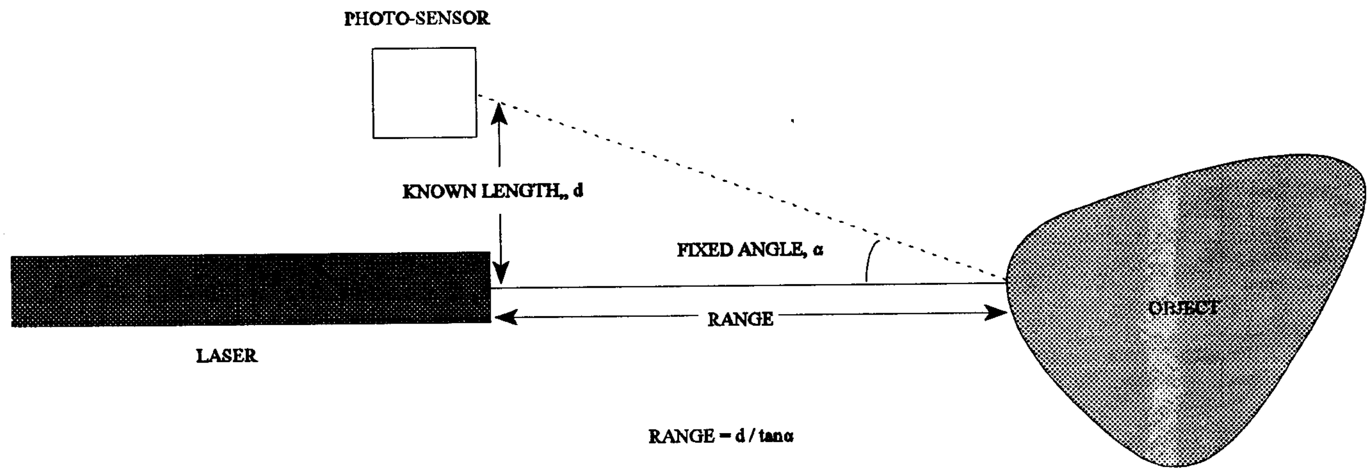


FIGURE 1 - TRIANGULATION TO DETERMINE RANGE

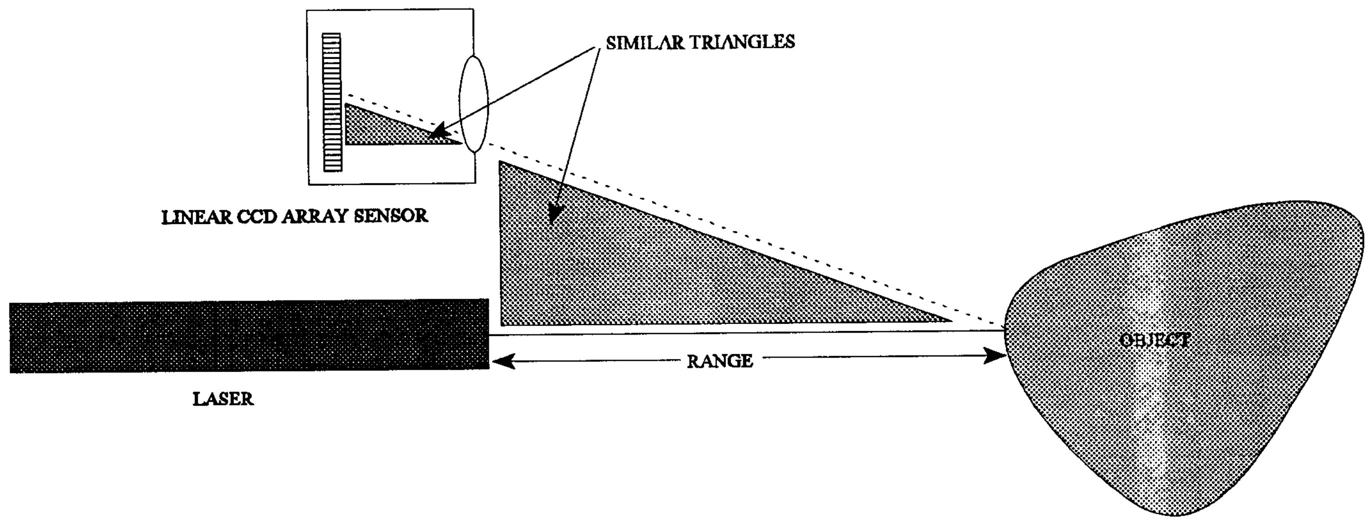
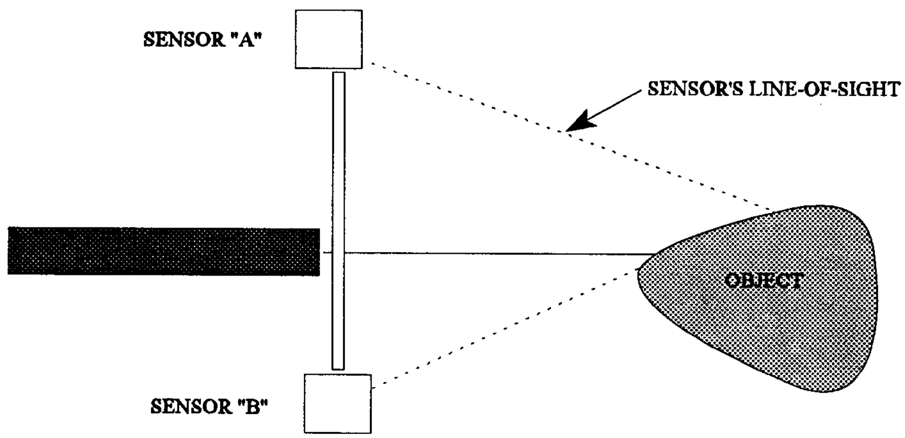
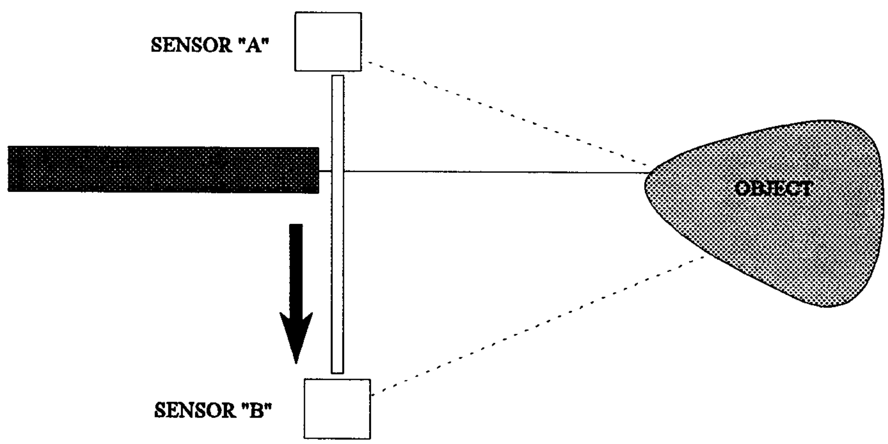


FIGURE 2 - PASSIVE TRIANGULATION via. LINEAR CCD ARRAY



a.) LASER POINT OBSCURED BY OBJECT, NO TRIANGULATION via. SENSOR "B"



b.) REQUIRES SENSOR UNIT TRANSLATION FOR SENSOR "A" TRIANGULATION

FIGURE 3 - ACTIVE TRIANGULATION

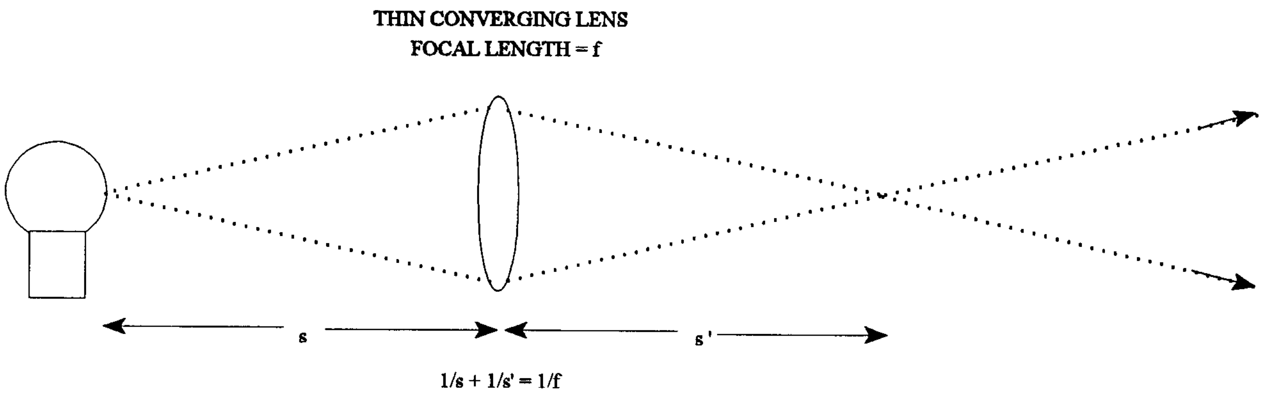


FIGURE 4 - FOCAL LENGTH PRINCIPLE

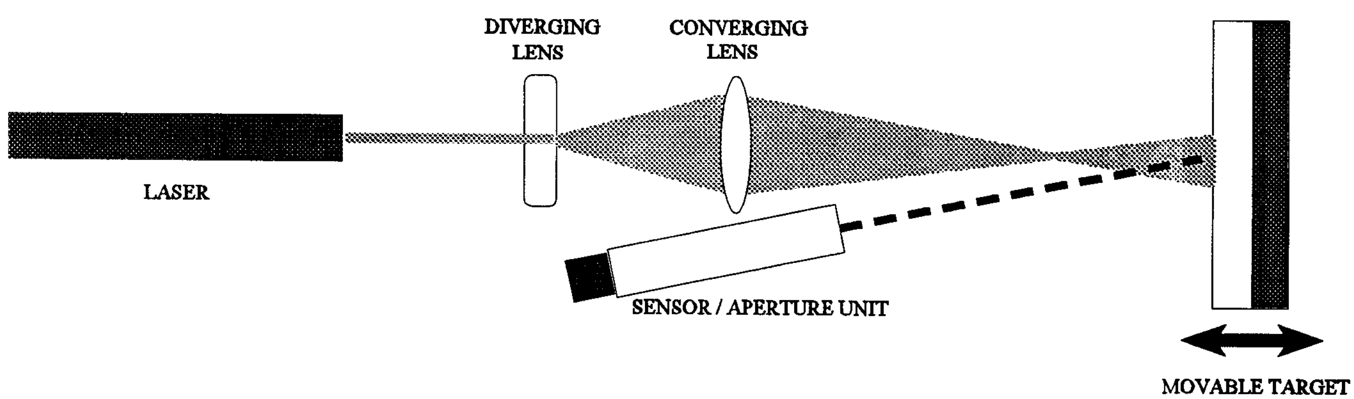
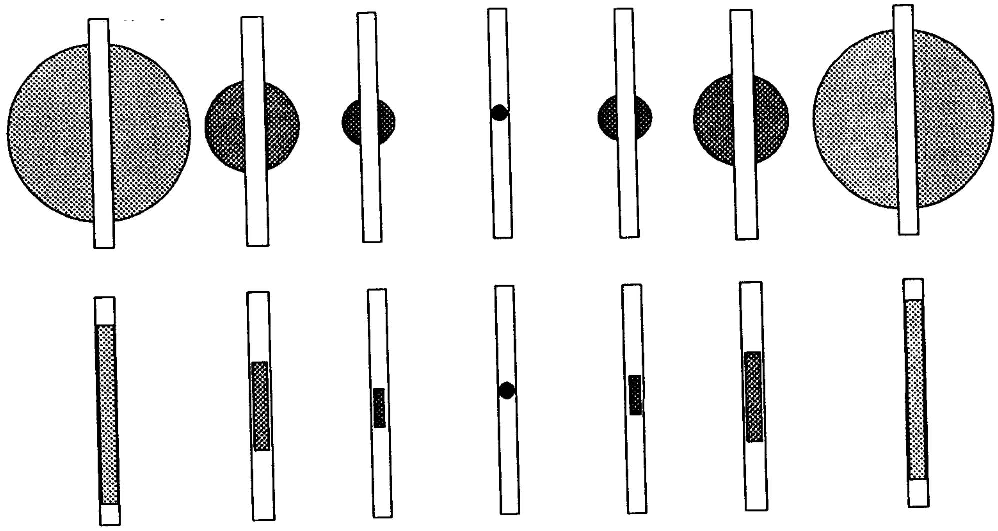
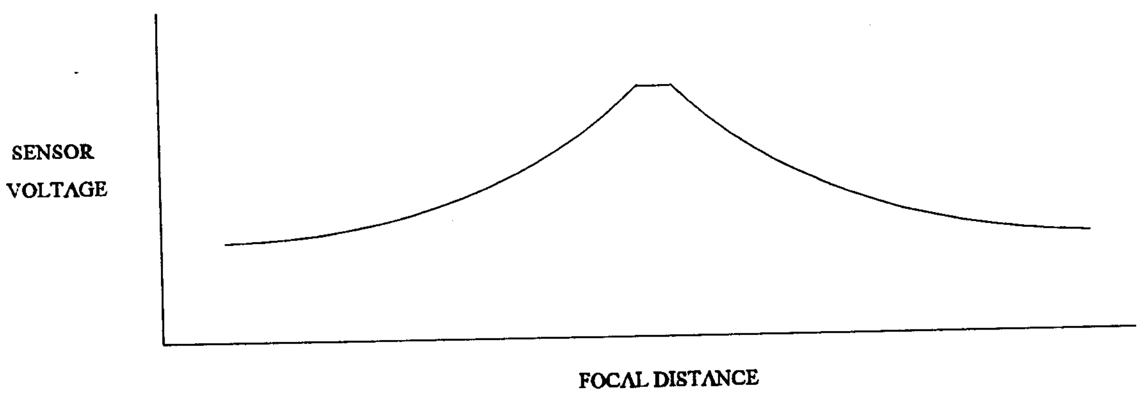


FIGURE 5 - EXPERIMENTAL VFLDS SET-UP



a.) AS SPOT SIZE DECREASES AND ENERGY / UNIT AREA INCREASES

TOTAL ENERGY SEEN THROUGH THE VERTICAL APERTURE INCREASES



b.) ANTICIPATED VFLDS SENSOR RESPONSE

FIGURE 6 - ENERGY SEEN THROUGH VERTICAL APERTURE

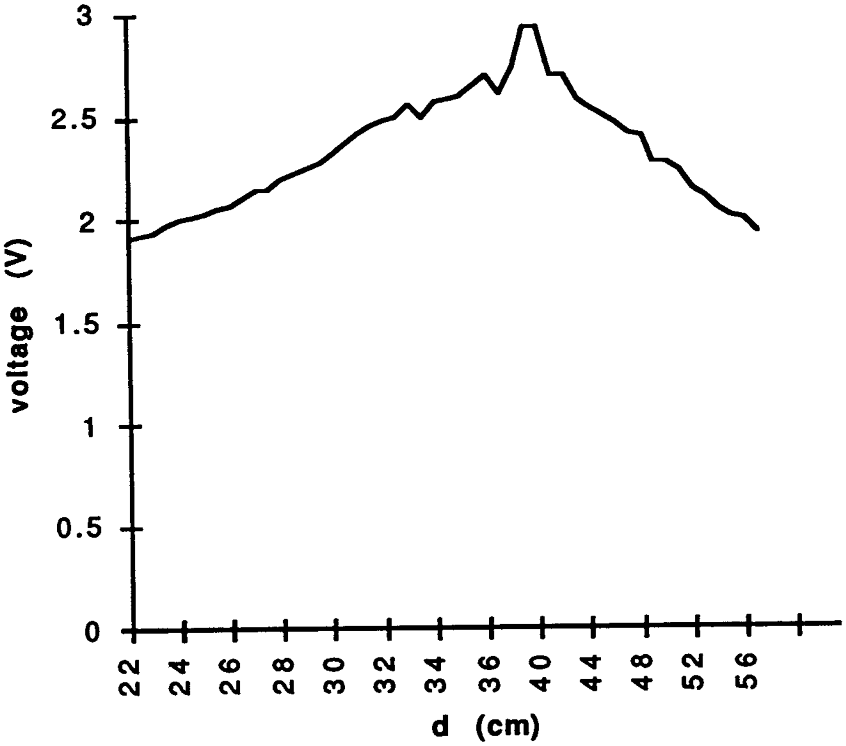


FIGURE 7 DISTANCE FROM LENS VS. SENSOR VOLTAGE

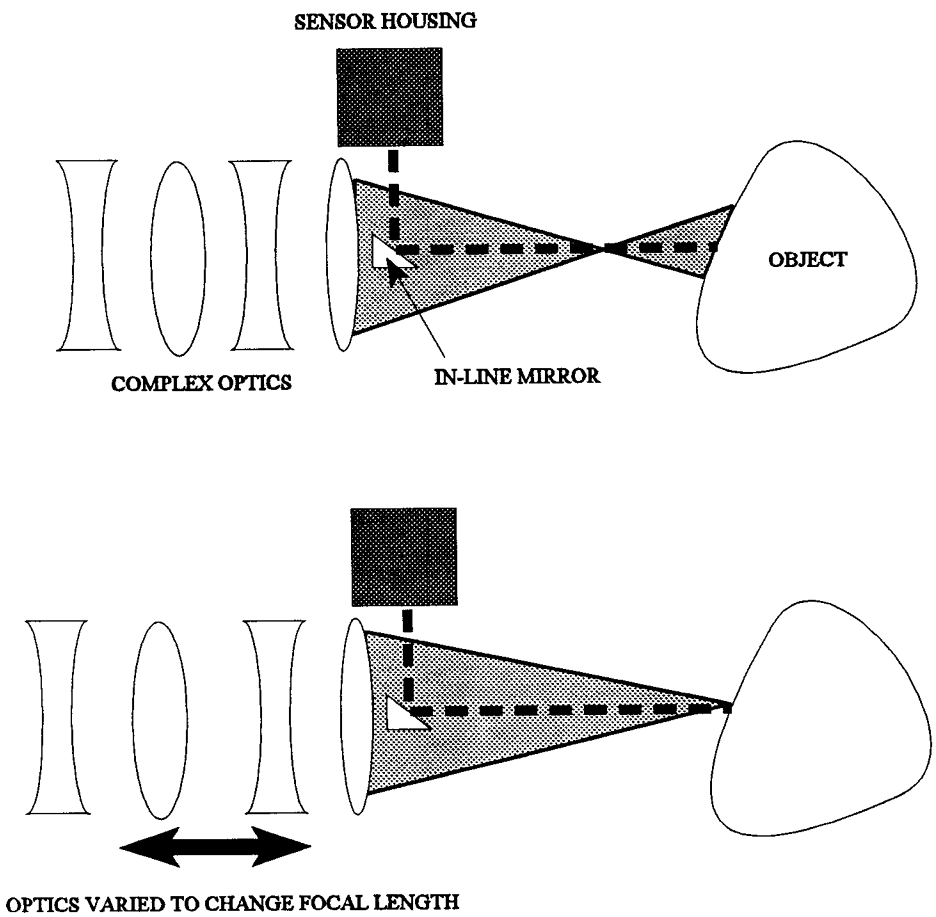


FIGURE 8 - ON-AXIS VFLDS DESIGN UTILIZING COMPLEX OPTICS AND IN-LINE MIRROR