LASER RANGE FINDER DEVELOPMENT FOR 3-D VISION

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Abstract

Laser range finders can be used in a variety of geometries to match requirements of applications such as robot vision, inspection, prosthesis fabrication, CAD/CAM, computer graphics, automatic assembly and many others. This paper reviews the development of five prototypes which have specific advantages for a class of applications. One of these is based on the use of a mask with conventional TV camera lens and the others are variations of synchronized laser scanners. We are also describing a collection of 3-D images data base which we make available for computer vision researchers.

Résumé

Les capteurs de distance par laser peuvent être utilisés dans une grande variété de géométries afin de satisfaire les exigences d'applications aussi variées que la vision automatique, l'inspection, la fabrication de prothèses, la CAO/FAO, l'infographie, l'assemblage automatique et bien d'autres. Cette présentation décrit le développement de cinq prototypes ayant chacun des avantages spécifiques pour une classe d'applications. Un de ces prototypes est basé sur l'utilisation de masque à l'intérieur de lentilles de caméra vidéo, et les autres sont des variations d'une approche appelée le balayage laser synchronisé. Nous décrivons aussi une collection d'images 3D, lesquelles sont disponibles pour les chercheurs en vision automatique.

Key Words

Three-dimensional vision, laser scanner, computer vision, range imaging, three-dimensional measurement, robot vision.

Introduction

Why 3-D sensing? Mainly because 2-D pictures are projections of 3-D scenes in a 2-D space. For very constrained situations where most objects of interest are flat and have few stable positions, 2-D imaging can be tuned to extract geometrical features with enough accuracy for manipulation and inspection. Otherwise, the 2-D projections of the 3-D objects are ambiguous. They are subject to modifications with any change of the illumination source, its spectral characteristics, or its orientation relative to the scene and/or camera. The projected contours in 2-D imaging also change with a change in the orientation of the object, a translation in the field of view, and with position of nearby objects which scatter incident light on the object of interest. A change in distance from the camera produces a scaling effect that must be taken into account at the image processing stage. As the processing is based on intensity data, in addition to the geometrical effects, the surface properties such as color and texture will modify the value of each pixel and their relationship to each other.

What motivates research in this direction is that the eye-brain system in humans has resolved the difficulty of 3-D reconstruction and as a consequence researchers know that it is possible to make sense from 2-D imagery. How is it done? Answering this question will require many more years of research. But it must be remembered that the task is complex.

In contrast, 3-D imagery keeps the invariance properties of 3-D objects. The relationship between pixels is invariant with rotation and translation. With structured light approaches, for example, the 3-D data are insensitive to background illumination and to surface color and texture of the object. These invariant properties, combined with the absence of scaling effects, make the image processing tasks easier. Although it seems more difficult, computer processing of 3-D data is greatly simplified.

As an illustration, Figure 1 shows 3-D and 2-D pictures of human faces. The illustrations in (b) are the 3-D data where the range (or elevation) is coded in grey level for display. These pictures represent the x, y, z coordinates of the surface topography of the faces. Figure 1(a) is an intensity picture (essentially a normal photograph) of the same subjects (x, y, I). The eye-brain system has learned to make 3-D reconstruction from this type of representation, but, if the mode of representation is changed (as illustrated in (c) and (d)), it is interesting to note that now, in the case of an isometric representation, it is the x, y, z display that makes sense to the human observer. The isometric view of the x, y, I shows the complexity of the processing required to recover the geometry.

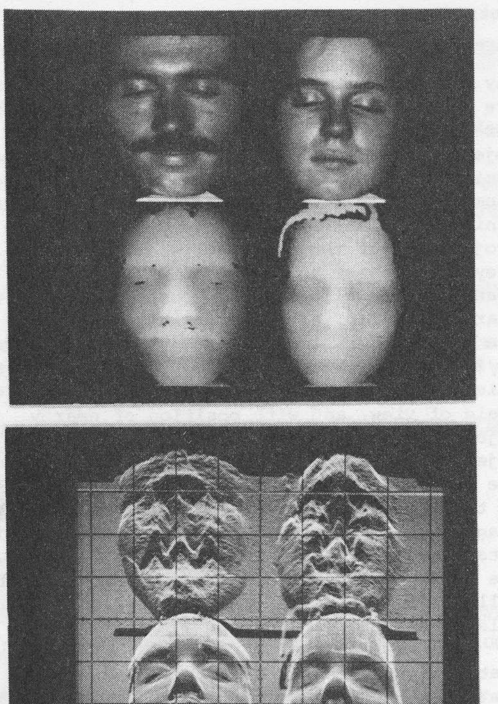

Figure 1. Range imaging of human faces.

In a) we display the image of the laser light intensity scattered back to the position sensor, in b) we display the range image as grey levels coding. White areas are closer to the camera than black areas. In c) we have an isometric view of the intensity image shown in a) and in d) we also have an isometric view of the range data shown in b).

BIRIS: A Double Aperture Mask in a TV Camera Lens

This is one of the geometries described in reference [1,2,3] to extract 3-D coordinates from a scene. Figure 2 is a diagram showing how triangulation through the lens is made. A double aperture mask is introduced in the camera lens. A reference plane is set by the camera lens focusing adjustment. For example, if the camera lens is set to be in focus at one metre, the reference plane is then one metre from the lens. At this position, the mask in the lens has no effect and a point A on the reference plane is imaged in a point A' on the image sensor (typically a CCD device). On the other hand, a point B on an object's surface will be imaged in B' and the cross section of the image at the CCD plane will show two points b' for which the separation is proportional to the distance between point A and point B.

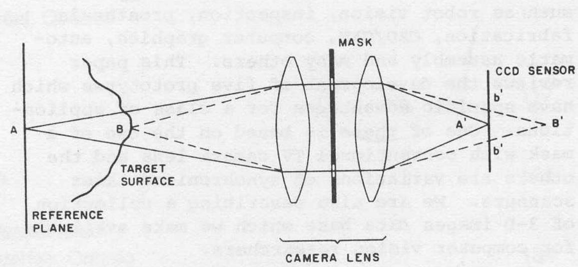

Figure 2. Geometrical arrangement used for BIRIS.

A mask is inserted in a normal TV camera lens in order to obtain 3-D measurements by triangulation through the lens.

In order to specify points on the object to be measured, we use laser projections of either points or lines. A grid of points can be used for sparse data acquisition, or multiple lines for high speed 3-D imaging. Indeed, data rates are proportional to the number of projected lines times the TV line rate (15.75 KHz). A laboratory prototype acquires and processes at video rate eight lines per frame which is providing more than 10^5 3-D coordinates per second. Figure 3 shows an isometric view of a step pyramid measured at one metre in front of the camera. Resolution is in the order of one millimetre.

Another interesting geometry is to use a single line projection and rotation of the TV camera around a vertical axis. In this arrangement, we were able to make panoramic range images of the interior of a room.

Because the resolution increases as we get closer to the object, it has potential in mobile robotics. Figure 4 illustrates experimental results where intensity (4(a)) and range image (4(b)) are shown.

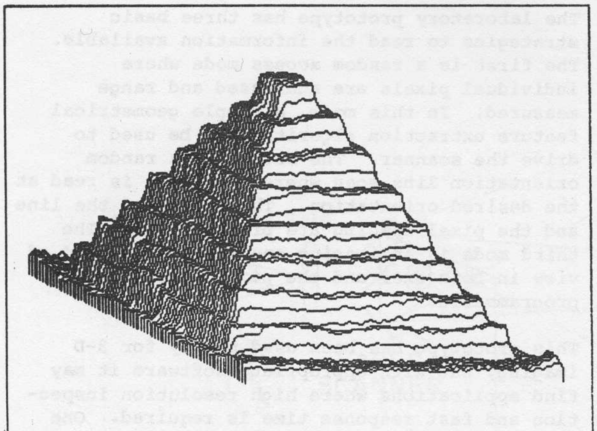

Figure 3. Isometric view of range data obtained using BIRIS.

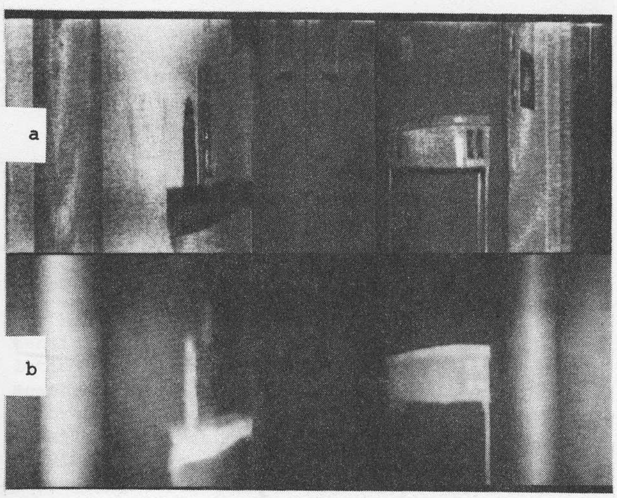

Figure 4. Panoramic view of a room using BIRIS.

In a) we display the intensity. In b) we show range data.

Range Imaging Using Synchronized Scanners

High Speed Prototype

The main interest for synchronized scanners [4] is the removing of the usual constraints of optical triangulation. In this geometry, the adjustment of image acquisition parameters can be set independently along each axis x, y and z. Figure 5 illustrates a typical arrangement for high speed range imaging. The pyramidal rotating mirror provides the x axis scanning while the stepper motor driven mirror provides the y axis deflection (slow scan axis). Range measurements (z axis) are acquired using a detector made of a lens and a position sensor. The focal length of the lens is chosen to set the depth of view, and the resolution, along the 2 axis, is equal to the resolution of the position sensor. For example, if the position sensor can resolve 300 positions, then 300 positions will be resolved along the range. A unique property of these geometries is that a change in the focal length of the lens does not change the lateral field of view (along the x and y axis) which is set by the scanners characteristics only. A side benefit is the reduction of shadow effects to its minimum. Figure 6 shows a photograph of a laboratory prototype using a lateral effect photodiode as a position sensor. The sampling rate is 600 KHz and the resolution is of the order of 0.5 mm. Again, an acquisition consists of an intensity image and a range image in perfect registration.

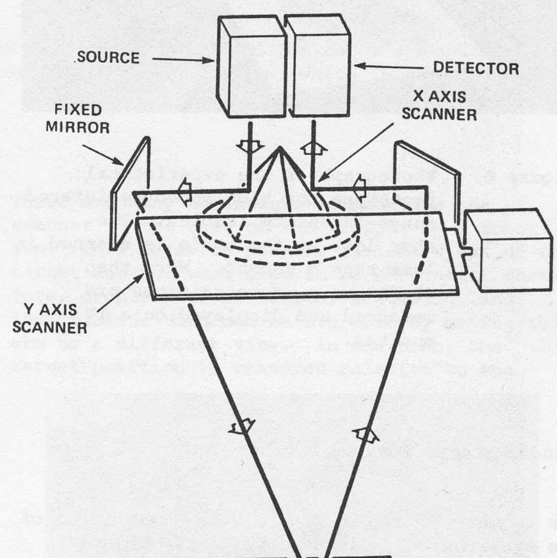

Figure 5. Geometrical arrangement for high speed range imaging camera.

Figure 6. Photograph of the experimental prototype for high speed registered range-intensity imaging. The shoe last on the table is scanned in less than a second. More than 65,000 x, y, z coordinates are measured and displayed on a TV monitor.

Random Access Imaging Device

The geometry shown in Figure 7 is a variation of the synchronized scanners approach. This is obtained using a double sided coated mirror. One side is used for projection of the laser source onto the scene and the other side is used for collection of the scattered light coming from the surface of the object. A second mirror deflects both the projection and the detection axes. Both mirrors are driven by a galvanometer. This gives fast access to any pixel in the field of view. The basic idea behind this development is to consider the scene as the computer memory and the scanner as an addressing device. The scene can then be interrogated without having to sample the whole field of view.

Because the resolution of the galvanometer can reach easily 12 bits, the "image" in the scene gives access to more than 16×10^6 pixels. The third coordinate is given by a position sensor on which is imaged the scattered laser light.

The laboratory prototype has three basic strategies to read the information available. The first is a random access mode where individual pixels are addressed and range measured. In this mode, a simple geometrical feature extraction algorithm can be used to drive the scanner. The second is a random orientation line scan where a profile is read at the desired orientation. The length of the line and the pixel spacing are programmable. The third mode is an imaging one where the field of view in both axes and the pixel spacing are programmable.

This prototype has been used mainly for 3-D imaging, but with appropriate software it may find applications where high resolution inspection and fast response time is required. One other application is the searching and tracking of a moving object in a large volume. We know that sampling the whole volume many times a second is impractical, so in those cases a random access geometry coupled with a model driven strategy of scanning may accelerate the process by many orders of magnitude.

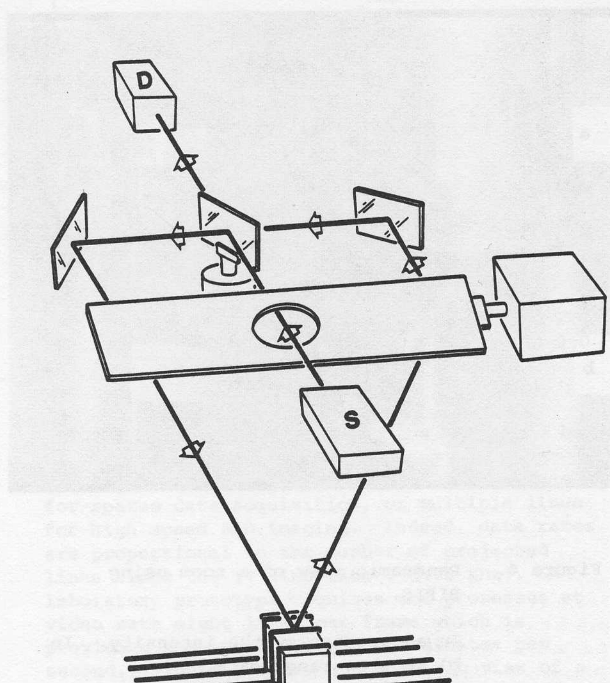

Figure 7. Two galvanometers are used to achieve random access imaging. One is used to drive the horizontal scan, the other the vertical. Although raster imaging is shown here, this geometry can be used for randomly oriented line profile acquisition or single pixel range measurement.

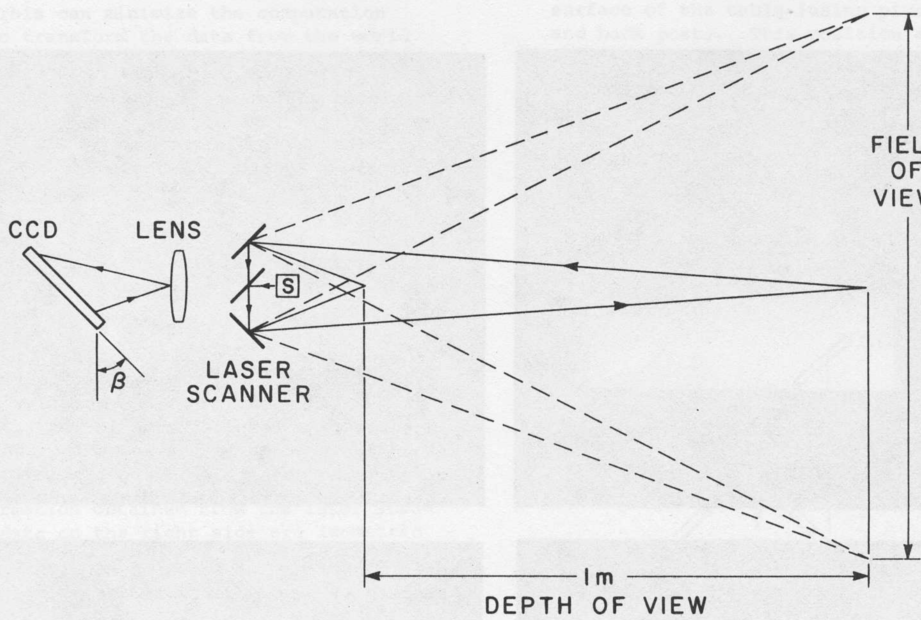

Figure 8. Laser scanner geometry for robot vision.

Here, the depth of view and the field of view have been matched to the robot's needs. Resolution is coarse at one metre from the camera and fine at 10 cm (which is at the gripper level).

Robot Mounted Prototype

This prototype uses the geometry shown in Figure 8. Here, we are interested in providing visual sensing to a robot arm. In this case, the resolution need not be uniform within the range of measurements, but the depth of view is extremely important. Generally speaking, we need to have detailed information when the robot hand is in proximity to the object in order to make a precise grasp. For distant objects, a coarser image is more appropriate in order to find objects in the scene without having to process a large amount of redundant data.

For this prototype [5], an He-Ne laser is coupled to a single-mode fiber using a rod lens. The other end of the fiber, placed inside the compact optical head, also has a rod lens, which collimates the laser beam for the required measuring range, which is at a maximum of 1 m in this case. The use of an optical fiber allows us to design a compact and lightweight scanner head, which is highly desirable for robot mounting. In a research environment, an additional advantage is the flexibility to change the laser source without redesigning the measurement head. The scanning mirror is attached to a galvanometer scanner, which provides up to 40° scan angle (corresponding to a 0.8 m field of view at maximum distance). The projected beam is scanned using the front face of the scanning mirror, while the detection is made using the back face.

There are many advantages to mounting the scanner at the base of the gripper on a robot arm. This location permits various views of the target and the work area to be obtained. Therefore, problems of occlusion, shadowing, and insufficient data can be overcome by moving the arm to a different view. In addition, the target position is measured relative to the

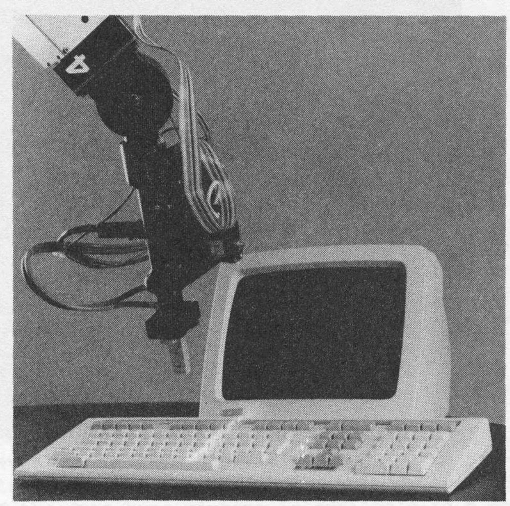

Figure 9. Small laser scanner mounted on the wrist of a PUMA 560. Line profile acquisition of the keyboard is made at about 30 cm from the camera.

a

b

c

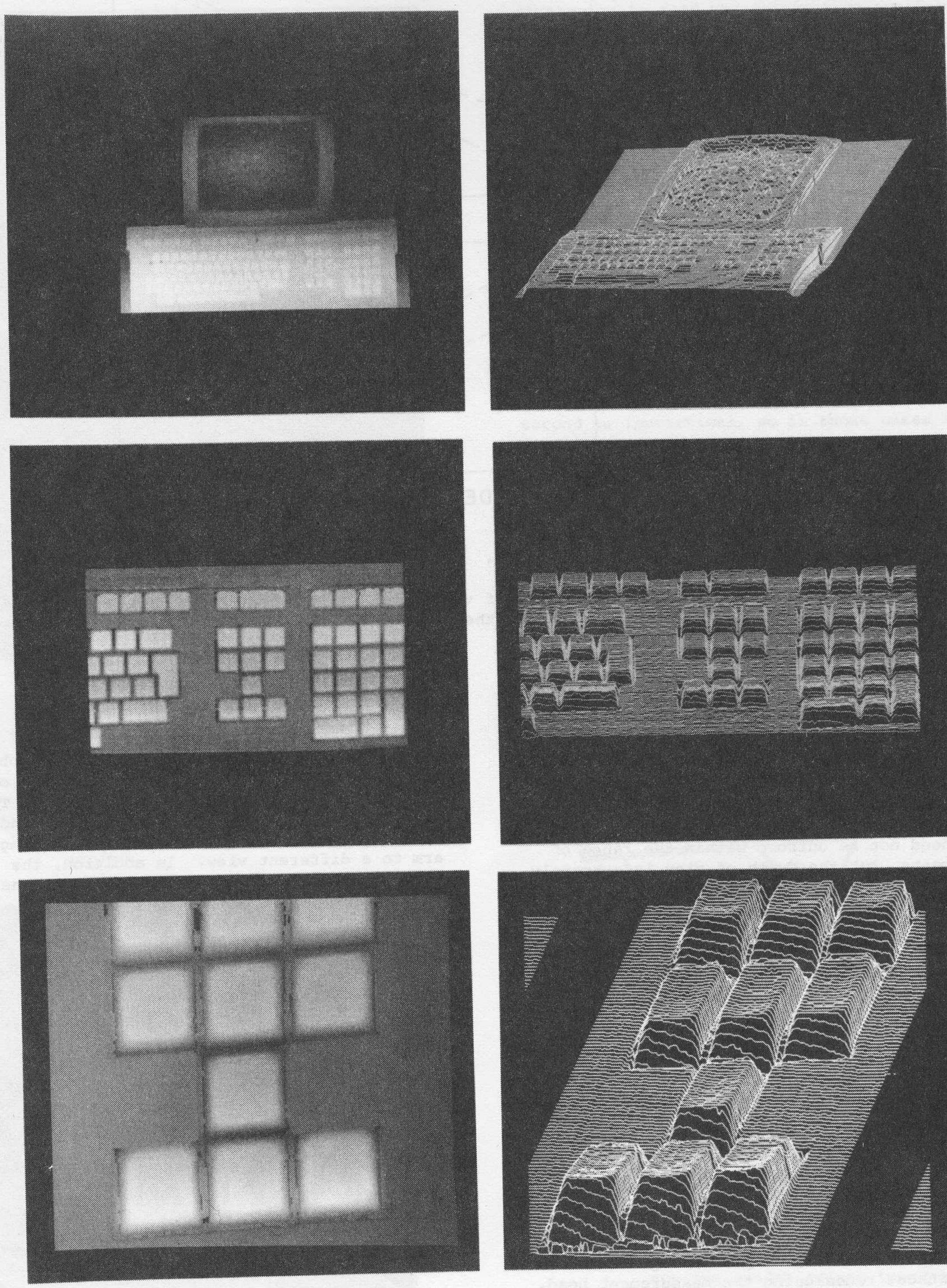

Figure 10. Range images obtained by the robot laser scanner.

In a) we display the range data obtained at one metre from the camera. On the left side, we have the grey level coded image, and on the right, we have an isometric view of the same data. In b) and c) we have the images obtained at 30 cm and 10 cm.

gripper. This can minimize the computation required to transform the data from the world coordinate system to the robot coordinate system to the gripper coordinates. The profile scanner was designed to be small, lightweight, and rugged to permit locating it at the gripper attachment. Figure 9 shows the prototype installed on a PUMA 560 robot.

The physical dimensions of the optical head are width = 80 mm, depth = 120 mm, height of body = 28 mm, and overall height = 80 mm. The weight is 450g, and the range is 10 cm to 1 m. The scan angle 40°, with a resolution of 256 angular increments, and the scan rate is 25 profile/s. The laser power on the scene is 4 mW.

A 3-D image is generated by moving the robot arm to acquire a series of profiles. This is shown in Figure 10. The data displayed on the photographs on the left side are intensity-coded range information obtained from the laser scanner. The data on the right side are isometric plots of the range data for the corresponding views. The top view is made at the maximum distance (~1 m from the scanner), the middle view at about 250 mm, and the bottom view at 100 mm.

High Resolution Prototype: The Optical CMM

The geometry of this prototype is very similar to the random access unit except that the second mirror used for deflection of both the projection and the detection axes have been replaced by mechanical translation of the whole camera [6]. A graphical representation is shown in Figure 11. For this prototype, a special care has been put on the accuracy of the laser beam pointing. A high accuracy galvanometer controller has been developed [7,8]. It uses partial reflection of the projected laser beam on the exit window to compensate errors due to temperature variation. The slow scan is made by a translation positioner using a DC motor. Both scanning axes have a resolution in the order of 25μm. The range measurement is made by a 512 elements CCD coupled to a sub-pixel peak detection circuitry [9] providing a numerical resolution of 1 part in 8000. Four lenses can be interchanged for the following volumes of view; volume I is a cube of 2 cm on a side, volume II has 10 cm, volume III had 30.0 cm and volume IV had 50.0 cm. The prototype geometry has been designed to ensure minimum readjustment for the different volumes of view. For example, the distance between the collecting lens and the CCD is the same for all volumes, also the CCD tilt angle is changing by only 5° over the whole range. Eventually, a zoom lens will be used in order to get very large variations for the acquisition parameters.

The photograph of Figure 12 shows the prototype operating in volume III. In this configuration, an object to be digitized is put on the table and a perpendicular raster scan is used to record its shape. In another configuration, the camera is scanning in an axis parallel to the surface of the table (using pivots on the front and back post). This position allows easy acquisition of object surface over 360° using a rotating table. It can be in a raster mode for few angular positions or in a line mode where a profile is read at very small angular increments (typically less than a degree). This position is also more convenient for human face recording. The subject sits at the opposite side of the table and the camera is used in a raster scan mode. The sampling rate of this prototype is limited by the position sensor. With a 512 element CCD, it is 20 KHz.

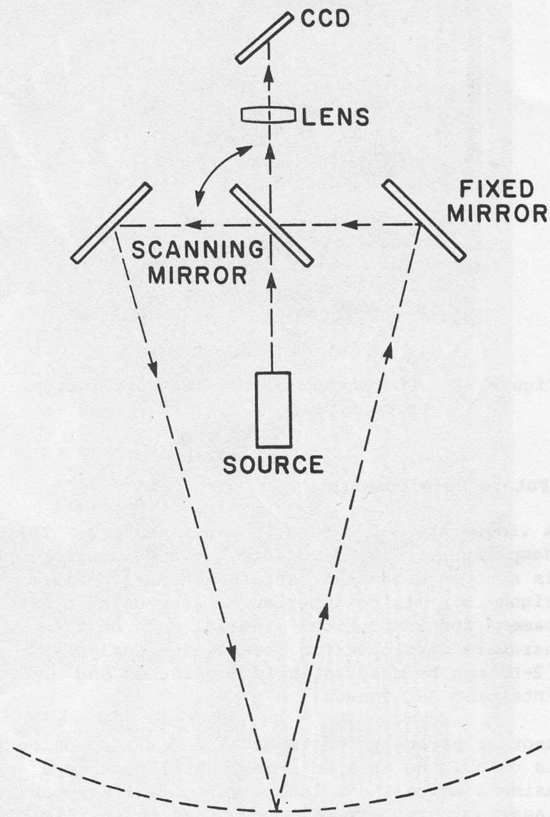

Figure 11. Laser scanner geometry for a high resolution prototype.

The RMS deviation measured with this geometry (Vol. III) is 40μm along the range axis. Depth of view is 300 mm. Figure 13 illustrates recordings made for the production of a 3-D image data file using the above described prototype. It is a collection of 214 images divided in four chapters. The photographs of figure 13 show samples of it. The 3-D representation we have chosen here is the display of the derivative of the recorded shape. It has the benefit of revealing surface details in addition to providing a shading effect. A detailed description of the data base content is available in a publication entitled "The NRC Three-dimensional Image Data Files" [10]. The whole collection or a part of it is available to computer vision researchers in the form of tapes, sun cartridges, or diskettes.

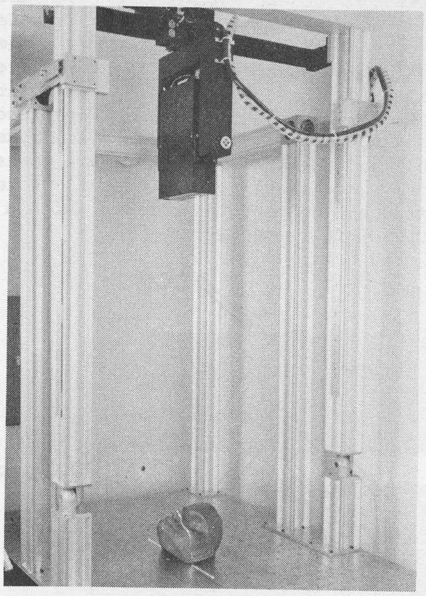

Figure 12. Photograph of the high resolution prototype.

Future Developments

A video-rate 3-D camera is under testing. The sampling rate is 10 MHz and the 3-D information is sent on a coaxial cable as an RS-170 video signal minimizing interfacing when using a 3-D camera for inspection. Indeed, much of the hardware developed for video image analysis (2-D) can be used as it is to process and interpret 3-D images.

Another parameter of importance for inspection is color. We have an experimental prototype using a white light laser, which is a krypton laser emitting six balanced lines in the visible part of the spectrum.

For applications where laser light poses human hazard (medical, mobile robotic, etc.), we are developing an eye-safe laser scanner using a 1.5μm laser source and a custom made position sensor sensitive to this wavelength.

Conclusion

Five 3-D imaging prototypes have been described. They all use optical triangulation. Applications range from robot vision to industrial inspection. Mobile robotics, medical, CAD/CAM and many other application fields will benefit from 3-D vision research. New developments such as registered color-range imaging should prove to be a powerful tool in the manufacturing and process industries.

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Figure 13. Samples of images contained in a collection of 214 range images.

Here, we display the horizontal derivative of the 3-D signal in order to display surface details of the recorded images.