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9 Recent Trend of Development and Application in Range Imaging

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Abstract

Three-dimensional position and shape measurement systems are widely used in industrial fields, but also in social environment fields. These are divided into 3 categories: distance measurement for navigation, position and shape measurement for manipulation and micro-structure measurement for observation of material. This paper describes recent trends of range imaging technologies.

1 Introduction

In many industrial, material, biological and social systems some properties of 3 dimensional objects are measured using a sensor. Among these properties are position and shape which play an important role in manipulation, perception, observation, inspection and monitoring of the information related to the 3 dimensional object. Various methodologies have been developed for the retrieving of 3 dimensional information.

They are roughly divided into 3 categories as follows:

1) To measure the distance to the object for path-planning and navigation.
2) To measure the position and shape of the object for manipulation, design and inspection.
3) To measure the shape of micro-structure for observation of material characteristics.

The methodology of 3D imaging is figured by the distance to be measured and the resolution. Several years ago measurement of 3D objects was not so common in real world applications. 3D imaging was available only for laboratory use and even then only within a limited measurement range of resolution, as follows: 1-10mm in incoherent optics and 0.1-1micro-meter by coherent optical system. There was no method to measure 3 dimensional shapes with the resolution of 0.01mm, but in recent years many 3D imaging systems have become available in a wide application field that cover the whole measurement range from 0.001nm to 10mm. Figure 1 shows recent state-of-the-art 3D imaging methods that have been developed. The figure shows the relation between method vs. distance and resolution.

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2 Measurement of Distance

It is well known that ERIM (Environmental Research Institute of Michigan) developed 3 types of AM (Amplitude Modulated) laser radar in which ALV (Autonomous Land Vehicle) sensors were used in the Navlab Project at CMU. This rangefinder is based on the measurement of transit time or time-of-flight by detecting the phase difference between transmitted signal and received signal(1,2). This type of rangefinder has great advantages in that there are no invisible region within the image and resolution is independent of distance, in principle. These features are suited for navigation, but there is a big demerit of low S/N ratio in measurement of long distances because received light power is very small. Several products have been introduced into the commercial market, but a robust system has not yet appeared in the commercial market place, in my opinion.

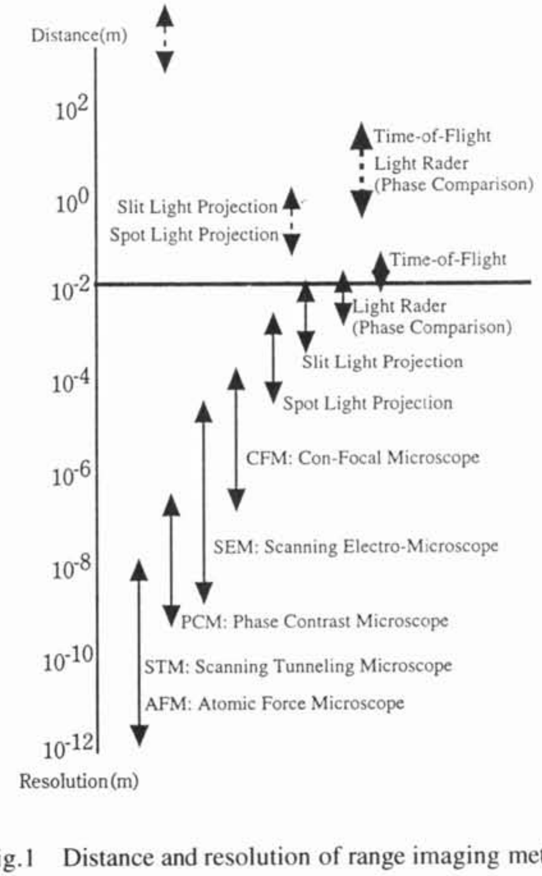


Fig.1 Distance and resolution of range imaging method

In civil engineering and architecture the size and shape of huge building materials have to be measured with high precision. For example, required precision to measure the length of a construction part of 10m in length must be within 5mm. In Japan several construction companies have pursued a collaborative project for developing a 3D shape measurement system that they have named "Brahms". The idea of this system is the fusion of active vision and active measurement. The vehicle having a sensing head moves around a large construction object and gets its 3D data from several points. The position of the vehicle is calibrated by observing the calibration target points fixed on the object from a measurement point. The sensor head is moved close to the surface of the object and the surface of the object is measured. The data is converted into a single world coordinate. Figure 2 shows "Brahms" and its sensor head.

Strictly speaking, this system cannot be classified into range imaging technology because its sensor head, containing only a distance sensor, cannot get range image. However, it can be easily extended to get range image by mounting a range finder in the sensor head. This idea has been developed to measure a whole 3D shape of an object on a small scale(3,4).

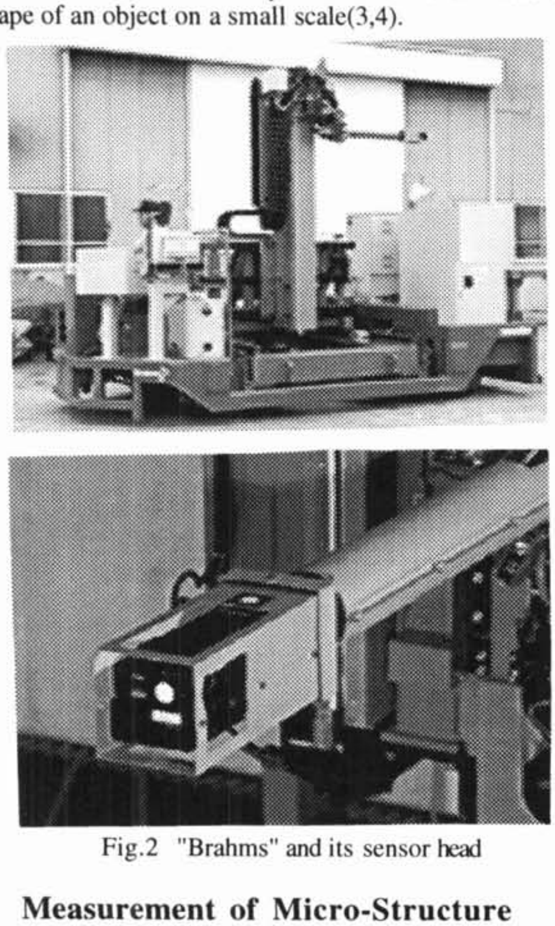


Fig.2 "Brahms" and its sensor head

3 Measurement of Micro-Structure

As described in Introduction, new methods for the measurement of shapes of micro-structures has been developed over the last decade. The current specification of resolution has been spread from mm to pm without any gap. In industrial applications 0.01- 1 micro-meter resolution is widely required as is the case of the observation of the 3D structure of an LSI pattern and the inspection of a magnetic head of a video recorder. In the field of material science 0.01-1 nm resolution was required for the observation of the micro-structure of a material surface.

For the purpose of 3D measurement at the resolution of micro-meters the con-focal system is effective. Figure 3(a) shows the principle of con-focal optics. The reflective light intensity is concentrated at the focal point. By vibrating the light source back and forth, in other words by shifting the focal plane in a back and forth direction, a series of intensity images are collected at the different focal lengths. A 3D depth image can be obtained by collecting the focal length at the position having maximum intensity at every pixel. At the same time an intensity image is also obtained by selecting maximum intensity at every pixel. Figure 3(b) shows a 3D structure of an IC surface. This can be extended to RGB color image.

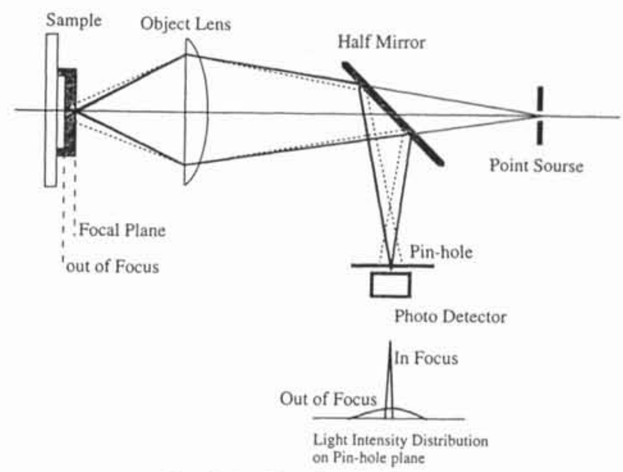


Fig.3(a) Con-focal Microscope

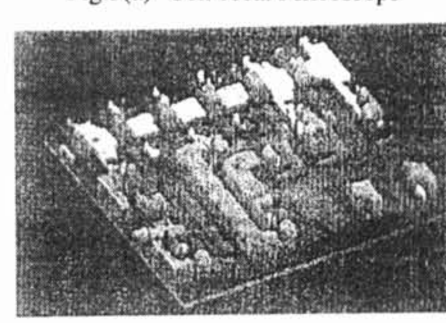


Fig.3(b) 3D structure of an IC surface

For the purpose of depth measurement of higher resolution (<0.01micro-meter) non optical systems have been developed such as the AFM (Atomic Force Microscope) and the STM (Scanning Tunneling Microscope). AFM is based on distance regulation by keeping the atomic force between the object's surface and the scanning probe tip, as shown in Fig.4(a), which is effective for measurement of surface shape of non-conductive materials. This device is widely used in micro component production. Figure 4(b) shows the surface shape of a spherical micro-lens.

STM is based on the measurement of current being tunneled between the object and the probe tip which means this system is used for taking measurements of conductive material. Figure 5 shows an STM topography image of Si(111). The specifications are as follows: Scanning range: XYZ=15x15x1.5 micro meters, Z resolution: 0.01nm, XY resolution: 0.1 nm. The distance regulation mechanism, one of the most important functions in these microscopes, is common in both AFM and STM. A recent trend for AFM and STM is to combine them together into a single instrument by exchanging the sensor head.

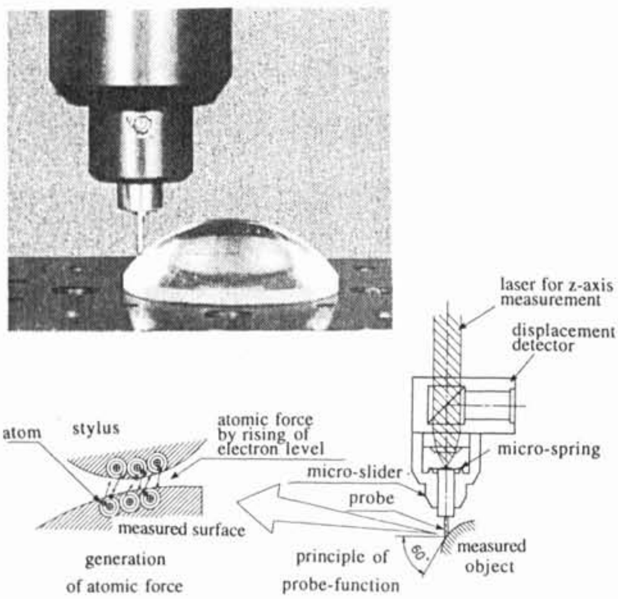


Fig.4(a) Mechanism of AFM

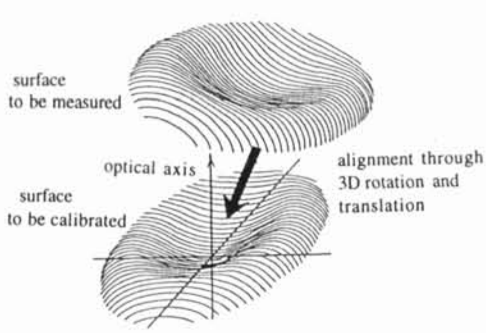


Fig.4(b) Surface shape of a spherical micro-lens

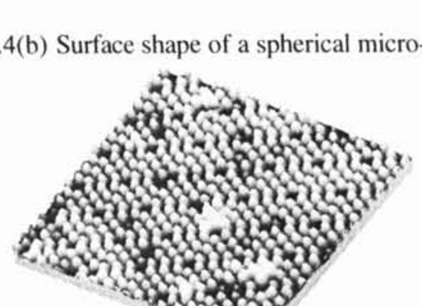


Fig.5 STM topography image of Si(111)

4 Database of Human Body

Recent trends of image processing has been to focus on the human body and the human face. These recent trends serve the purpose of improving the quality of life through standardizing technologies for measuring physical human features and evaluating characteristics of the human body which may improve working conditions and the quality of consumer products. The research institute of Human Engineering for Quality Life, called HQL, is promoting research for achieving high quality life by accumulating objective data on human characteristics(5). HQL had a big project for creating a database of information pertaining to the human body which now contains information about 34,000 Japanese persons of the age of 7-90. This database is widely accessed for improving the life environment in the industrial field for such reasons as improving apparel, furnishings, housing, vehicle design, etc.. Figure 6 shows a special purpose bus designed for this project and its interior which contains 3D range imaging system, based on slit light scanning, is used for human body measurement. A feature of this range imaging system is the utilization of an image encoder which stores slit address and light intensity into two image planes, but only if the input pixel value (light intensity) is larger than the pre-stored pixel value in the image plane. The slit-address plane, which contains projection angle of slit light in each pixel, can be converted into a depth map. 3D imaging of the human body has many very interesting applications that different organizations are just now beginning to develop.

The human face is an interesting subject for 3D imaging from the view-point of communication and cosmetic industry. The shoe industry is looking at developing a 3D measurement system for making custom shoes as well as being able to order correct fitting shoes from a catalog or the Internet. 3D imaging systems are also expected to appear in social application fields such as environmental engineering, welfare technology, security, rescue, etc.. How to rescue some one in a devastated environment such as in the case of a serious earthquake or how to a find a person in an environment filled with fire and smoke, are some of the important applications of 3D imaging.

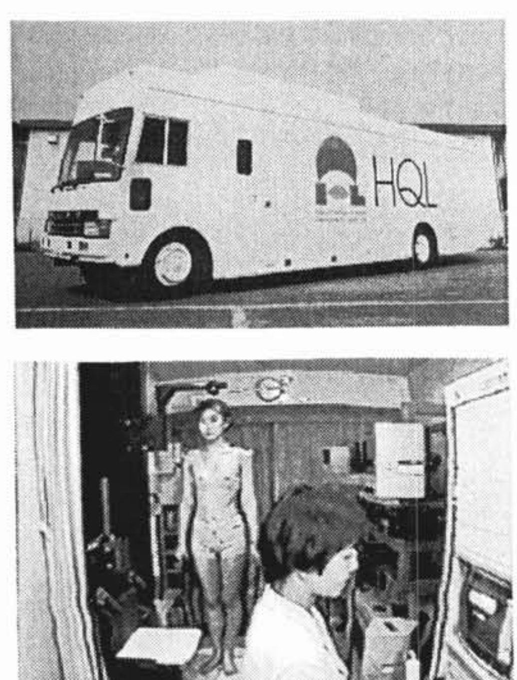


Fig.6 HQL Human body measurement bus

5 Commercially Available Rangefinder

Range finder is a name of active range imaging systems which collect three dimensional coordinate data from object surfaces. Until now, many different principles have been proposed to obtain range data by active sensing(1,2,6).

In this section recent products and reports are surveyed in the field of practical measurement system which are used for manipulation, inspection, shape acquisition i.e. for the creation of a database of 3D information about artifacts, etc..

5-1) Construction-related rangefinder

Optical Radar (time-of-flight) method has not been widely used, as mentioned in the chapter 2, because of low S/N. However, in limited applications where data acquisition time can be left out of consideration Optical Radar (time-of-flight) method can be used. Cyrax 2400 was developed for measuring plant structure and construction as shown in Fig.7(7).

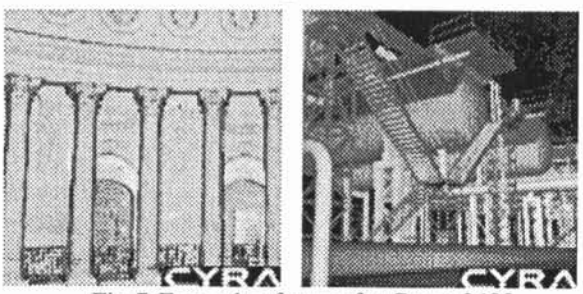


Fig.7 Example of scene for Cyrax 2400

By using pulsed laser the Cyrax 2400 system has a number of advantages over systems that use conventional lasers. The high power of each pulse allows the operator to conduct a survey without the use of targets or reflectors. Part of the emitted laser energy is naturally reflected back to the instrument by the natural surface of the object being measured, even for surfaces that are not perpendicular to the incident laser beam. This means that no additional personnel are needed to hold a range pole or to place targets. This reflectorless feature also lets the user accurately measure structures that are inaccessible such as mine walls or suspended utility cables. Likewise, users can measure areas that are unsafe to occupy such as busy highways, airport runways or areas with hazardous materials. The Cyrax 2400 can also be used for structures up to 100m away. Data acquisition rate is 800 points per second. This system can be used for measuring building structures, terrain profile, plant construction, etc..

5-2) Portable rangefinder

Recently we have been able to find many commercial products based on light stripe triangulation, but most of them are designed for industrial applications or laboratory use. In many field-work projects such as those found in the fields of archeology, biology, mineralogy, etc., compact and portable rangefinders are required. Recently Minolta put a portable rangefinder, named VIVID 700 shown in Fig.8, on the market(8). This system is based on conventional triangulation using slit light projection. However, as it was designed for on-site use we can find several advantages over conventional products. It is equipped with a 5X auto-focus zoom lens. The VIVID 700 has a built-in LCD display and touch-panel which allows non-technological users to easily frame an object and set the field of view.


Fig.8 Minolta VIVID 700 Rangefinder

Data acquisition rate of this system is fairly fast. By using an image processing unit each image is acquired in just 0.6 seconds enabling the delivery of geometrical data with a 200x200 range image and a 400x400 color image at the same time. It uses a CCD which can be operated in 2 modes (charge output and charge drain modes) to enable high-speed acquisition of range images. After 1-frame CCD exposure, of those signal charges transferred to the memory only those of the reflected light from the object surface are extracted by block readout whilst the other signal charges are drained at once.

The stripe light is scanned on the CCD image plane at one horizontal line per frame. The CCD is driven so that the block readout start position is shifted one line per frame to acquire a total of approximately 250 frames of an image.

5-3) Whole body scanner

To capture the intricacies of the human body in one pass the whole-body scanner of Cyberware uses four scanning instruments mounted on two vertical towers,as shown in Fig.9 (9). Each tower has a linear ball-bearing rail and servo motor assembly that moves the scanning instrument vertically. With a person standing on the scanner's platform, the scanning instruments start at the person's head and moves down to scan the entire body. A primary goal of this system is to acquire as complete a model as possible in one pass.

The use of multiple instruments improves the accuracy of the capturing of data pertaining to the sides of the body and in difficult to reach areas, such as under a person's arms. While the simple anthropometric pose gives the best results this system is designed to handle many different poses for a wide range of applications. It scans a cylindrical volume 2 meters high with a diameter of 1.2 meters.

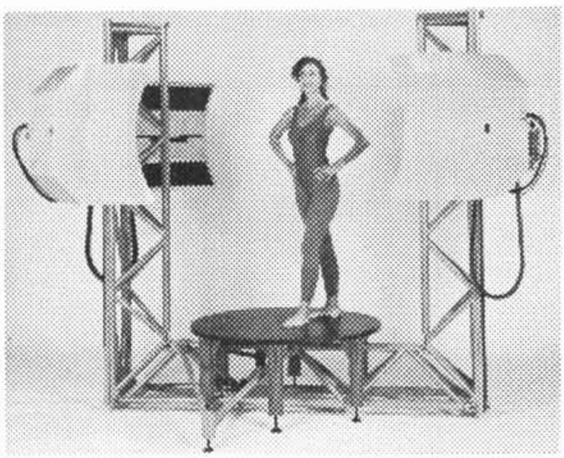


Fig.9 Whole-body scanner of Cyberware

5-4) Fully electronic rangefinder

The rangefinder, that is, 3D camera is very expensive compared to 2D camera, because it contains mechanical component, such as slit-lay scanner. A fully electronic rangefinder may lead to reliable and inexpensive system. Space-encoding projection can be realized by only electronic devices(10).

Figure 10(a) shows the principle of space encoding and position detection, and (b) shows the process-flow of the system. LCD (Liquid Crystal Device) mask generates Gray coded spatial light patterns for space encoding. A CCD video camera is used for observing the scene. The object space is encoded into bright regions and dark regions by a binary pattern illumination. A set of n binary patterns can encode the space into 2 wedge-shaped regions. For example, the point P in Fig. 10 is encoded into bright region "1" by mask A. Similarly, it is encoded into "1" by mask B, into "0" by mask C. The obtained binary space code 110 shows that the point P is in the wedge-shaped region 5. Range data in global coordinates (3D) is obtained from triangulation calculation of the projector coordinate (1D) and the camera coordinates (2D). The projector parameter (4*2) and camera parameter (4*3) serve for the calculation in homogeneous representation, justly they are calibrated in advance.

As the Gray code has the property that Hamming distance between the two adjacent numbers is always one, the ambiguity in extracting the space code on the boundary of the projection pattern can be limited within +1 LSB width. If the number of Gray coded patterns is n, the resultant range picture contains the positional information obtained from 2^n mono-slit images. It means that the range imaging of 2^n slits can be realized by acquiring only n images without special slit scanning hardware.

The input image is binarized depending upon whether a pixel belongs to the illuminated region or not. Complementary pattern projection method, using both positive and negative pattern for each mask as shown in Fig.10(b), results in stable binarization by comparing the intensity of the image with positive pattern illumination to one with negative. This method can be realized by using the liquid crystal shutter as shown in Fig.10(c).

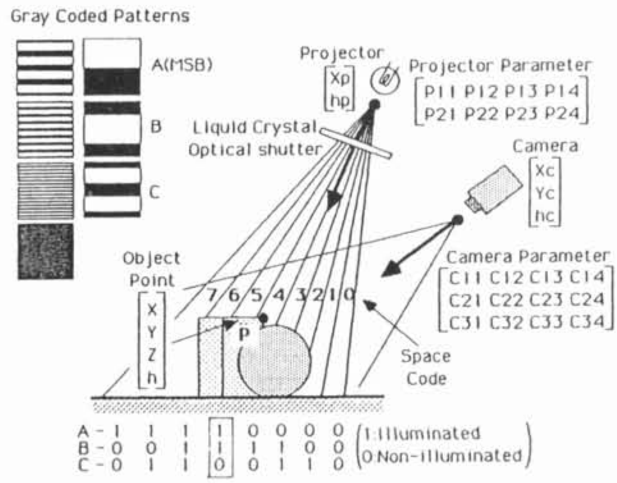


Fig.10(a) Principle of space encoding

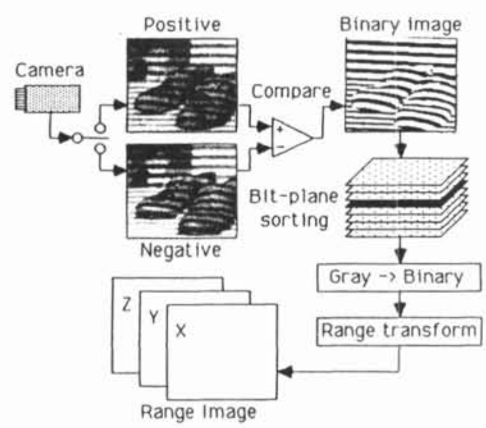


Fig.10(b) Process-flow of the system

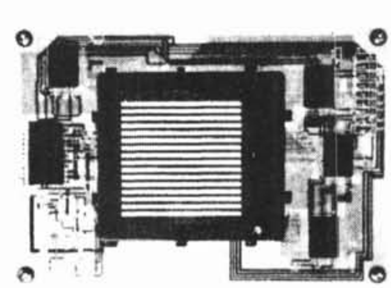


Fig.10(c) Liquid crystal shutter

5-5) High speed handy rangefinder

Space-encoding projection can be also realized by slit light projector, as shown in Fig.11(a). Y. Sato developed space illumination by high speed galvano mirror(11). In his rangefinder, the beam of the semiconductor laser is expanded vertically to form a slit-ray, and it is scanned horizontally by a galvano mirror. The mirror is controlled by a triangular wave signal, synchronized with the video signal. The slit-ray is scanned once within one video of field (1/60 sec) which is a half of video frame. In the period of the field, the CCD camera shutter is open and each sensor stores electronic changes corresponding to the input light intensities. The CCD camera then outputs the video signal in the next video field, discharging the electrons. Therefore, the same image is obtained when an ordinary point illumination projects the scene. As the semiconductor laser is switched in a high frequency, generally higher than hundreds kHz, an arbitrary stripe pattern of light can be synchronously generated by temporal signal switching. This scanning and switching technique potentially allows the most rapid light pattern generation: within one image frame, a pattern of light is generated, the reflected image is taken, and switched for the next frame with no lag time.

A prototype rangefinder is shown in Fig. 11(b), named by Cubicscope. It uses a 1/2 inch CCD camera, 30 mW semiconductor laser, and a galvano mirror. This rangefinder is so compact that it can be installed at the tip of a robot manipulator and is controlled in the 3D space to change its view point or direction quickly. The CCD camera equips a infrared filter that filters out visible light. Since the semiconductor laser used here is infrared (830 nm), the camera stably detects the reflections of the laser in an ordinary luminous circumstance.

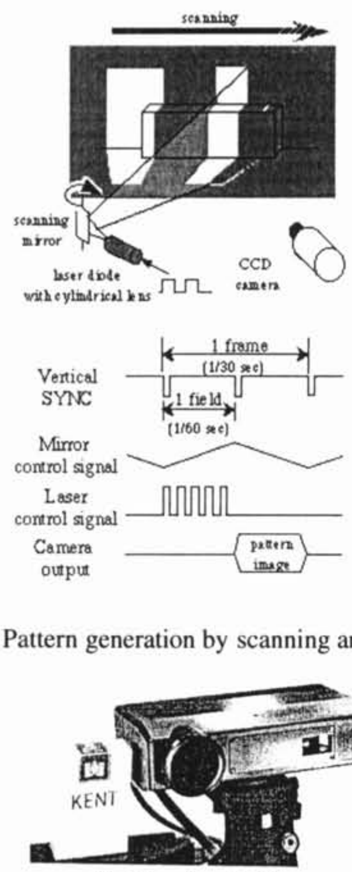
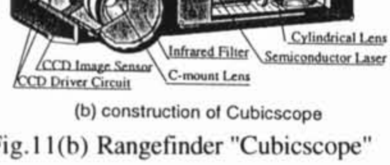


Fig.11(a) Pattern generation by scanning and switching

(a) picture of real Cubicscope



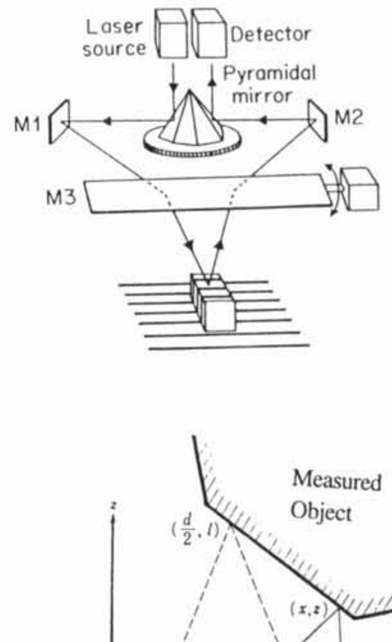
(b) construction of Cubicscope

Fig.11(b) Rangefinder "Cubicscope"

6 High Density Rangefinder

The use of a TV camera or photo detecting array may limit the spatial density of the range image. A sophisticated scanner concept proposed by Rioux allows the implementation of a rangefinder without reducing resolution and response speed(12). The design is based on the angular synchronization of both the projection and the detection of a laser beam. Structure of projected light is not a line but a spot because two types of scanners cover the field of view. Figure 12(a) and (b) show its optical arrangement and geometry, showing the difference between a conventional scanning system and a synchronized scanning system.

By placing a synchronized scanner at (0,0) the position of the spot image on the sensor is moved to p' which is closer to the reference point. This means that a change along the X-axis produces a smaller shift of the spot image position and the effective area of the position sensor may be smaller, in the case of the synchronized



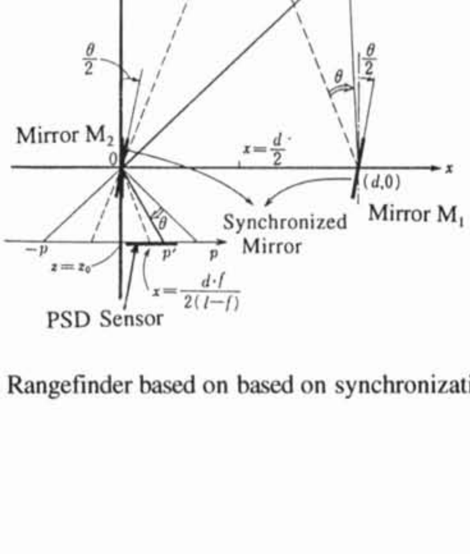


Fig.12 Rangefinder based on based on synchronization

scanner. In other words, a high resolution image is obtained without reducing the view-field.

In addition the response of the PSD (Position Sensitive Detector) is very fast and the acquisition rate of the range image can be increased. TV rated real time image speed can be obtained. For the purpose of the inspection of PCB (Printed Circuit Board), this type of rangefinder can acquire a 2,000x2,000 image in just a few seconds.

7 Real-time Chip Sensor

Recently there have been several efforts to realize real time rangefinder. T. Kida et al., Osaka Univ., have built a realtime rangefinder measuring 4*4 range image with discrete photo-diodes and parts(13). It holds the time-stamp as an analog saw-teeth voltage signal by a sample-hold circuit. S. Pathasarathy et al., Nagoya Institute of Technology, have also built a 32*32 rangefinder with discrete photo-diodes(14). It holds the numeric time by digital latches.

The earliest silicon chip for rangefinding was fabricated by T. Kanade et al., CMU. It has 28*32 pixels and holds the time-stamp as capacitance in a MOS capacitor with an analog saw-teeth signal(15). Its disadvantage is that a photo-sensing element consisting of a photo-diode, a preamplifier and a thresholding comparator needs an external threshold voltage. A fine adjustment of external threshold voltage is necessary depending on the ambient light, the reflectance of an object surface and the operation temperature. K. Sato developed a realtime VLSI sensor, named SRF (Silicon Range Finder), which can be operated in adjustment-free(16). It has an advantage to capture reliable 3D data without disturbance due to several noises.

SRF consist of photo-diodes and operational circuits in each pixel in mixed analog-digital hybrid technology, as shown in Fig.13(a) and (b). Each pixel of SRF includes a pair of photo-diodes, two current-mirrors, two CMOS inverter pre-amplifiers, a clocked comparator and a readout gate. The comparison of incoming light onto the left photo-diode (PDA) and the right one (PDB) is done by the clocked comparator. In order to prevent noise disturbances, the area of PDA is 3% greater than that of PDB. Whenever the sensor measures an object having uniform brightness or is located in the dark room, the comparator outputs the inactive status stably, because of the superior photo-current of PDA.

The pair of current-mirrors amplifies the photo-currents two times. Also, it isolates the analog photo-diodes from the following clocked digital circuits; it prevents the noisy clocked pre-amplifiers from disturbing the photo-diodes, and does large PN capacitance of the photo-diodes from degrading the amplification.

The each pre-amplifier consists of a CMOS inverter and a CMOS switch, which shorts the input and output of the inverter time-periodically to reset it to the high-sensitive intermediate voltage. It amplifies the photo-current and transforms it from current to voltage.

Then, a pair of amplified voltage is compared. For the high-sensitive comparison, a clocked comparator consisting of a pair of positively feedbacked CMOS inverters is involved. All node of the comparator is shorted by a CMOS switch time-periodically to reset it.

The readout gate transfers the status of the clocked comparator into the output raw line Yj according to an input column select line Xi. The column select lines are scanned from X_0 to X_n. Then, raw lines Y_0 to Y_n are buffered and transferred to outside in parallel.

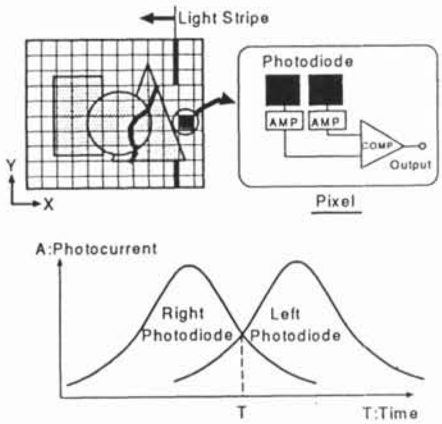


Fig. 13(a) Complementary photodiode pair

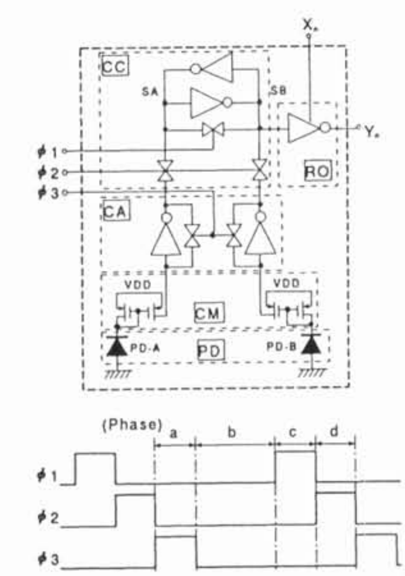


Fig.13(b) Sensing element circuitry

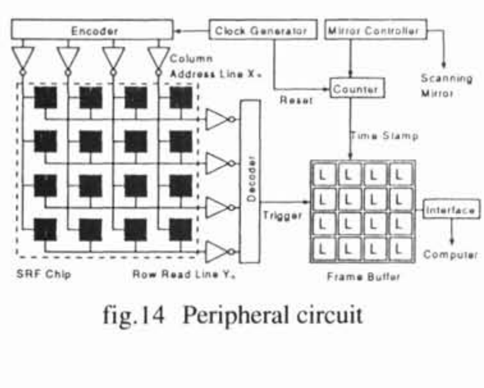


fig.14 Peripheral circuit

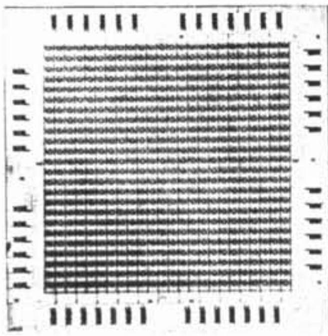


Fig.15 24x24 SRF chip

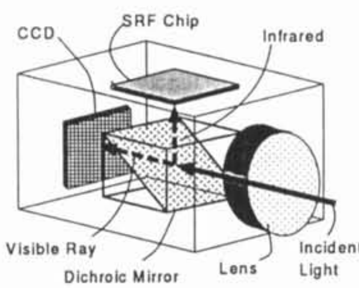


Fig. 16 Camera module with SRF and CCD

A peripheral circuit scans Yn at a clock 30KHz to 100KHz. When some pixel (Xi, Yj) transits L to H, the corresponding digital latch in a frame buffer acquires the time-stamp count in 16 bits. Thus, the resolution of rangefinding is determined by both scan rates; the clock rate of raw (Xn) scanning and the rate of slit light scanning. For example, in case of 30Hz slit light scanning and the above clock rate of raw scanning, the resolution of rangefinding ranges 1/1000 to 1/3333.

For construction of an image, several micro-rangefinders, the above sensing elements, have to be arrayed two-dimensionally on a chip as much as the image resolution they need. The chip has n-parallel raw select lines (Xn) and n-parallel column outputs (Yn). A peripheral circuit encodes raw select lines and decodes column outputs, as shown in Fig.14.

A time-stamp counter holds the current time. A mirror controller resets a time counter, so that the time-stamp is synchronous to the mirror rotation. After laser scanning over a scene, all digital latch in the frame buffer holds the time-stamp. An interface module transfers the time-stamp data to a computer.

SRF chip is fabricated in 1.5mm CMOS; double metal, single poly-silicon process. 24*24 pixels are arrayed two-dimensionally on the chip. Each pixel shares 250*250mm. The total die size including external pads is 8*8mm. The photograph of the die is shown in Fig. 15. And camera module, consisting of SRF and CCD color sensor, is shown in Fig.16.

8 Future Directions

The chapters 5, 6 and 7 dealt current technologies of rangefinder which can be applied for real measurement. Some researchers doubt the importance of range image in computer vision, because the widely accepted paradigms do not state exactly how range images should be used (2). Range data should be used for specified objectives, for example, obstacle avoidance or object tracking. In some case, dense range image is not necessary (17).

Color is useful for space-encoding as described in (18). Recently several reports, in which color structured light is used, have appeared (19). They will be presented in my talk at MVA'98.

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