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Fiber Optic Coherent Laser Radar 3d Vision System*

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ABSTRACT

Recent advances in fiber optic component technology and digital processing components have enabled the development of a new 3D vision system based upon a fiber optic FMCW coherent laser radar. The approach includes a compact scanner with no moving parts capable of randomly addressing all pixels. The system maintains the immunity to lighting and surface shading conditions which is characteristic of coherent laser radar. The random pixel addressability allows concentration of scanning and processing on the active areas of a scene, as is done by the human eye-brain system.

1. INTRODUCTION

This paper describes a fiber-optic based Coherent Laser Vision System (CLVS) being developed to provide a substantial advance in high speed computer vision performance to support robotic operations.

The CLVS development program will be a progression toward a 256 x 256 pixel, one frame per second vision system with an rms accuracy of 1 millimeter for any surface closer than 15 meters in a 10 meter working range. The range accuracy and number of resolvable range values will be order of magnitude improvements over existing technology such as systems using pulsed or amplitude modulated sources and direct detection.[1,2]

The CLVS is a "3D vision system" as opposed to a "programmable 3D mapper." In the terminology to be used in this paper, a 3D vision system provides raster-scanned range images and is oriented toward the high speed end of the accuracy vs. speed performance curve (see Figure 1-1) achievable by a coherent laser radar (greater than 10,000 range measurements per second). By contrast, a programmable 3D mapper dwells longer for each range measurement (fewer than 10,000 measurements per second) and performs range measurements at a programmable computer-controlled sequence of azimuth and elevation angles.

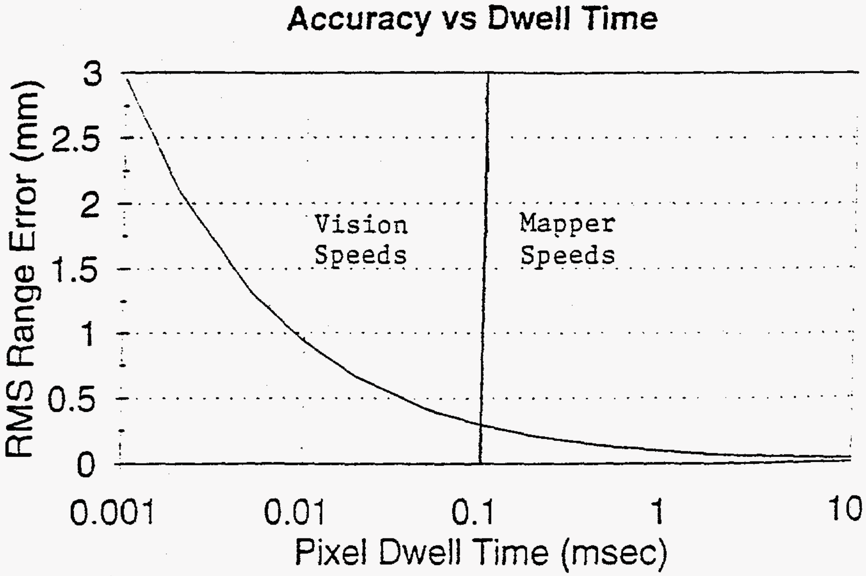

Figure 1-1. Coherent laser radar accuracy vs. pixel dwell time. Laser radar parameters: 50 GHz tuning 1cm aperture, 10mW optical power, 10m range.

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A 3D vision system will provide live 3D monitoring for situations in which it is necessary to update the 3D geometry of significant portions of the world model on the order of once per second. A 3D programmable mapper can less frequently provide very high precision maps or can track single objects such as robot end effectors.

A 3D vision system will monitor the 3D position of all pixels of a scene simultaneously, keeping precise track of the entire scene. Thus, whole scene, real-time, digitized data will be available to support autonomous vehicle operations and operations in which robotic systems are altering the geometry of a scene as in waste removal, surface scarafacing or equipment disassembly and removal.

Fiber-optic coherent laser radar (CLR) based systems such as the CLVS are immune to variations in lighting, color, or surface shading, which have plagued the reliability of existing 3D vision systems, while providing substantially superior range resolution. The primarily fiber-optic construction of the CLVS will be more resistant to shock and thermal effects than bulk optic systems, and will be more economical to manufacture and maintain.

The superior accuracy of the CLVS is a direct result of the orders of magnitude greater signal bandwidth involved in the coherent range detection process. The coherent detection applied to optical frequency modulation (FM) is also the source of the CLVS's immunity to amplitude distortions by lighting or surface shading, just as FM radio, unlike AM radio, suppresses noise from lightning bursts. The fiber-optic implementation of the CLVS allows a more sophisticated optical circuitry to be employed than would be practical with bulk optics, and with less cost for assembly and alignment during manufacturing.

The CLVS fieldable prototype will be developed by Coleman Research Corporation (CRC) in a two phase program.

During the first development phase a baseline CLR 3D vision demonstration system will be developed with the following projected performance:

Frame size:	(128 x 128) 3D coordinates
Frame speed:	1 frame per second
Range accuracy:	σ_R = 1mm

During the second phase, the baseline system will be developed into a fieldable prototype 3D vision system with expanded performance parameters including the ability to scan a (256 x 256) frame of 3D measurements at a one frame per second rate. This enhanced performance will be accomplished by the implementation of "smart receiver" processing algorithms which maximize the use of a priori range information to streamline the real-time CLR range processing computation. The effort will also yield a compact, no moving parts 3D vision scanner.

The fieldable prototype CLVS will output both range and intensity images on both standard video and digital interfaces.

2. TECHNICAL APPROACH

2.1 Technology description

The Coherent Laser Vision System (CLVS) is a fiber optic coupled FMCW coherent laser radar which is an advance over bulk optical versions previously developed by the Digital Signal Division of Coleman Research Corporation (CRC).[3,4] The radar uses the relatively large tuning range of injection laser diodes to achieve greater precision than available with other techniques. As shown in Figure 2-1, the optical frequency of the laser is swept linearly as a function of time. The laser output is divided and used both as a local oscillator (L.O.) and as the signal to be transmitted. After being time delayed by the round trip transit time to the target, the received signal is mixed with the optical L.O. on a photodetector. The resultant beat frequency is equal to the sweep rate of the optical signal multiplied by the time delay between the received signal and the local oscillator. Since this time delay is proportional to target distance, the RF beat frequency is also proportional to target distance.

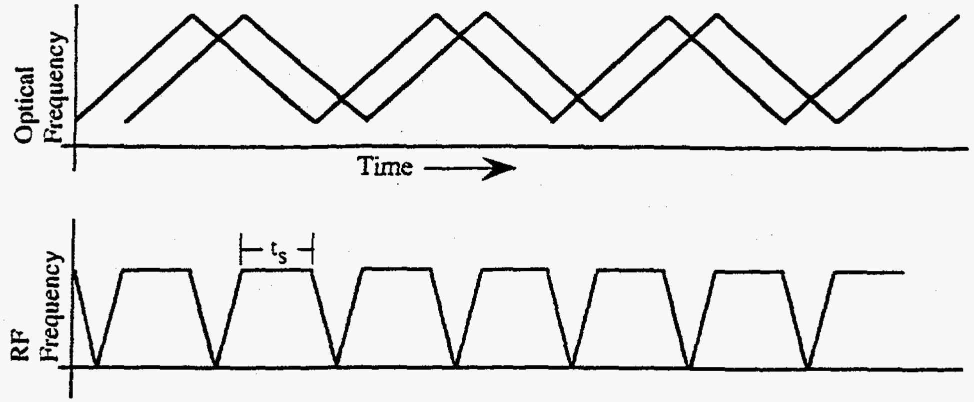

Figure 2-1. Laser Optical Frequency and Heterodyned RF Signal Coherent Laser Radar

Due to the short wavelength of the laser, a small wavelength deviation results in a large beat frequency. For example, at an optical wavelength of 1550 nm, a shift in wavelength of only 1 Angstrom (0.1 nm) results in a frequency shift of 12 GHz. This frequency modulation is accomplished by modulating the laser's injection current, thereby thermally tuning the laser wavelength. The basic fiber optic coherent laser radar system optical configuration is shown in Figure 2-2.

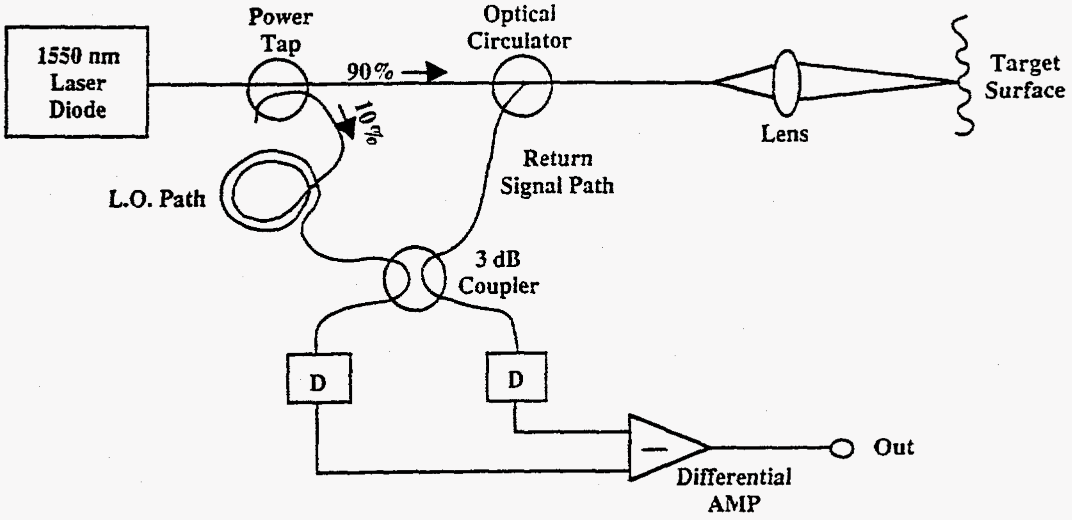

Figure 2-2. Basic Fiber Optic FMCW CLR Configuration

The FMCW coherent laser radar's source consists of a 1550 nm single mode diode laser pigtailed to an optical fiber. The laser's optical output is frequency modulated by varying its injection current. In the basic configuration shown, a small portion of the output light is directed into the L.O. path via a power tap. The remainder of the light is focussed by the antenna lens into the range measurement area of interest. Light reflected from a surface in this area is recollected by the lens, directed into the return signal path by the optical circulator by means of a polarization diplexing scheme and mixed with the L.O. light at the second 3-dB coupler. By utilizing two detectors and a differential amplifier, common mode rejection of amplitude noise is achieved.

Rms range error is proportional to 1/(Tuning) and proportional to 1/(pixel dwell time)$^{1/2}$. This is true for all radar system, AM or FM as expressed in equation 1.

$$\sigma_R \propto \frac{1}{(\Delta f)\, T^{1/2}\, (SNR)^{1/2}} \qquad (1)$$

This relationship indicates that, with the coherent FM radar CLVS enjoying a 20 to 50 tuning bandwidth advantage over AM radars of the same power level, it obtains far greater accuracy for a given dwell time. Taking this relationship another way, for a given accuracy level the AM radar must have a dwell time from 400 to 2500 times as long.

For a CLR vision system the capabilities and operation of the laser transmitter subsystem, the scanner subsystem, and the receiver-range processor are intertwined and will be discussed as they impact receiver requirements and overall system performance. All optical components considered for the CLVS are fiber coupled, which insures a more rugged, more easily manufacturable system than can be constructed with bulk optics. An overall system block diagram is given in Figure 2-3.

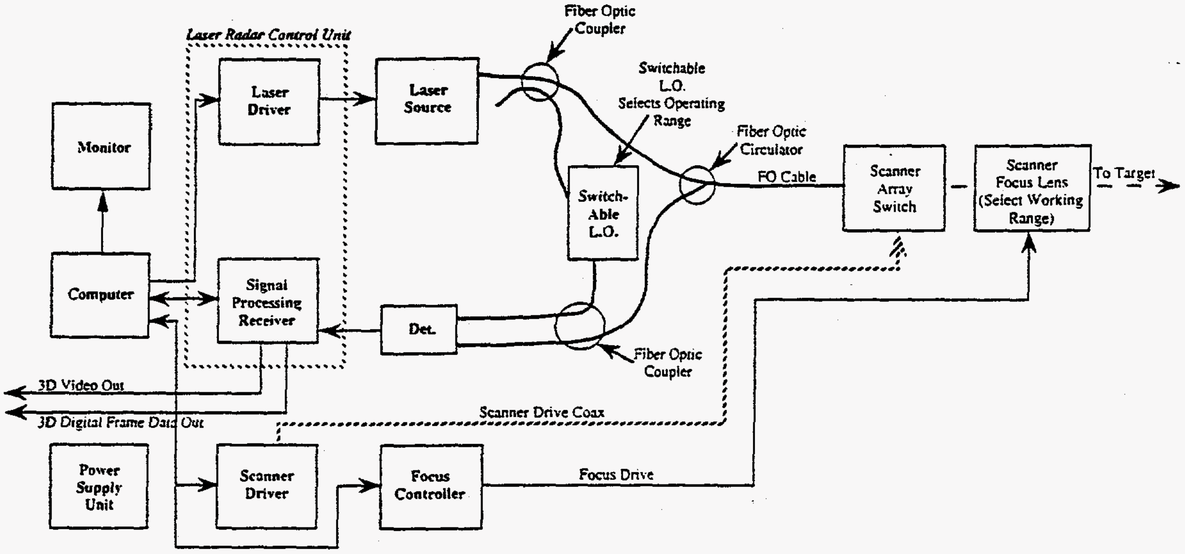

Figure 2-3. Fiber Optic CLR 3D Vision System Block Diagram

2.1.1 The laser transmitter

The laser transmitter is based upon a fiber pigtailed laser diode which is frequency modulated by varying the laser drive current. Each linear FM chirp must be accomplished in approximately 50 µsec for a 128 x 128 pixel frame, one frame per second baseline scan rate. Wide FM chirps are desirable because they lead to greater range accuracy (see Eq. 1 above). Fast, wideband FM chirps are desirable because the sensitivity of the system to target motion is inversely proportional to the FM chirp rate.**

** Velocity induced detected frequency offset $(\delta f)d = 2Vr / \lambda$ is proportional to target radial velocity Vr and laser frequency $f_1 = c/\lambda$. The range induced detected frequency offset

$$(\delta f)_R = (\delta R)\left(\frac{df}{dt}\right) \cdot \left(\frac{d\tau}{dR} = \frac{2}{c}\right)$$

is proportional to the laser chirp rate $\left(\frac{df}{dt}\right)$. Therefore, the faster the laser chirp, the less is the apparent range difference induced by the target motion frequency shift. Of course, this sensitivity can be turned into an advantage for a "smart" CLR vision system processor. By processing both the up and down chirp, both range and velocity can be unambiguously detected at each pixel and the CLR vision system can output velocity images as well as range images. This information can serve as the basis of further "smart" processing which concentrates primarily on the changing portion of the image.

2.1.2 The scanner

Up to this time the scanner has been a critical and problematic component of CLR 3D vision systems. In order to move a laser beam over the desired angular field of view at the desired frame rates, a bulk optic based scanner has necessarily involved fairly large optical mirrors moving at substantial angular speeds. Target speckle effects combined with the finite optical aperture yield doppler scatter in the range measurements if the scanner motion continues during the range measurement dwell. This problem has been suppressed in a previous system with a counter scanner which keeps the beam angle fixed during the dwell period, but at the cost of greater scanner complexity. There is an obvious advantage to a no-moving-parts CLR scanner which accomplishes angular beam motion during the time intervals between FM chirps.

The new fiber optic implementation of the CLR leads naturally to a promising approach for a 3D vision scanner. This new approach has compact size, no high speed moving parts, and no differential doppler-induced range scatter.

The scanner approach, in its general form, is illustrated in Figure 2-4.

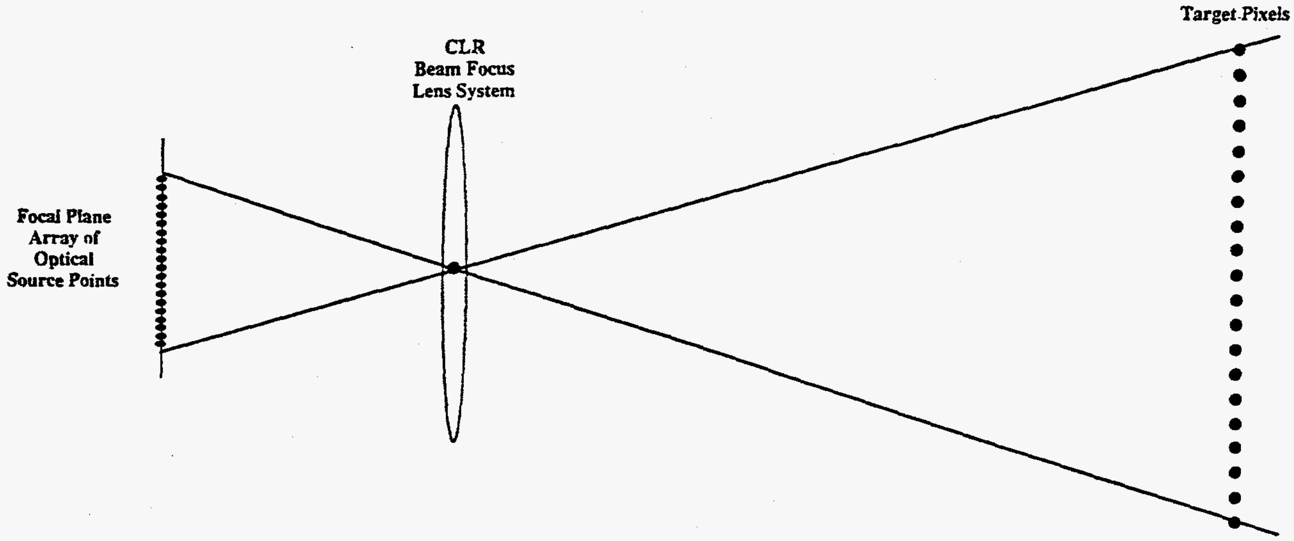

Figure 2-4. Simplified Schematic of Fiber Optic-Based Scanner

The laser light source is switched between focal plane array points in the time intervals between target dwell periods. If the focal plane array is a linear array, scanning in the other dimension may be accomplished with a nodding mirror. A two dimensional focal plane array of optical source points allows scanning in two dimensions with a no-moving-parts scanner and has the additional advantage of allowing random pixel addressability. Two dimensional focal plane scanning will be pursued in the current development program.

2.1.3 The digital receiver

A number of companies are now producing high speed digital processing boards which singly, or in a cascaded architecture, can accomplish the 3D CLR receiver processing task. In general, a CLR 3D vision system will process one laser FM chirp for each pixel of an (n x n) frame at the operating frame rate. The processing consists of the detection of the beat frequency of the mixed local oscillator and target return signals. The bandwidth of potential signals is defined by the chirp rate (which determines the frequency offset per meter of target range) and the depth of range of the region being 3D imaged.

The bandwidth of potential signal frequencies and the dwell period per pixel define the sample rate and the total number of samples per pixel. This, combined with the total pixel rate, yields the total average rate in samples per second at which the digital receiver must process the detected radar output.

For example, a 128 x 128 pixel CLR vision system operating at frame per second may use a 50 GHz laser chirp during a 50 μsec pixel dwell. This leads to 33.3 MHz spectrum bandwidth for a 5M depth of range. Since the 50 μsec pixel dwell occurs every 61 μsec, there is an average bandwidth of 27.3 MHz for digital power spectrum computations. In addition, there will be processing steps for peak determination and for centering the spectrum on the frequencies corresponding to the CLR working range.

Commercial DSP hardware suppliers can now deliver configurations which will perform these processing steps at the rates required and have already demonstrated this capability on previous (microwave) radar applications.

The range for each pixel, along with the known azimuth and elevation for that pixel, constitute a 3D location in "radar coordinates." Radar coordinates will generally be processed into rectangular coordinates by subsequent 3D scene processing hardware which supports robotic operations, 3D scene analysis, or multiperspective remote viewing.

The receiver configuration of Figure 2-5 computes a new range for every pixel of every frame, using no a priori knowledge of range. It seeks a range detection over the full working range of the 3D vision system as a first and only range estimation step. This would be an acceptable approach if cost were not a consideration. Since cost is a consideration we are motivated to pursue a "smart receiver" approach (see Figure 2-6) which use a priori knowledge to reduce processor load.

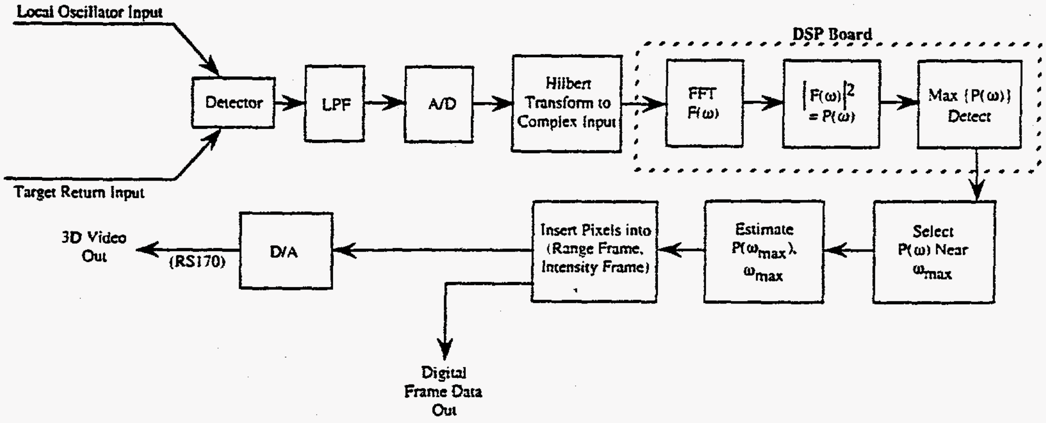

Figure 2-5. CLR 3D Vision Receiver Processor
(No "Smart" Receiver Staged Range Detection)

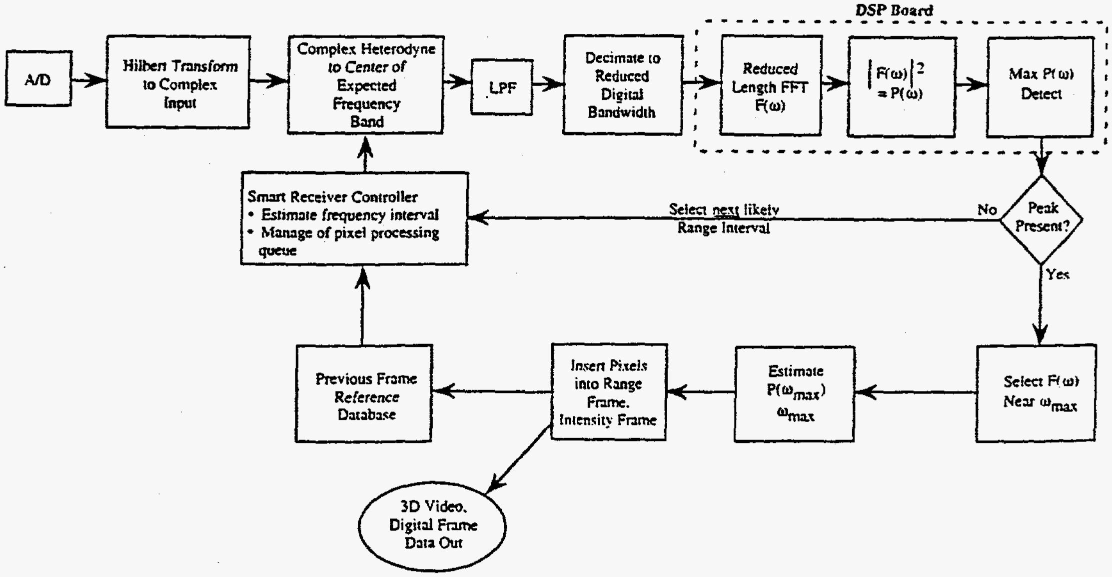

Figure 2-6. CLR 3D Vision "Smart" Receiver Processor

2.1.4 The "Smart" CLR digital receiver

For each pixel range estimate the "smart" receiver stores and makes use of the range of that pixel and surrounding pixels for the previous frame. The smart receiver also retains knowledge of which pixels have changed recently. By this process the receiver has the ability to center the first round of a staged range search on a range which is likely to be very near the correct range for that pixel. Searching a range interval consists of performing a spectrum analysis of the CLR signal for the corresponding frequency interval and detecting a power spectrum peak. If the peak is found, the range search is concluded. If not, the receiver processor continues to search other intervals of the working range through spectrum analysis until the spectrum peak and range is found. A number of strategies for this search may be pursued which may depend upon the application, the environment, or the portion of the image being processed. For example:

(1) A robot in the center of the working range operates in front of a background in the rear of the working range. In this case, when the robot arm no longer occupies a pixel, the background surface does and the range to that surface defines the second interval to search.

(2) For a CLR 3D vision system on a continuously moving platform, surface points move in range and progress from pixel to pixel in an organized fashion. This organized progression of surface geometry will be approximately predicted, using also the range velocity available directly from each pixel, to determine the most likely range interval for each pixel for each frame.

It should be emphasized that only very approximate predictions of pixel range are necessary to achieve substantial reductions in required processing capacity. For example, if, on the average, pixel range can be predicted within a 1 m interval rather than a 10 m working range, a factor of ten savings in required spectrum analysis processing power is achieved. With this advantage a single board processor will be able to support a (256 x 256) pixel frame per second rate. For the lower density (128 x 128) pixel frame, a higher frame rate than 1/sec may be supportable. The smart receiver coupled with a switched fiber optic scanner which allows random pixel addressability will allow the scanning to visit those pixel locations most frequently which are in the vicinity of the changing parts of the 3D scene. This will allow further increase in receiver efficiency, improved capability to follow changing scenes, or both.

The "smart receiver" implementation, primarily a software development, is one of the objectives of the current development effort.

2.1.4.1 Smart receiver initialization

For a "smart" receiver it is understood that, when the CLR 3D vision system is first turned on several frame periods may be required to conclude a search for range for each pixel. This search will be aided by the fact that neighboring pixels will tend to have similar range.

2.1.4.2 Variable pixel density processing

With the use of a fiber scanner it is possible to alter the scanned pixel density or the frame rate programmably and, thus, adjust the processed pixel density to match the predictability of the pixel ranges and the processing capacity of the receiver's DSP hardware. When operating at low density, the 3D video output could continue at high density with (2 x 2) pixel blocks tied to the same range.

2.1.5 Impact of expected DSP hardware performance growth

DSP hardware manufacturers predict that, within three to five years, the brute force (no smart receiver) processing loads required by one 256 x 256 frame per second over a 10m range, will be manageable by a single, general purpose, DSP board. This expected hardware performance growth will not remove the benefit of a "smart" receiver architecture. The reduction in processing load for a given pixel density and frame rate can always be exploited to improve pixel density, angular aperture or frame rate. In summary, a "smart" receiver should allow the production of a CLR 3D vision system which processes a (256 x 256) pixel frame at one frame per second, for a 10 m depth of range with the same DSP hardware which will be able to process a (128 x 128) pixel frame with 5 m depth of range without a "smart" receiver.

2.1.6 Range accuracy

The spectrum bin resolution yields a range resolution of 6mm, independent of pixel rate, for a laser chirp bandwidth of 25 GHz. Interpolation can be used to yield finer range resolution. The stability or accuracy of range measurements depends upon signal-to-noise, dwell time and laser chirp bandwidth through the formula

$$\sigma_R = \frac{\sqrt{3}}{2} \frac{c}{\pi(\Delta f)\, T^{1/2}\, (S/N_o)^{1/2}} \tag{2}$$

where

S = signal power
N_o = noise power/Hz
Δf = radar FM chirp bandwidth
T = chirp period

For 10mW of optical power, a 1 cm aperture, 50 GHz chirp bandwidth, and accounting for defocusing for a fixed focus system the resulting SNR and Eq. 2 indicate that for the 50 µsec dwell time for one (128 x 128) pixel frame per second the CLR 3D vision system should be able to perform better than σ_R = 1mm for a working range between 5 and 10m.

2.2 Application of CLVS technology

2.2.1 The generic CLVS application

The intended use of the CLVS is to generate raster scanned range images which provide a precision 3D-world model to support robotic operations. In general, the CLVS will overcome the problems of current 3D vision technology - lack of resolution and sensitivity to ambient lighting or surface shading. A programmable beam CLR 3D mapper can provide an extremely precise three dimensional map of a facility and can concentrate the density of its scanning and mapping on areas of interest and can precision track the position of a single object such as a robot end effector. With lesser precision (1mm) but still far greater precision and reliability than any other existing raster scanned 3D vision system, CLVS will monitor the 3D position of all pixels of a scene simultaneously, thus keeping track of the whole scene, not just one tracked object. The generated 3D image can be overlaid on color video, infrared or other raster-scanned two dimensional images.

2.2.2 Specific CLVS applications

CLVS monitoring is intended for scene altering operations such as:

- structure and equipment dismantling
- equipment moving or removal
- waste retrieval
- surface scarafacing
- excavation
- autonomous vehicle operation

A significant fraction of the whole three dimensional scene, thousands of pixels, may change in a few seconds. There is still the need in robotic operations to move precisely while gripping, shoveling or otherwise interacting with scene objects or avoiding collisions even though positions of objects often may not be precisely predictable. Variable lighting conditions and surface shadowing will preclude reliance on 3D vision systems which are sensitive to these environmental factors.

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