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Fiber Optic Coherent Laser Radar 3D Vision System

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Fiber Optic Coherent Laser Radar 3D Vision System

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1.0 Introduction

There is a need for high speed robotic vision systems that are immune to variation in lighting, color and surface shading. Coleman Research Corporation (CRC) is developing a fiber-optic based Coherent Laser Vision System[1] (CLVS) which will provide a substantial advance in high speed computer vision performance to support robotic Environmental Management (EM) operations.

This three dimensional (3D) vision system employs a compact fiber optic based scanner and operator at a 128 x 128 pixel frame at one frame per second with a range resolution of 1mm over its 1.5 meter working range. By employing acousto-optic deflectors, the scanner is completely randomly addressable.

Such a 3D vision system can 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 can monitor the 3D position of all pixels of a scene simultaneously, thus keeping precise track of the entire scene. Thus, whole scene, real-time, digitized data will be available to support autonomous vehicle operations.

A 3D vision system can be used for Decontamination and Decommissioning (D&D) operations in which robotic systems are altering the geometry of a scene as in waste removal, surface scarafacing or equipment disassembly and removal. The fiber-optic coherent laser radar (CLR)

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based system is 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.

2.0 System Description

The CLVS system consists of; optical receiver, scanner, digital receiver, and video monitor. The CLVS system is shown in Figure 2-1.

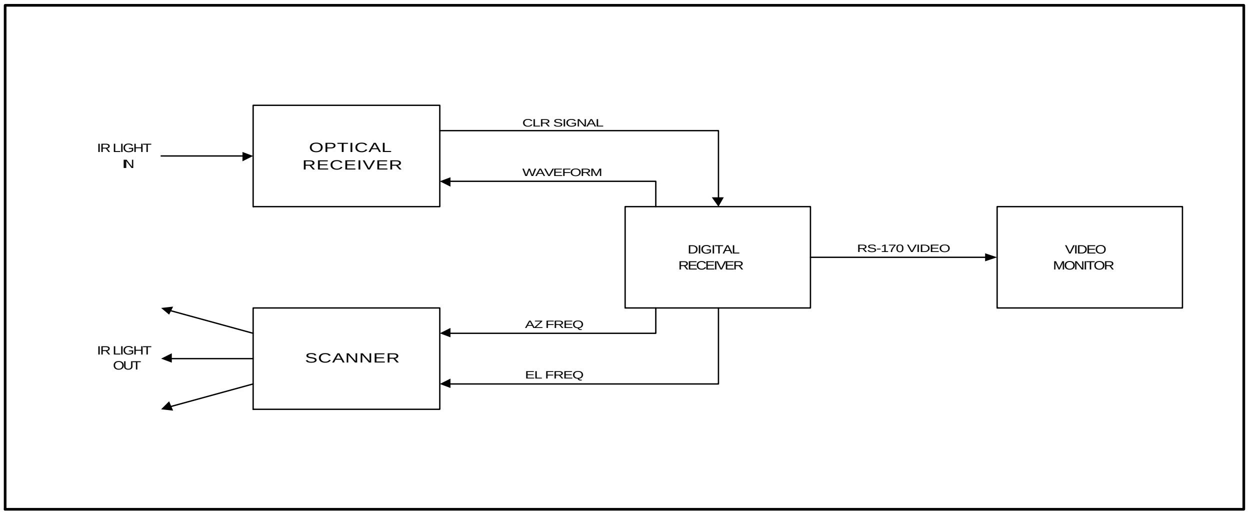

Figure 2-1. CLVS Systems Block Diagram

2.1 Laser Transmitter

The laser transmitter is based on a fiber pigtailed laser diode which is frequency modulated by varying the laser drive current. The linear frequency modulated (FM) chirp duration is approximately 61µsec, per pixel, for a 128 x 128 pixel frame, one frame per second scan rate. Wideband FM chirps are used because they provide greater range accuracy. Fast, wideband FM chirps are desirable because the sensitivity to target motion is inversely proportional to the FM chirp rate. The laser tuning bandwidth (chirp) used is $\Delta f \sim 25$ GHz. This is the maximum tuning bandwidth achievable, at the CLVS pixel rates, by the 1.5µm DFB laser diode.

A small portion of the laser's output light is directed into the local oscillator (LO) path via an LO power tap. The remainder of the light is amplified and passes through a fiber optic circulator and polarization rotator to the acousto-optic (AO) scanner to be focused by the scanner 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 and mixed with the LO light at the mixing 3-dB coupler. This generated range signal is detected by the pinFET photodiodes receiver.

2.2 Scanner

Figure 2-2 is a schematic of the AO scanner. The approach to the implementation of a rapid IR scanner was to use an acousto-optic scanner to deflect light in the Fourier plane and use this scanner to address a lenslet array just in front of the focal plane of a wide-angle lens as shown in the Figure 2-3. This allows the rapid access and high light throughput efficiency of AO scanners, and achieves wide angular scan with large aperture because of the utilization of the lenslet array.

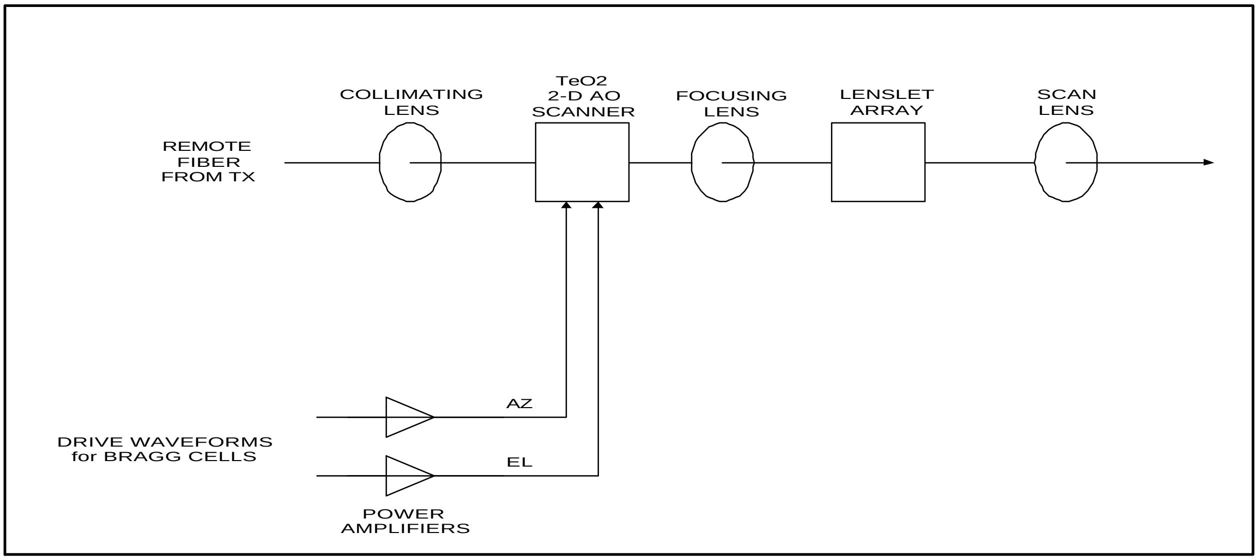

Figure 2-2. Scanner Schematic

CRC has developed a fully optimized 2D acousto-optic scanner for the IR wavelength regime that utilizes a 128x128 lenslet array to achieve rapid (10 µsec) scanning over a full 20-degree field of view, while maintaining a large (1 cm) collection aperture.

The light from the input fiber is collimated, and illuminates a 2-dimensional wide bandwidth TeO_2 AO deflector at the Bragg angle[2]. The diffracted light is focused with a long enough focal length lens to illuminate the full scan lens input aperture, which is about 1 cm. At this input plane is placed a one-dimensional lenslet array containing 128x128 microlenses that further reduce the spots produced by the AO deflector to the spot size required to fully illuminate the scan lens aperture, thereby achieving the full resolution and deflection angle capabilities of the scan lens. A high addressing speed of 10 µsec is achievable with 50 MHz bandwidth TeO_2 AO deflectors since less than 500 resolvable spots are required per axis.

This short length cell (6 - 8 mm) allows a circular aperture to be utilized to implement a compact 2D scanner with a penalty factor of about 6 in loss of RF efficiency, requiring about 6 watts of RF drive. High throughput approaching as little as 9 - 12 dB is achievable since the entire circular beam from the collimated fiber can be diffracted without truncation, and acoustic loss is

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[2] Bragg angle = angle light should enter the AO modulator in order to maximize throughput.

very small for this short aperture. Since the height to acoustic aperture ratio in this case is about 6 times larger than necessary, as dictated by the near field condition in the height dimension, the entire device is 36 times closer to the near field. This dramatically improves the homogeneity of the diffracting acoustic field, which improves the diffracted beam quality and the corresponding fiber coupling efficiency.

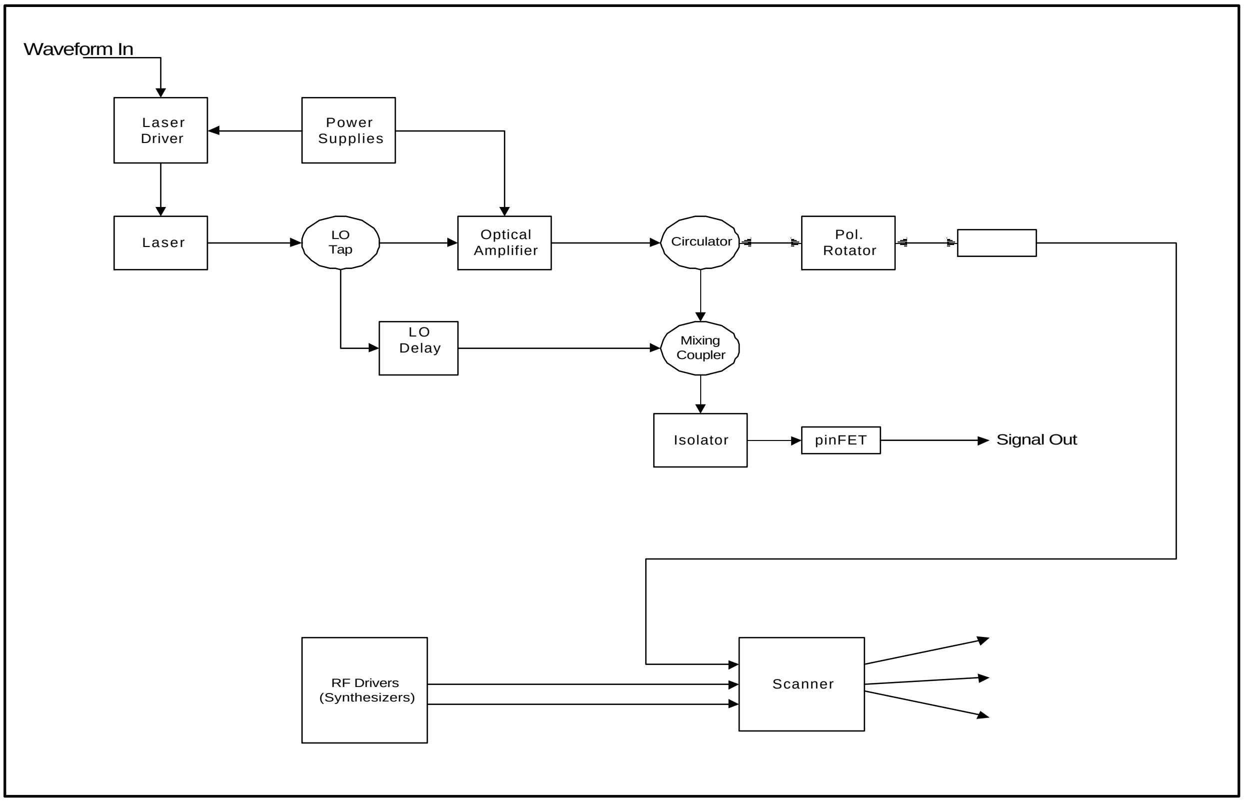

Figure 2-3. Optical Transceiver and Scanner Block Diagram

2.3 Digital Receiver

The Digital Receiver computes a new range for every pixel of every frame using no priori knowledge of range. The actual range, over the full working range of the system, is computed as a first and only range estimate step. Range is determined by performing a spectrum analysis of the CLR signal for the corresponding frequency interval and detecting a power spectrum peak. The CLVS system processes one laser FM chirp for each pixel of a (128 x 128) frame at one frame per second. The processing consists of the detection of the beat frequency of the mixed local oscillator and target return signals. The bandwidth of potential signal frequency is defined by the chirp rate (which determines the MHz of frequency offset per meter of target range) and the depth of range of the region being 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, gives the total average rate in samples per second at which the digital receiver processes the detected CLR output.

The digital receiver estimates signal frequency, and the associated range, for each pixel by the following steps:

1) mix signal to baseband in quadrature
2) digitize signal
3) compute FFT-based power spectrum
4) detect and interpolate peak frequency
5) add LO offset and multiply by a constant to yield range, and
6) insert range intensity into output frame

The Digital Receiver configuration is shown in Figure 2-4. The Receiver down-converts the CLR signal frequency to a frequency range usable by the analog to digital (A/D) converters. The Digital Receiver consists of: down-conversion hardware, A/D Converter card, and a Signal Processing card.

The down-conversion hardware converts the CLR signal frequency from the 150 MHz to 450 MHz range to a frequency range (DC to 4 MHz) usable by the A/D converters. The down-conversion hardware consists of a frequency synthesizer and two mixers. The frequency synthesizer outputs are mixed (subtracted) from the CLR input signal frequency to provide a lower frequency signal (below the Nyquist sampling rate of the A/D converters) to the A/D converters. The CLR input signal is mixed with the in-phase and quadrature outputs of the synthesizer to produce a complex in-phase and quadrature (I & Q) signal input to the A/D converter card.

The A/D converter card samples the CLR input signals (I & Q) at a 10 MHz rate. The A/D card is configured to acquire 512-samples of the CLR signals per pixel. The A/D acquisition starts upon receipt of a Sync signal from the Waveform card in the PC. The Sync signal is generated once per pixel. Acquisition of 512-samples requires 51.2 µsec.

The Signal Processing card processes the 512-samples acquired by the A/D card by performing a 512-point complex Fast Fourier Transform (FFT), converting the resulting complex (I & Q) FFT output to phase and magnitude, selecting the peak magnitude from the spectral data, and outputting the peak data to the DSP card in the PC. The 512-point complex FFT requires approximately 50 µsec and the peak-pick requires approximately 25 µsec. The signal processing flow is illustrated in Figure 2-5.

CLR data acquisition and signal processing are pipelined operations. This pipelined operation allows data acquisition and processing to occur simultaneously. Overall CLVS system timing is shown in Figure 2-6.

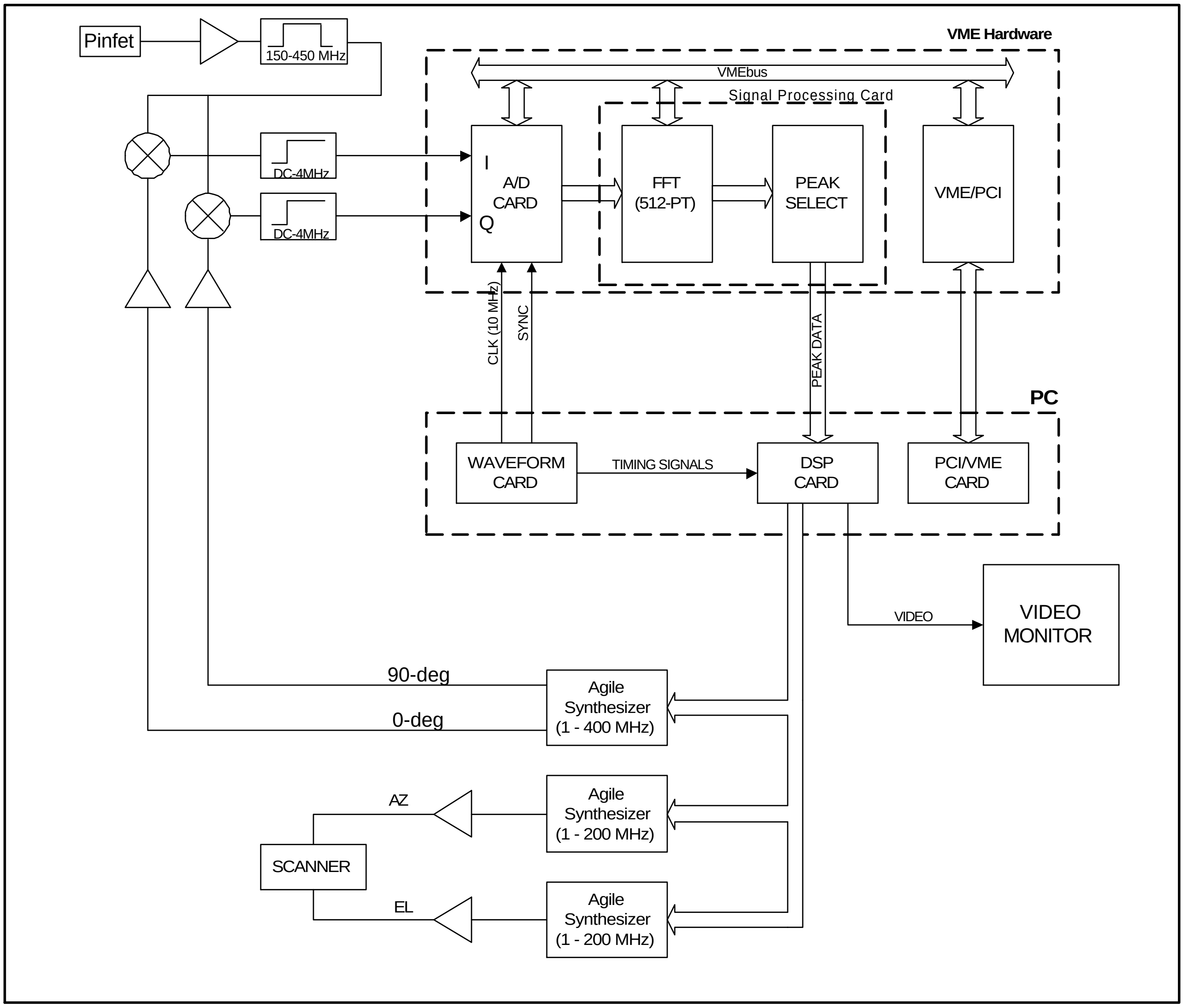

Figure 2-4. Digital Receiver Diagram

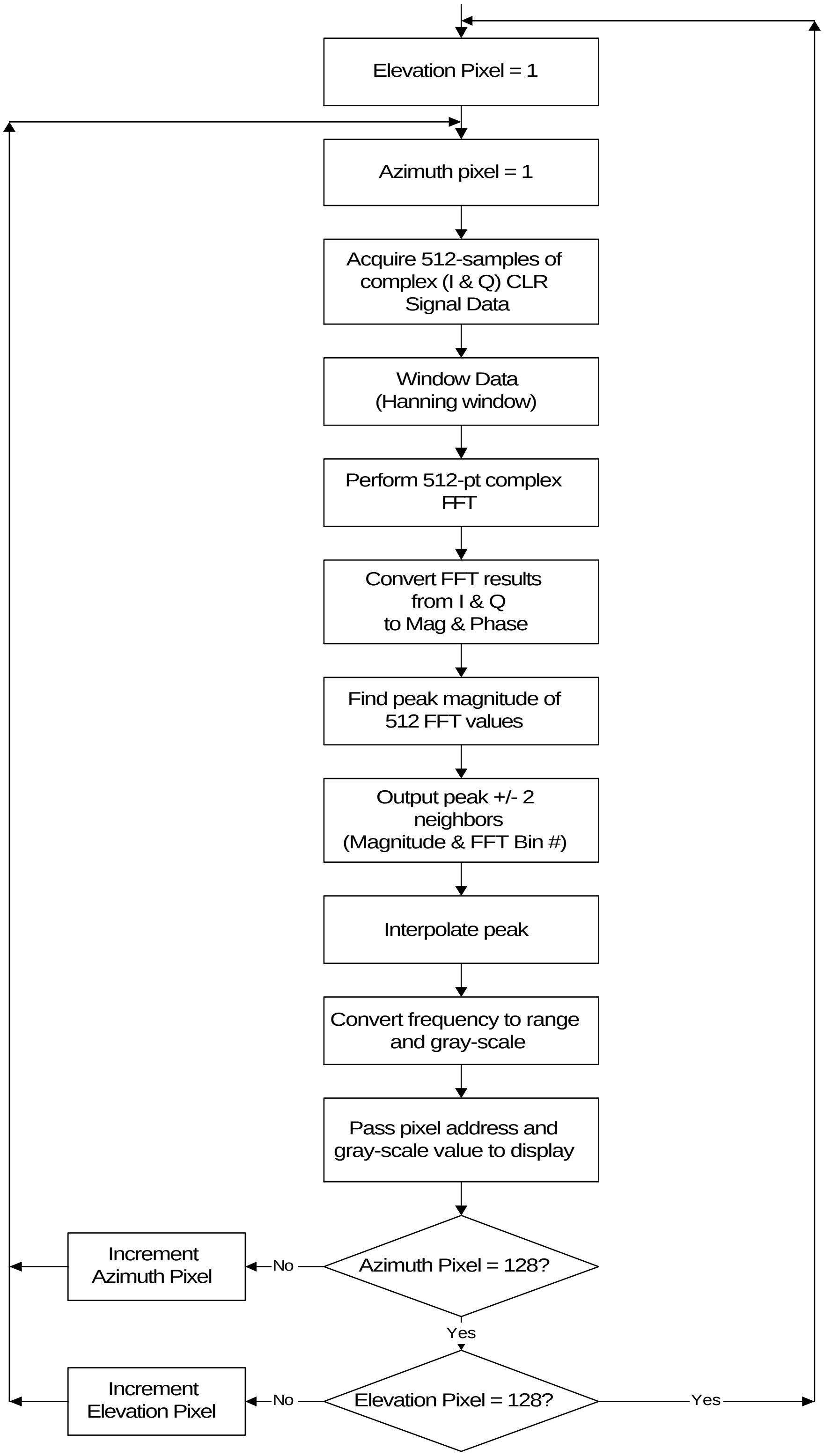

Figure 2-5. CLVS Signal Processing Flow

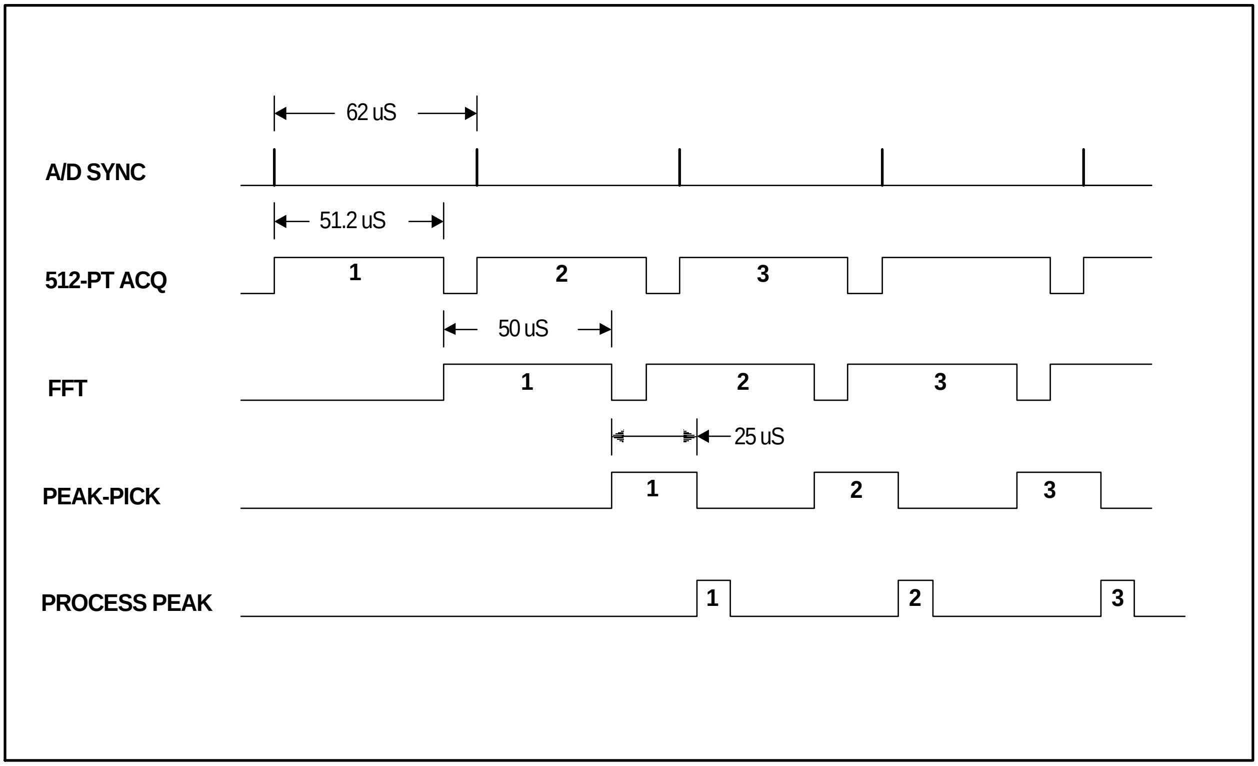

Figure 2-6. Process Timing Diagram

2.4 Host Computer and Monitor

CLVS system control and graphical user interface software is installed and implemented on PC based hardware. The PC hardware configuration is shown in Figure 2-7. The PC configuration consist of: CPU, Waveform card, DSP card, and PCI/VME card. The PC operating system is OS/2.

The OS/2 operating system was used to allow use of existing CRC application software written for other existing CLR type systems. The CLVS GUI command and control software was derived from other existing CLR application software.

The Waveform card outputs a sample clock (10 MHz) to the Digital Receiver A/D converters and generates timing signals to the DSP card. These timing signals establish the CLVS frame rate. The DSP card consists of two TMS320C40 DSP processors. The C40_AV processor; acquires peak signal data from the Digital Receiver, controls Scanner frequencies for pixel selection, controls Digital Receiver front end frequency translation, and outputs 3D image data to the C40_BV processor for display on the video monitor. The C40_BV processor; acquires 3D image data from the C40_AV processor, loads pixel data into the pixel frame, converts the video frame to RS-170 video format, and outputs video data to the video monitor.

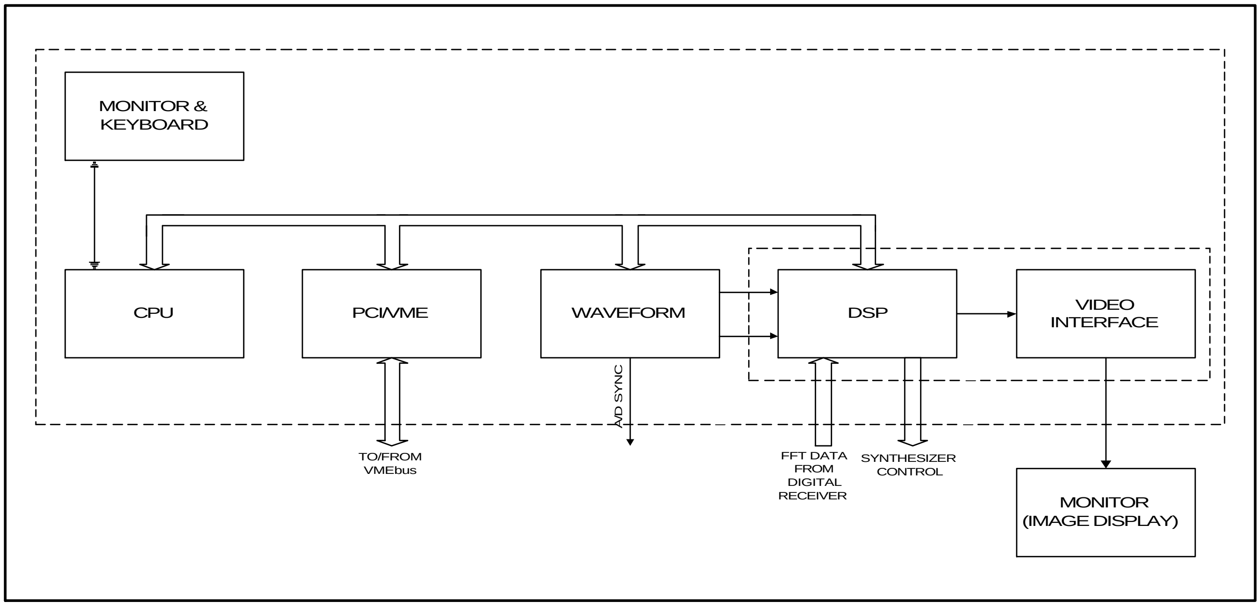

Figure 2-7. CLVS PC Hardware Configuration

The PCI/VME card provides a link between the computer's PCI bus and the Digital Receiver VME bus. This PCI/VME interface is used to load and configure the Digital Receiver hardware and software as required by the CLVS system.

3.0 Applications

The intended ues 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 less precision (1mm) but still far greater precision and reliability than any 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. This whole scene monitoring is useful for autonomous vehicle operations since in the vehicle frame the whole scene, not just one object moves as the vehicle maneuvers.

D&D Scene Altering Operations: CLVS monitoring is ideal for scene altering D&D operations such as:

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

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.

Unmanned Vehicle Navigation: the three-dimensional world view to be used in navigating an autonomous or semiautonomous vehicle may be acquired by a CLVS, avoiding the inaccuracy and susceptibility to lighting of current 3D vision sensors. The precision of the CLVS will be valuable in melding information from past and present frame scans into an integrated world view. Although the scene perspective from the vehicle is constantly changing, the 3D world model (except for other moving objects) may be kept as a constant and details added in as they are revealed to the CLVS. In the eventual evolution of the CLVS for maneuvering vehicle applications, the stored world model information will be used to reduce greatly the vision system processing load since this model, along with a projection of vehicle motion, may be used to predict the approximate range values for pixels of the CLVS range image frame.

Augmentation of Color or Stereo for Surveillance or Inspection Operations: Low contrast features or features of low level geometric distortion may not be detected with stereo or color monitor images. Detecting these patterns will be important for early detection of leaks or potential rupture of waste storage barrels or other vessels. For high speed inspection operations the CLVS range map information may be overlaid on color video images for greatly enhanced feature detection, either by machine pattern recognition or enhanced image human recognition. Just as "false color" is used to enhance human detection of low contrast color or shading features, "enhanced contour" may be used to emphasize bulges or depressions for human detection.

4.0 Acknowledgements

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5.0 Acronyms

3D	Three Dimensional
A/D	Analog to Digital (converter)
AO	Acousto-optic
CLR	Coherent Laser Radar
CLVS	Coherent Laser Vision System
CRC	Coleman Research Corporation
D&D	Decontamination and Decommissioning
DFB	Distributed Feedback
DSP	Digital Signal Processing
dB	Decibel
EM	Environmental Management
FFT	Fast Fourier Transform
FM	Frequency Modulated
GUI	Graphical User Interface
I & Q	In-phase and Quadrature
LO	Local Oscillator
OS/2	Operating System/2
PC	Personal Computer
PCI/VME	PCI (Peripheral Computer Interface) bus to VME bus interface
pinFET	positive-intinsic-negative Field Effect Transistor
RF	Radio Frequency
RS-170	Video Signal standard
TeO_2	Tellurium di-oxide