Full Field Image Ranger Hardware

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Abstract

We describe the hardware designed to implement a full field heterodyning imaging system. Comprising three key components - a light source, high speed shutter and a signal generator – the system is expected to be capable of simultaneous range measurements to millimetre precision over the entire field of view. Current modulated laser diodes provide the required illumination, with a bandwidth of 100 MHz and peak output power exceeding 600 mW. The high speed shutter action is performed by gating the cathode of an image intensifier, driven by a 50 Vpp waveform with 3.5 ns rise and fall times. A direct digital synthesiser, with multiple synchronised channels, provides high stability between its outputs, 160 MHz bandwidth and tuning of 0.1 Hz.

1. Introduction

Range data is a critical component of many developing research fields. High precision measurement combined with high spatial resolution, often in real-time, is a common requirement for disciplines such as machine vision. Laser scanners can provide high precision real-time measurements, but are limited in resolution due to the long acquisition time required. Full field techniques are therefore preferred where high spatial resolution is necessary, and also often have the advantage of not requiring moving parts.

The accuracy of stereo techniques is dependant on the separation of the cameras, constraining the precision achieved for long range measurements. Pulsed time-of-flight systems require complex high speed receivers with high sensitivity, which generally limits the resolution when designing an array for a full-field configuration. The homodyne technique [1,2] modulates a light source at radio frequency illuminating the entire field of view. The light is reflected back from any objects onto a high speed shutter (often an image intensifier) modulated at the same frequency. A CCD camera integrates the light received through the shutter, which experiences a phase delay due to the distance travelled. The range is therefore encoded into the intensity measured by the camera. Various methods are then used to remove the background intensity from the measurement. The dynamic range of current CCD camera technology is quite limited, and therefore severely restricts the performance of the system.

A heterodyne technique is being developed by the authors [3]. With a configuration very similar to that of the homodyne technique, the frequencies used to modulate the light source and shutter are slightly different producing a continuously varying phase. The result is a low frequency signal, where the range is encoded as phase rather than amplitude; refer Figure 1. A CCD camera operating at a standard frame rate is capable of capturing this signal.

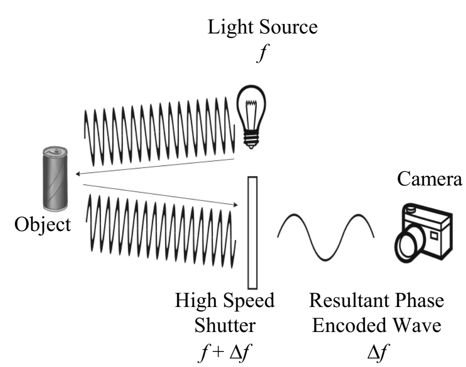

Figure 1: Heterodyning range imager

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The heterodyne configuration is less susceptible to errors due to intensity variation (colour and texture of the object), and because the range is encoded into a continuous variable (phase) the accuracy of the measurements are not directly constrained by the dynamic range of the camera. Quantisation distortion can lead to phase determination errors with low amplitude signals, however the resulting errors in range determination are very small compared to errors caused by low amplitudes using the homodyne method.

The light source must have an appropriate intensity to illuminate the entire field of view, and provide modulation bandwidth to 100 MHz. The shutter bandwidth must match that of the light source. A signal generator is required to control these components; providing stable outputs up to 100 MHz preferably with sub-Hz tuning.

2. Shutter

The high speed shutter function is provided by an image intensifier. Light is focused onto a transparent window coated with a suitable photocathode material, such as S20 or GaAs. Electrons are emitted from the photocathode and are accelerated towards a micro channel plate (MCP) by an electric field, refer Figure 2. Within the MCP, secondary electron emission occurs, providing multiplication of up to four orders of magnitude. The electrons are again accelerated with an electric field, impinging on a luminescent (phosphor) screen where they are converted back into light which can be measured with a standard CCD camera.

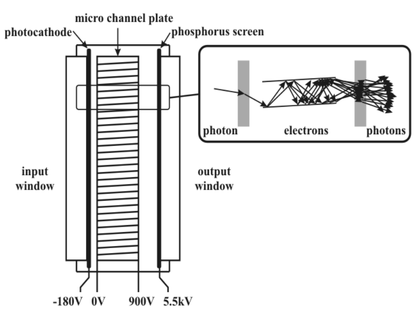

Figure 2: Image intensifier

Two methods are available to control the intensifier gain; i) modulate the voltage across the MCP (and hence the amplification), or ii) modulate the acceleration voltage between the photocathode and the MCP input. A negative voltage at the photocathode accelerates the electrons towards the MCP, while a positive voltage deflects electrons away and turns the intensifier off. We use the latter method as the voltage required is much lower, the modulation depth is increased, and the gain is less susceptible to thermal drift [4,5].

Continuous modulation is preferred for this application to maximise the light collected. Typically pulsers are used with a voltage of +50 V (off) to -200 V (on) at low repetition rates (kHz) [5,6], however high repetition rates or continuous modulation at these voltages is impractical due to the heat dissipated within the intensifier. To reduce the power dissipation the photocathode voltage can be lowered, although this reduces the gain and defocuses the image (as the electric field is responsible for focusing the emitted electrons onto the MCP input). A typical response curve, such as that shown in Figure 3 [7], illustrates that -50 V can be used with minimal loss of focus. The output intensity using -50 V is reduced by approximately half of that at -180 V, but as the CCD is integrating over time for this application, two successive pulses achieve the same final intensity while dissipating less than 15% of the power. The waveform shape also influences the focus. A square wave is preferable as it will pass through the poor focus range (shaded region) quickly compared to a sinusoidal wave.

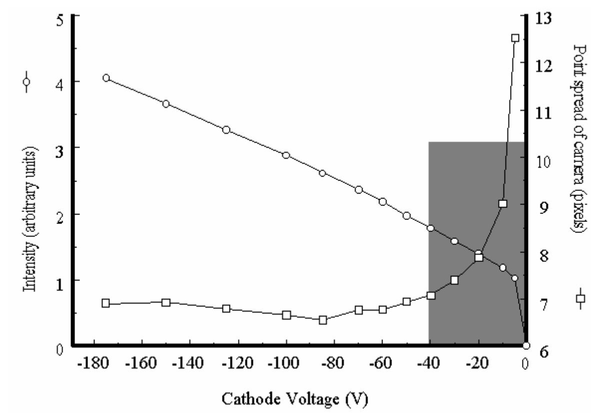

Figure 3: Typical image intensifier response (figure from [7])

The constructed circuit utilises a monolithic triple CRT driver, National Semiconductor LM2412, to provide a 50 V peak to peak output. Our 25 mm intensifier provides a load of approximately 60 pF (in series with 12 Ω). As the LM2412 is stable for 0-20 pF capacitive loads, all three outputs have been connected in parallel (through current limiting resistors) to maintain stability and speed. A block diagram of the circuit is shown in Figure 4. The input from the signal generator is converted to a square wave by passing it through a comparator. A counter is loaded with an 8 bit value through a parallel input, and counts up at the frequency of the input. Upon reaching the maximum value, the Terminal Count (TC) output from the counter is activated, and the counter is reloaded with the parallel byte. By NOR'ing the terminal count and comparator outputs together, the pulse repetition rate can be continuous or divided by an integer value up to 256, although the pulse width does not change. This has been incorporated to further reduce the power dissipation within the image intensifier at high frequencies if necessary. The enable input allows a convenient method of disabling the output when it is not in use.

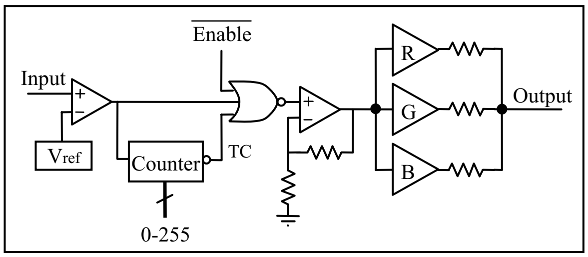

Figure 4: Image intensifier driver

The comparator, counter and logic OR gate used are all ECL devices, configured so that the propagation delay through the counter would not alter the pulse width from the original signal. The ECL signal is converted to TTL (not shown in Figure 4 for simplicity) after which a high speed current feedback amplifier, Texas Instruments THS3201D, is used to adjust the gain and bias voltage, and provide drive to the CRT driver. The CRT driver is a class AB amplifier, with rise/fall times specified as 2.8 ns with a load of 8 pF (per channel) and 40 V_{pp} output.

Figures 5 and 6 show the driver output with a load of 12 Ω in series with 60 pF (equivalent load to our intensifier). The output rise and fall times are 3.5 ns, providing a bandwidth of 100 MHz with a 50 V_{pp} output. A single pulse is shown in Figure 6, demonstrating the ability to reduce the power dissipation within the intensifier. A DC offset (70 V) is added to the MCP and phosphor screen voltages which are shown in Figure 2 to compensate for the non-negative output of the driver.

The DC control of all voltages allows the image intensifier to be "turned off" when it is not in use, in contrast to systems where the rf signal is AC coupled onto a DC bias. This includes during the readout and charge refresh time of the CCD between frames. Although operating at a lower voltage than commercial pulsers, the continuous output (with the option to reduce the repetition rate if necessary) provides superior illumination over the CCD integration period with minimal degradation of image focus.

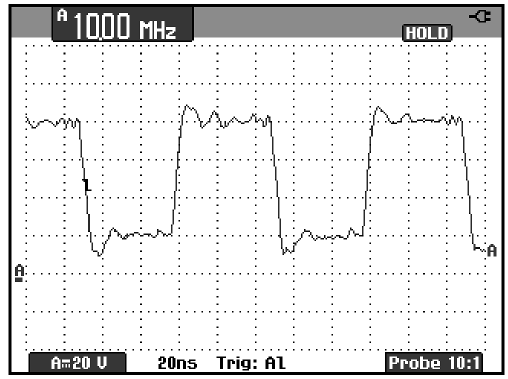

Figure 5: Intensifier driver at 10 MHz

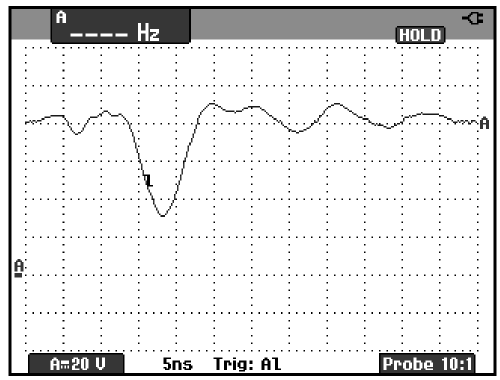

Figure 6: Single pulse (derived from 100 MHz)

3. Light source

A low cost light source with a modulation bandwidth of 100 MHz is required to illuminate the entire field of view. Although LEDs can be modulated to tens of mega-Hertz, laser diodes are preferred for the bandwidth necessary here. Mitsubishi ML120G21 diodes were selected for their combination of low cost and high power (80 mW continuous, 160 mW peak), despite operating at 658 nm where the S20 photocathode sensitivity is only 40% of that at the 450 nm peak.

A 155 MHz laser switch (iC-Haus part number iC-HK) is utilised to provide a constant bias current up to 150 mA in addition to a pulsed current up to 700 mA. This component is low cost (less than US$4) and implementation only requires a very simple circuit as shown in Figure 7 [8]. The combination of the control voltage V(Cl), R1 and R2 set the appropriate current levels, and CMOS inputs EN1 and EN2 enable the bias and pulsed currents respectively.

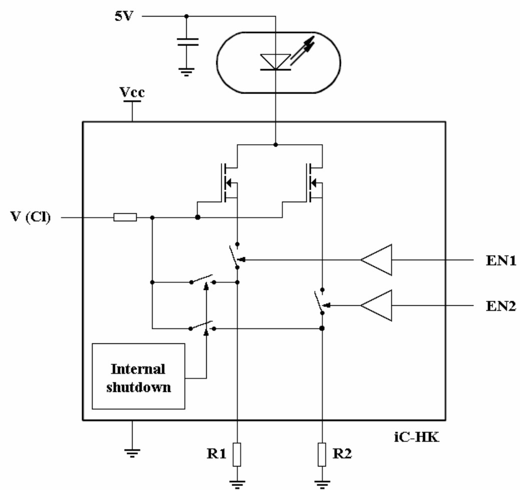

Figure 7: Laser driver circuit

The PCB design incorporates up to four iC-HK drivers and ML120G21 laser diodes to provide a pulsed output exceeding 600 mW if required. Soft start and power supply conditioning is also included to protect the diodes from voltage transients. Figures 8 and 9 illustrate the optical output from the circuit operating at 10 and 100 MHz respectively.

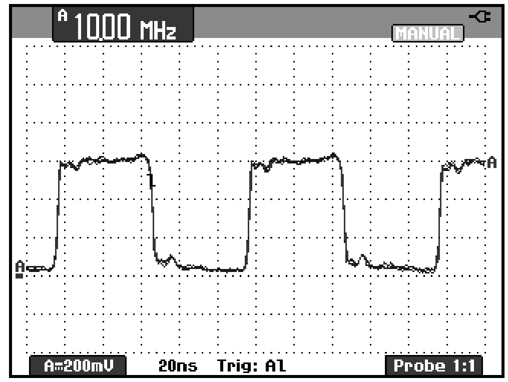

Figure 8: Optical output at 10 MHz

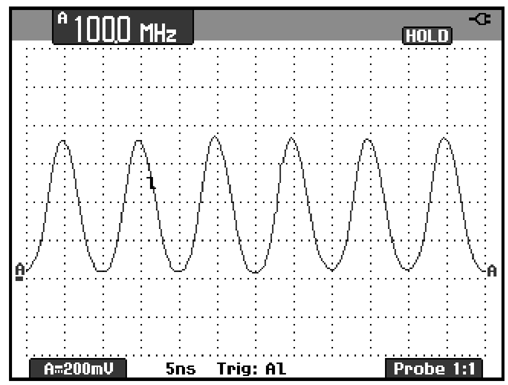

Figure 9: Optical output at 100 MHz

4. Signal generator

The signal generator needs to generate two high frequency outputs (with a bandwidth of 100 MHz) with a small difference frequency (potentially sub-Hz), and high stability to control the light source and shutter. A method of measuring the phase difference between these two outputs is also required so that the imager can make absolute range measurements (within the 2π unambiguous range of the modulation frequency being used). Direct digital synthesis (DDS) provides the stability and frequency tuning required.

A DDS operates from a digital clock and steps through a sine wave lookup table, passing the values to a digital to analogue converter. By changing the step size through the lookup table (the frequency tuning word in Figure 10), the output frequency can be precisely adjusted in very small increments from DC to the Nyquist frequency. Operating multiple synthesisers from the same digital clock source will produce highly accurate relative frequencies as any drift will be common to all outputs.

Measuring the phase difference between the two outputs is a challenging task due to the high frequencies involved and the resolution required. The distance to phase relationship is given in (1), where θ is the phase, F_{mod} is the modulation frequency, d is the distance being measured, and c is the speed of light.

$$\theta = \frac{4\pi \cdot F_{mod} \cdot d}{c} \qquad (1)$$

To obtain millimetre range measurements while operating at 100 MHz requires the phase to be measured with an accuracy of 4 mrad – the reference phase precision must exceed this and therefore be known to 12 bit precision (1.5 mrad). A simple solution is to generate a third synchronised signal at the low frequency difference of the two outputs; its phase can be directly measured providing the light source and shutter phase difference.

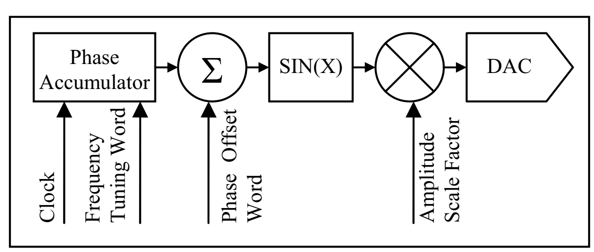

Figure 10: Direct Digital Synthesiser Core

A block diagram of the PCB design is provided in Figure 11. The DDS ICs, Analog Devices AD9952, have a maximum clock rate of 400 MSPS which provides an output bandwidth of 160 MHz. The frequency tuning word is 32 bit, providing 0.1 Hz resolution (when operating at the maximum system clock rate), and phase tuning of 0.4 mrad resolution is available from the 14 bit phase tuning word.

The digital reference clock is provided by a 20.0 MHz temperature compensated crystal oscillator, C-MAC Microtechnology CFPT-9006, with stability of ±1 ppm over the extended temperature range of -40 to 85 °C. It also allows fine frequency adjustment. A clock buffer, Texas Instruments CDCV304, is used to reduce loading on the oscillator and to minimise skew between devices. The 400 MHz system clock is generated independently by each AD9952 using an internal PPL, leading to a synchronisation problem (as there is no global system clock). To overcome this, one AD9952 generates a "synchronisation clock" at one quarter the system clock frequency, which is used by all devices when receiving commands.

The outputs from the AD9952 are low pass filtered by a 7th order elliptic filter, and then amplified by a wideband, high gain operational amplifier, Texas Instruments OPA686. The amplifier provides 1 Vpp when driven into a 50 Ω load through the impedance matched output. A fourth output has also been generated, operating at a multiple of the beat frequency. This is used to synchronise the camera frame trigger with the rest of the system. Controlled by an Atmel 89LS8252 microcontroller, the DDS PCB can be operated stand-alone using a keypad and LCD display, or controlled through RS232 from a PC.

The output spectrum is shown in Figure 12 for an output frequency of 72 MHz. The wideband spurious free dynamic range (SFDR) is 36 dBc. Harmonics of the main signal can clearly be identified, which we believe are caused by the slew rate of the output amplifier. Because the image intensifier is non-linear, and is being driven by a square waveform (to improve resolution as described above), these harmonics are not of concern and therefore have not been investigated further. Low amplitude peaks visible at multiples of 20 MHz are due to the harmonics of the digital oscillator being coupled onto the analogue output. To improve future designs, a differential clock driver and improved PCB layout will reduce the level of these digital harmonics.

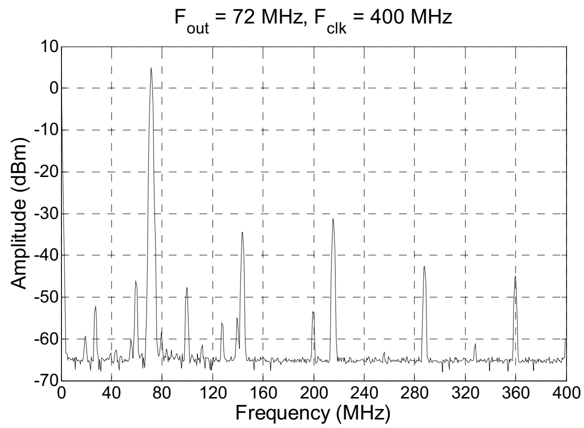

Figure 12: Output Spectrum, F_{out} = 72 MHz, F_{clk} = 400 MHz

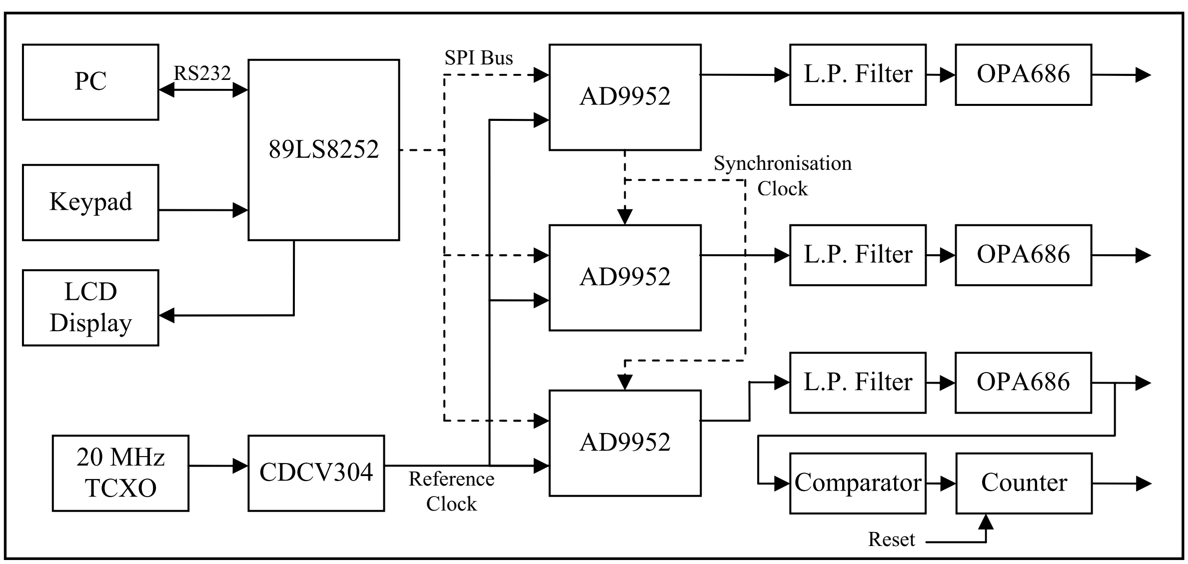

Figure 11: Block diagram of synchronised DDS PCB

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5. Camera

A Dalsa 1M60 camera provides 12 bit data at up to 60 fps when operating at the maximum 1024 × 1024 resolution. The use of binning to reduce the resolution provides even higher frame rates. The camera frame trigger is synchronised to the system through the DDS board, allowing the scene to be recorded at an exact multiple of the low frequency input light signal. Simple Fourier analysis of the known frequency bin provides the phase measurement of each pixel (without any spectral leakage occurring), from which the range can be calculated by rearranging (1).

6. Evaluation

The image intensifier driver meets the requirements of the image ranger project. It provides a 50 Vpp output with a bandwidth of 100 MHz when driving a 60 pF load equivalent to our 25 mm image intensifier. Because this ranger does not attempt to capture single events and instead integrates over continuous time, the voltage used is lower than that of commercial pulsers. This decreases the power dissipation within the intensifier, allowing much higher repetition rates to be used which increases the light level received by the camera without significantly reducing the focus. The driver repetition rate can be reduced to further decrease the intensifier power dissipation if required.

Up to four laser diodes, capable of providing 160 mW (peak) each, provide the required 100 MHz bandwidth while flood illuminating the field of view. The driver circuit is very simple and low cost. The controlled current drive (rather than controlled power) means that the light output power is sensitive to temperature changes. This is not a problem operating in a laboratory environment, however automatic power control could be added if required by using an external photodiode (as high power laser diodes do not generally contain an internal photodiode) and a circuit to dynamically adjust the control voltage.

The DDS constructed exceeds the project requirements, providing bandwidth of 160 MHz with 0.1 Hz tuning, very high stability between outputs, and ±1 ppm absolute frequency stability. The outputs are synchronised and control the laser driver, image intensifier, camera trigger, and provide a reference phase for the range measurement. Analog Devices have recently (August 2005) released a multichannel DDS, AD9959, with four output channels and a maximum system clock of 500 MHz. This part will replace the multiple AD9952s in any further PCB revisions to decrease the physical size by up to 30% (currently 140 × 110 mm), power consumption by 5-10% (currently 3.5 W) and circuit complexity. The configuration presented here can also be applied to the AD9959 to provide more than four synchronous outputs if required by similar applications.

7. Conclusion

The full field image ranging system has been demonstrated operating at 10 MHz using LEDs and low voltage modulation of the image intensifier photocathode, combined with an 8 bit camera. Centimetre precision has been recorded over a 1-5 m range with excellent linearity and repeatability [9]. The electronic circuits presented here are currently being incorporated into the system in addition to the improved 12 bit camera. These additions will greatly improve the modulation bandwidth of the light source and image intensifier, while also increasing the modulation depth and gain of the image intensifier and reducing the quantisation error from the camera. Preliminary testing has achieved range measurements with millimetre precision over the field of view, with range reconstructions expected to be available for presentation at this conference.

8. References

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