The Waikato Range Imager

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Abstract

We are developing a high precision simultaneous full-field acquisition range imager. This device measures range with sub millimetre precision in range simultaneously over a full-field view of the scene. Laser diodes are used to illuminate the scene with amplitude modulation with a frequency of 10 MHz up to 100 MHz. The received light is interrupted by a high speed shutter operating in a heterodyne configuration thus producing a low-frequency signal which is sampled with a digital camera. By detecting the phase of the signal at each pixel the range to the scene is determined. We show 3D reconstructions of some viewed objects to demonstrate the capabilities of the ranger.

Keywords: Range imaging, imaging lidar, heterodyne, image intensified

1 Introduction

The Waikato Range Imager is a full-field imaging lidar system that is capable of producing high resolution images by simultaneously measuring the range in the field of view as seen by each pixel. The ranger is capable of acquiring sub-millimetre precision in range under optimal conditions for a full-field in 10 seconds. In this paper we give an overview of the system and present some recent range images and applications that we have investigated.

2 Imaging Lidar

Image ranging systems can usefully be classified as laser point scanning or full-field (simultaneous) image acquisition. The high precision ranging and x-y positioning of the laser scanner is obtained by moving a laser dot over a field of interest, however the acquisition times can be very long. Such systems are numerous in the literature and in models commercially available [1]. Full-field acquisition, or imaging lidar as it is sometimes called, offers the potential of fast and precise measurement over the whole field of view, but remains somewhat in its infancy with few systems demonstrated with varying degrees of success [2, 3, 4, 5, 6, 7, 8]. Despite the variety of implementation methods, there is much commonality in operating principles and hardware configurations. The operating principle is the expansion of time-of-flight point laser rangers to operate simultaneously over a full field of view. The Waikato Range Imager falls into the imaging lidar category.

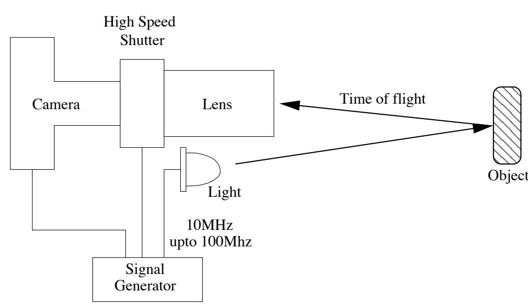

Figure 1: Basic components of an imaging lidar system.

The basic means of operation of imaging lidar is as follows (also see figure 1): A modulated light source illuminates the scene and the light is scattered by objects in the scene to be collected by a camera system. The camera system incorporates a high speed (non-mechanical) shuttering system to modulate the intensity of received light. The major difference in imaging lidar systems lies in the high speed shuttering mechanism and in the modulation control signals. The most common shuttering mechanism is an image intensifier with high speed photocathode modulation capability. Image intensifiers have a number of disadvantages thus there is a move to integrate the shuttering mechanism into custom image sensors. A number of these types of sensors have been described, but they are currently limited by low spatial resolution [4, 8].

The modulation control philosophies can be grouped as pulsed, homodyne or heterodyne. In pulsed systems the illumination source and the high speed shutter are controlled with a single pulse in the nano-seconds region [6]. The scattered light from the scene entering the camera is time delayed due to the path length travelled. The received pulse from a close object will align well with the shutter pulse and an intense signal is received. A received pulse from a far away object will not coincide well with the shutter pulse and a weak signal is received. The brightness of a pixel is therefore correlated with range. Homodyne systems are similar, but a continuous modulation in the 10 MHz to 100 MHz region of the illumination and shutter is used to improve SNR and reduce the requirements of high-speed electronics. Some decoding of the signal is required to derive actual range values from intensity, and such schemes as quadrature or phase-shift keying are often used. Nevertheless systems based on the pulsed or homodyne philosophy have range precision that is limited by the dynamic range of the camera (often a CCD) and these systems typically achieve at best centimetre precision over a distance of less than five metres.

Heterodyne systems are different from homodyne systems in that the modulation frequencies applied to the illumination source and the high speed shutter differ very slightly. The mixing process at the shutter produces a low frequency beat at the difference of the frequencies of the illumination source and the high speed shutter. The phase delay of the received light (hence the range information) is preserved on the heterodyne beat signal. Thus a scene observed by the camera appears to flash, with close objects flashing at a different time to those far away. Range information can be obtained by calculating the beat signal phase (over time) for each pixel. The range precision is therefore limited by the accuracy with which the phase of the beat signal can be measured. This is the approach used in the Waikato Ranger Imager.

3 The Waikato Range Imager

Figure 2 shows the Waikato Range Imager. The illumination source is a bank of four laser diodes (658 nm) rated at 80 mW for continuous output. These are fibre optically coupled to illuminate the scene from a ring surrounding the camera lens. This scheme helps to ensure that the path length from the light source to scene can be calculated as originating from the optic axis about the plane of the lens focal point. The light from the ends of the fibre optics is allowed to disperse to illuminate the whole scene.

Like many other imaging lidar arrangements [2, 6, 7] the Waikato Range Imager employs an image intensifier as the high speed shutter. A Photek 25 mm single microchannel plate (MCP) image intensifier is used. The 25 mm diameter on the entrance window allows easy imaging of the scene with standard F-mount lenses. Image intensifiers are often used for high speed photography by switching the MCP voltage on and off in a very short single pulse. This provides extremely good contrast between the on and off shutter states. Because the MCP voltage is approximately 700 V and we require continuous switching at frequencies up to 100 MHz, switching the MCP voltage is not feasible. We therefore choose to switch the photocathode voltage with a 50 V amplitude signal. Image quality is affected by the photocathode voltage and as the voltage passes through the low voltage régime some blurring of the image formed by the image intensifier occurs. We use square wave modulation to minimise the transit time through low voltages.

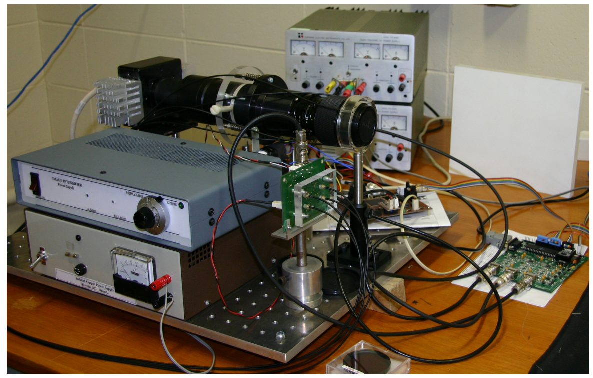

Figure 2: The University of Waikato Range Imager

The illumination wavelength is not optimal for the image intensifier as the S20 photocathode sensitivity at 658 nm is only 40% compared to its 450 nm peak. The laser diodes were purchased for their combination of low cost and high power. There are other issues with using image intensifier technology and they are discussed in a companion paper [9].

A Dalsa Pantera TF 1M60 digital video camera is used to acquire video sequences of the beat signal appearing on the phosphor screen of the image intensifier. This camera is a 1 megapixel, 60 fps, true 12-bit camera with good sensitivity. Since the image intensifier is the resolution limiting component we run the camera in the 2×2 binning mode providing 512×512 pixels at up to 100 fps. This provides two advantages: better photon statistics (hence better SNR) and a higher video sampling rate (hence quicker estimation of phase). The camera is coupled to the image intensifier with a high quality fixed focal length relay lens that has a working distance of 15 mm. Better collection of light of an order of magnitude would result from using direct fibre optic coupling between the image intensifier and camera CCD, however at this stage we prefer the flexibility of using the relay lens.

The modulation signals for the image intensifier and illumination source and the frame trigger for the camera are generated by three direct digital synthesis (DDS) chips driven by a common digital clock source. Operating multiple synthesisers from the same digital clock source produces highly accurate relative frequencies as any drift is common to all outputs. To enable absolute range measurements the phase of the beat signal generated by mixing of the received light of an object at zero range in the image intensifier is required as a reference. 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 by

$$\theta = \frac{4\pi f d}{c} \tag{1}$$

where θ is the phase, f is the modulation frequency, d is the distance being measured and c is the speed of light. Hence to obtain millimetre range precision using 100 MHz modulation requires the phase to be measured to a precision of less than 4 mrad. The reference phase precision must better this and be known to 12 bit resolution (i.e. 1.5 mrad). This is achieved by using the third DDS to produce a synchronised signal at the low frequency difference of the first two outputs; its phase can be directly measured to provide the reference phase difference. This signal is also used to provide the camera frame trigger keeping it synchronised with the rest of the system allowing the scene to be sampled at an exact multiple of the low frequency beat signal.

The availability of the beat reference and frame grabber signals has also allowed the ability to switch off the image intensifier to blank the view during CCD readout. This is important as the CCD continues to integrate the received light even during readout thus smearing scene data down columns of the CCD [10]. This can lead to contamination of the phase of the beat signal along columns of the CCD. By switching off the image intensifier during CCD readout this problem is completely eliminated.

4 Signal Processing

Video sequences are collected of a scene over time with the ranger system. Each pixel is analysed in time for the beat signal. In earlier incantations of the ranger, in which the frame grabbing was not synchronised to the beat signal, Fourier analysis was used to estimate the phase of the beat signal [11, 5]. Now that the hardware has been improved so that the frame grabber is precisely synchronised to the beat frequency an inner product of a sine wave of the known beat frequency with the signal at a pixel suffices to isolate the signal to calculate the phase and, hence, the range. This approach affords a significant advantage: the signal processing can be implemented in real time, thus eliminating the need to save video data, other than maintaining a buffer for the current frame.

There is a potential problem for the naïve: the image intensifier has a non-linear response thus there are harmonics on the signal. It is not possible to low-pass filter the signal (the beat on the image intensifier) before sampling (frame-grabbing) therefore any harmonics above the nyquist limit are aliased. If an aliased harmonic happens to land at the fundamental frequency after sampling then it can contaminate the phase estimation thereby reducing range precision. Not only must there be an integer number of beat cycles in the sample period for inner-product processing, it is also important to choose the sampling frequency and the beat frequency to have no common factors [12]. This is contrary advice to that normally given in phase measurement problems such as occurs in interferometric phase shifting for profile measurement. There the signal is cleanly sinusoidal.

5 Results

A number of objects were imaged to show the capability of the Waikato Range Imager. A steel block of height 100 mm and width 70 mm was imaged as a first example (see figure 3). A second example is a wheel of diameter 175 mm (see figure 4). Ideal imaging conditions were used; in particular the blocks were painted matte white to improve signal detection and reduce specular reflections. A modulation frequency of 78 MHz, beat frequency of 1 Hz and camera frame-grabbing frequency of 29 Hz was used to capture these two examples.

For both examples we show both a photograph of the object and the three-dimensional rendering reconstructed from a single view of range data of the object. Details such as the 2 mm high ridges on each spoke of the wheel and the sharp edges of the block are clearly visible. Unfortunately the chosen visualisation method tends to accentuate the measurement noise. An in-depth discussion of the error sources is beyond the scope of this paper, but can be found in references [9, 13, 14]. In previous experiments under the same operating conditions we have demonstrated 0.4 mm precision for ranging at the one standard deviation uncertainty level over distances of up to 6 m [13]. To estimate the precision achieved in the range images we have fitted a plane with a least-square fitting approach to a number of small areas of various faces of the block (fig. 3) and used the mean of the

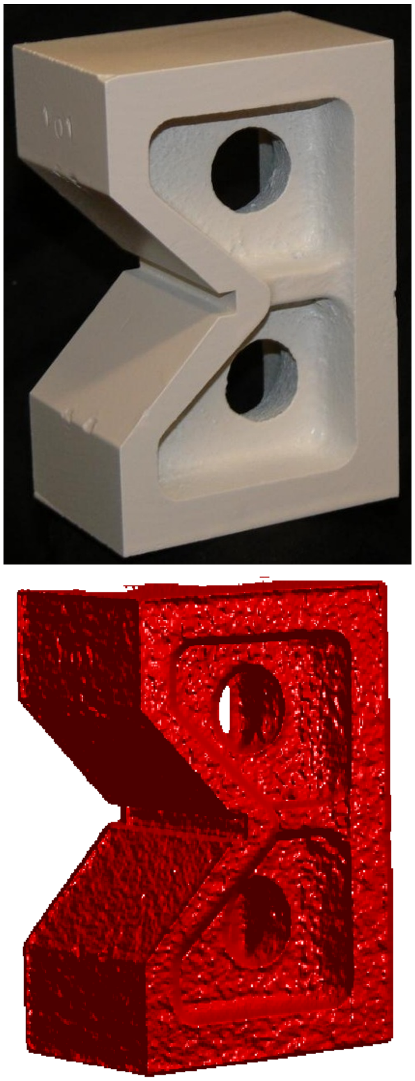

Figure 3: Photograph (top) and 3D reconstruction from range data (bottom) of a block.

Table 1: Precision achieved for various small areas of the block

Size of Area (pixels)	Precision (mm)
16×16	0.385
18×18	0.332
16×16	0.345
20×20	0.342

residuals as an estimate of precision. The results are listed in table 1 and indicate that the 0.4 mm precision is being achieved in these examples.

As a third example we show the range image (figure 6) and the three-dimensional reconstruction (figure 7) of 'Stumpy' – a garden gnome (see figure 5). Stumpy was imaged with 80 MHz modulation frequency, 1 Hz beat frequency and 29 fps sampling rate for a period of 10 s. For this case Stumpy was imaged 'as is' and one can see the noisier reconstruction (see figure 7) resulting from

Figure 4: Photograph (top) and 3D reconstruction from range data (bottom) of a wheel.

Figure 5: Stumpy: the garden gnome under investigation (for various unresolved crimes).

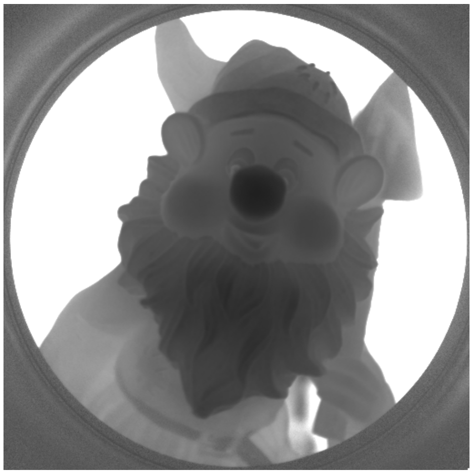

Figure 6: Range image of Stumpy. Increasing intensity represents increasing range to the scene.

the dark areas (such as the spade) where a poor signal is received. Despite the poor signal (signal amplitude less than 2% of that of the bright regions) the general shape of the spade is nevertheless reconstructed. Note the detail of features detected where good signal is received, such as the eye lashes that are less than 2 mm deep and the ridges in the ears that are less than 1 mm deep. The Waikato Range Imager measures intensity at the same time as measuring range and in figure 8 we show a visualisation in which the intensity data is overlaid the 3D reconstruction.

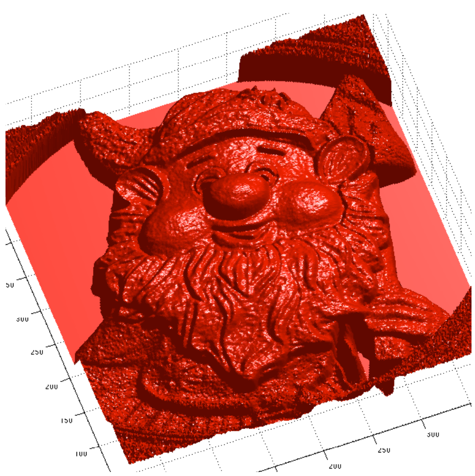

Figure 7: 3D reconstruction of Stumpy.

6 Discussion

We have demonstrated precision, operational distance and spatial resolution all at the upper end of the scale compared to other solid-state range imagers. Furthermore, we have demonstrated all those characteristics simultaneously, which, to our knowledge, no other group has demonstrated.

Figure 8: 3D reconstruction of Stumpy overlaid with intensity information.

Even though we have achieved one of our main aims with the Waikato Range Imager, namely high precision simultaneous full-field ranging, there remain a number of factors that can be improved. The high precision has been obtained at the expense of time; acquisitions reported here take 10 s. It would be nice to get the acquisition time below 1 s for near real time imaging. Currently one can only reduce the acquisition time at the expense of range precision, for example, we have demonstrated approximately 1 cm precision with 1 s acquisitions.

Our reported precision is only for repeated range measurements from a single pixel. There remain systematic errors across the field of view. These are due to geometrical distortion for off axis viewing, lens distortions and image intensifier distortions. In principle they can be calibrated for. Geometrical distortion corrections and lens calibrations are well reported and could be easily applied. The behaviour of the image intensifier is less well described and we report some of our own investigations in a companion paper [9]. One important problem is irising in the image intensifier. This occurs because the switching off (or on) of the image intensifier proceeds from a ring at its outside and progresses over time towards the centre of the image intensifier. This leads to a phase delay in the measurements at the centre of the field of view compared to those at the periphery. Thus range reconstructions report inflated range values as a function of radial distance from the optical axis in the field of view.

The image intensifier requires high voltages and, with its power supplies, is bulky. It remains the greatest obstacle to miniaturising the technology. A few custom image sensors that incorporate the high speed shuttering function in the sensor have been described but they are currently of low resolution and typically only achieve 1 cm range precision [8, 4].

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