TriDAR: A HYBRID SENSOR FOR EXPLOITING THE COMPLEMENTARY NATURE OF TRIANGULATION AND LIDAR TECHNOLOGIES

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ABSTRACT

3D ranging technologies generally fall into either position-based (triangulation) or time-based (LIDAR) approaches. Triangulation can provide much higher precision at close to mid-range but degrades quickly with the square of distance. LIDARs can provide reasonable precision over much longer distances but, unlike triangulation, they do not improve in capabilities at short range where precision and speed are critical for many applications such as autonomous rendezvous and docking, guidance and navigation, obstacle avoidance, and inspection.

This paper discusses the complementary nature of the two technologies and presents an overview of a hybrid Triangulation-LIDAR sensor (TriDAR) currently under development at Neptec. This design has been chosen as an autonomous rendezvous & docking sensor for the Hubble Robotic Vehicle (HRV) but other space and terrestrial applications are also discussed. Performance estimates of the hybrid sensor are also presented.

1. INTRODUCTION

Traditional intelligent machine vision systems have made use of advanced image processing techniques, such as edge detection and correlation approaches, on two-dimensional (2D) imaging systems. While many advances have been made in this field, these systems are usually limited to engineered environments, such as industrial or laboratory settings, and are not reliable enough to operate as the main decision system for critical operations where incorrect interpretation can be catastrophic such as collision avoidance or autonomous rendezvous & docking of satellites.

Limitations of 2D systems usually come from the fact that they measure only intensity of reflected light, whether through active illumination or passive sources. Thus the size, shape, and range to objects are all derived from interpretations of the surface reflectivity and this leaves them sensitive to lighting conditions (e.g., shadows), imprecision in measurement of object features, and calibration of the intrinsic camera geometry (focal length, optical distortion). Successful 2D vision systems have largely relied on engineered environments such as cooperative high-contrast targets [1,2,3].

Over the last few decades, 3D sensing technologies have matured greatly and have proven to be very reliable [4,5,6,7,8]. Three-dimensional sensors directly provide the size, shape, and range to objects by measuring the location of each point, usually referred to as voxels (for volume elements), in three-dimensions either in perspective coordinates (angle, angle, range) or Cartesian coordinates (X,Y,Z). These systems also often measure the surface reflection and so provide a greyscale or colour component.

The measurement principles behind the 3D ranging technologies vary widely but generally fall into one of two categories: position-based or time-based [9,12,13]. Position-based systems usually rely on the triangulation principle shown in Fig. 1. Time-based systems rely on the principle of the round-trip time-of-flight (ToF) of an emitted light signal, either in direct time measurement or indirectly by the phase shift of the signal. ToF systems are also commonly referred to as LIght Detection and Ranging (LIDAR), LAser Detection and Ranging (LADAR), or Laser Radar.

The principles behind triangulation and LIDAR have different advantages, disadvantages, and limitations. Rather than being directly competitive, these principles are better seen as complementary. This paper discusses the complementary nature of triangulation and ToF (LIDAR) technologies particularly in three areas: scanning techniques, measurement principles, and performance. An approach of exploiting this complementary nature using triangulation and LIDAR in a single 3D sensor design (dubbed TriDAR) is presented. Finally, application of the TriDAR design is discussed with respect to space and terrestrial applications including autonomous rendezvous and docking (AR&D), guidance and navigation, obstacle avoidance, surface inspection, and as a single multi-purpose sensor for robotic and remote applications.

The TriDAR design has been selected for autonomous rendezvous and docking on the Hubble Robotic Vehicle (HRV) for both short (less than 10 m) and mid-range (10 – 150 m) tracking and pose-estimation, as well as a Detailed Test Objective (DTO) shuttle flight. A prototype TriDAR has been built and operationally tested at Neptec.

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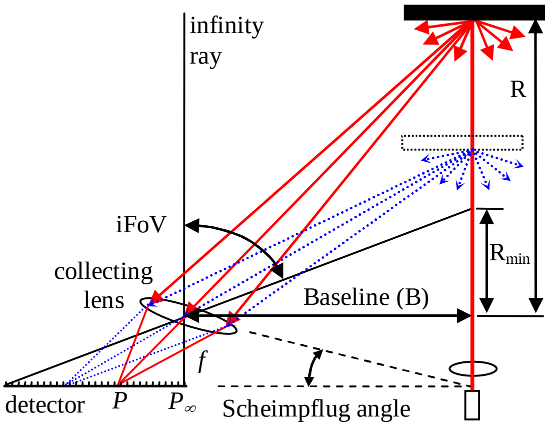

Fig. 1: Basic triangulation geometry.

2. BACKGROUND

Fig. 1 shows the basic triangulation principle. An active source, such as a laser, is projected onto a surface and the location of the reflected image on an offset detector depends on the range to the surface at that projected location, hence measurement of the image position indicates range.

The triangulation principle can provide very high precision range measurements at close range but the nature of the triangulation geometry means that imprecision grows approximately with the square of range and so even the best systems tend to only be practical up to the order of 10 – 20 meters [4,25]. Additionally, the $1/R^2$ light law means that maintaining sufficient SNR for measurement requires that the integration time of the return signal also increases with the square of range, and hence the voxel acquisition rate diminishes quickly.

It should be noted that although stereo-vision is a form of 3D triangulation measurement, it is more similar to the earlier discussed 2D vision systems than active 3D sensors. As in the other traditional 2D approaches, stereo-vision relies on interpretation of the (often passively) reflected surface intensities to correlate features between two images. It is therefore similarly limited in performance by lighting conditions, object features and contrast, and calibration of both intrinsic and extrinsic (relative location) camera parameters. In active triangulation systems, calibration can affect the accuracy of converting raw perspective measurements to Cartesian coordinates, but it generally does not affect the ability to make individual 3D measurements. In stereo-vision, the ability to make even raw measurements is limited by the camera calibrations.

Furthermore, in stereo-vision the number and location of 3D measurements within the camera images is governed by the object feature correlations rather than by a pre-defined scanning pattern and is therefore unpredictable. For example, a uniformly coloured or regularly patterned scene such as a wall, floor, or flat ground does not provide sufficient information for correlating points between the stereo image and so few, if any, 3D measurements are made. An active 3D sensor can successfully scan these scenes with 3D measurements at all scanned points.

The second category of 3D ranging technology is time-based, often referred to as time-of-flight (ToF), which covers several principles that measure range based on the time shift between the emission of a light signal and its return to a detector.

Basic ToF LIDAR consists of an emission of a short laser pulse, a detector to measure the reflected pulse, and timing circuitry to directly measure the time between pulse emission and detection. The largest advantage of this pulsed approach is that it can operate as almost any distance as long as enough reflected light can be collected to make a measurement. Pulsed LIDARs are capable of measurements up to kilometres and in some cases even hundreds of kilometres.

Pulsed LIDARs also have a variety of limitations and disadvantages. First, the spot size of the laser must be relatively large to work over long ranges which can affect resolution, precision, SNR, and number of reflections. The spot will typically be on the order of tens of centimetres to meters in diameter at ranges in the hundreds of meters to kilometres, respectively. Any surface within the spot will produce a reflection and therefore multiple surfaces or a non-uniform surface shape will produce multiple or distorted reflected pulses, reducing the ability to distinguish what the actual range to be measured is.

Furthermore, there is no direct ability to determine where in the spot a reflection comes from so it is typically associated with the centre of the spot even if the reflection comes from the edge. This reduces the lateral measurement precision and resolution (smallest measurable feature) [9, 28]. Finally, a large spot size means that the laser power is less concentrated and so the reflected peak heights are lower than for a smaller spot size, thereby reducing SNR.

Pulsed LIDARs are also limited in measurement speed because a second measurement cannot start until sufficient time has passed to guarantee that a measurable reflection will not return from the first pulse. Finally, pulsed LIDARs are also limited in range precision and resolution due to pulse length and can be limited by resolution of the timing circuitry, though this is typically not the limiting factor.

A variation of single-pulse LIDAR is the use of pulse-trains in which a phase-locked loop can be used to measure the phase change between emitted and reflected pulses. While this approach can increase the measurement speed, it limits the range measurement to the interval between pulses due to the phase ambiguity. Other variations have similar limitations.

Another increasingly common ToF approach is the use of modulation principles such as amplitude modulated continuous wave (AM/cw) or, less commonly, frequency modulated (FM/cw). These approaches use a continuous light emission, either laser or LED, that is modulated with time. The reflected signal is optically compared to the reference signal (e.g., heterodyne) and the difference (either signal amplitude or frequency) is a function of the phase shift due to the round-trip travel time of the signal to the surface and back. Three or four successive reflection measurements are necessary to calculate the phase shift.

Modulated continuous wave LIDARs provide the distinct advantage of high voxel rates about two orders of magnitude faster than typical pulsed LIDARs [8,9]. The major disadvantage of this approach is the trade-off between operational range and measurement precision and resolution. Because they infer range from a phase shift, there is a maximum operational range (ambiguity) of half of the modulation wavelength. This means to achieve a long operational range the modulation must occur with a long period. Unfortunately, the range measurement precision and resolution are directly related to the modulation period and so high precision requires short periods.

This paradox in performance is often solved by either compromising to get acceptable precision over an acceptable range, or by using multiple modulation frequencies. The latter approach uses a low frequency (long period) modulation to get a coarse range measurement over a long operational range and a high frequency (short period) modulation to provide a fine-tuning of the range precision whose absolute range ambiguity is solved by the low frequency [10,11]. More frequencies can be used to improve the trade-off but the disadvantage this approach is that the voxel rate is divided by the number of frequencies used.

This trade-off between operational range and precision also provides a benefit in terms of flexible performance. The modulation frequency can often be changed on the fly and so the same system can be used for coarse long range measurement and fine short range (or small motion) measurements.

Generally speaking, modulated cw LIDAR with similar range limitation as autosynchronous triangulation will not have as precise 3D measurements. The benefit of this approach is mostly seen in the voxel rates that can be generated in a scannerless configuration discussed in Section 3.1.

3. COMPLEMENTARY TECHNOLOGIES

This section describes and compares the scanning techniques, measurement principles, and performance of triangulation and ToF ranging systems. More complete analyses of these systems can be found elsewhere in the literature [9,12,13];

3.1 Complementary Scanning Techniques

There are three general approaches for performing 3D measurements over a region or field-of-regard (FoR)[1]: flying spot, line scanning, and scannerless. *Flying spot* scanning makes individual point measurements and scans the FoR by moving the spot (and corresponding detector aim) via dual-axis steerable mirrors, a pan-tilt unit, or translation of the sensor such as from an airborne platform.

Steerable mirrors allows the measurement to be placed anywhere within the FoR and is therefore sometimes referred to as *random access scanning*. The advantages of random access include on-the-fly flexibility for changing spatial resolution (zoom), scanning pattern, field-of-view (FoV), location of the scan within the FoR, and the number of measured voxels. There is also some robustness to motion during scanning because individual measurements often occur on the order of microseconds or faster and so the range measurement is not blurred by motion. The trade-off is that there can be distortion of the measured object shape as the scan continues over the moving surface. Dynamic imaging techniques exist for correcting for this distortion in real-time [15]. Pan-tilt units also have random access capability but must move the entire sensor mass and therefore are significantly limited in scanning speed in comparison.

Airborne imaging makes use of the translation approach, often using a single rotating mirror to scan the spot in one axis while the path of the airplane provides the other axis. This approach has a fixed scanning pattern and so is not random access. It does take advantage of the necessary airborne platform motion to perform relatively fast scanning of a ground or water-based region of interest.

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[1] Field-of-regard is the viewing angle over which the sensor can make measurements. Field-of-view is the viewing angle for a given scan. Instantaneous field-of-view is the angle seen by the optics for a single measurement.

At the other extreme of scanning techniques are scannerless systems that have a fixed FoV similar to a more traditional 2D camera, and no moving parts. Triangulation based scannerless systems include binary projection encoding [16] and fringe projection [17]. These approaches generally use a video projector to display a structured light pattern and have an offset camera to view the reflected patterns to interpret the range. These systems are generally limited to very small volumes due to the focus limitations of the optics and are therefore not generally useful for applications discussed in this paper.

ToF scannerless systems are often AM/cw [11, 18], range-gated cameras [19,20], or flash LADARs [21,22]. AM/cw scannerless systems use the a wide dispersion beam and an array of detectors (often CMOS or CCD) that measure phase, and hence range, at each pixel across several video frames.

Simple range-gated cameras use a shuttering technique in which a wide-dispersion pulse is generated and a high-speed shuttering pattern is used to gate the reflection. If the reflection for the region of a given pixel arrives at the detector at a time when the gate is open, the measured intensity is recorded. If it arrives when the gate is closed, no (or low) intensity is recorded. By changing the shuttering pattern across several video frames, the exact range bin for a pixel can be uniquely defined. Fig. 2 shows a basic set of patterns across several frames. More complex methods for range-gated cameras exist than described here, but the principle is generally similar [19,20].

Flash LADARs use the direct pulsed-ToF method using an array of timing circuits but are currently limited to low resolution, generally 32x32 [21] or up to 128x128 [22]. The complexity of the pixel timing circuitry is the limiting factor for these experimental devices in performance, cost, and availability.

The great advantage of scannerless systems is the voxel rate because they provide multiple simultaneous range measurements, often hundreds of thousand to millions of measurements per second.

While scannerless systems are currently very popular in academia and experimental platforms, they do have a number of disadvantages for a variety of applications. They are inflexible, having fixed spatial resolution, scanning pattern, FoV, aim, and voxel positions. The AM/cw and range-gated cameras are also much more sensitive to object motion during measurement because, although the average voxel rate is high, the simultaneous measurements occur on the order of hundreds of milliseconds, at least three orders of magnitude slower than for flying spot scanners. Individual video frames are therefore more susceptible to motion blur and the use of multiple video frames (and especially multiple frequencies for AM/cw) means motion between frames can cause much loss in measurement precision. Flash ladars are generally not as sensitive to these problems since they make individual high-speed time measurements.

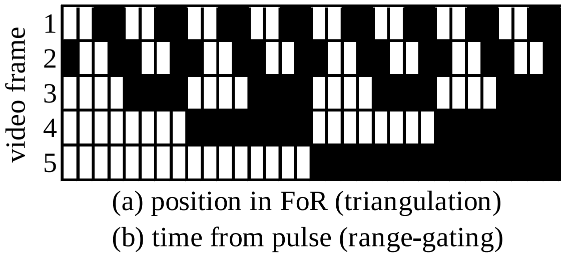

Fig. 2: Simple binary encoding patterns.

Perhaps the largest disadvantage of scannerless approaches for many applications is the enormous amount of data they generate. Storage, transfer, processing, and reduction of this overabundance of data can be particularly problematic for applications where speed is paramount such as object tracking, target recognition, navigation, or rendezvous and docking. In these applications, the data itself is not the end product and only a small portion of the data may be used and at the cost of high processing and transfer times and so the effective “useful” data rate may be comparable to, or slower than, flying spot scanning.

Clearly from these descriptions none of the scanning approaches are ideal for all applications. The scanning techniques are complementary because the advantages and disadvantages are generally opposite. A scannerless system can cover a FoV much faster than flying spot and is therefore quite useful as a quick search method to locate an object or region of interest. Once the object or region is found this information can be passed to a flying spot scanner to gather only the necessary data at much higher resolution and precision (if needed) and use the feedback from the application to direct continuing scanning.

3.2 Complementary Measurement Principles

The measurement principles described in Section 2 can also be tied to the scanning techniques described in Section 3.1. In flying spot triangulation the goal is to measure the location of the beam on a linear detector as shown in Fig. 3. In this case it is assumed that the beam profile is Gaussian, as is typical, and the peak is the measurement point of interest. For a single point measurement in a LIDAR, the measurement principle is the same except that the location on detector is in time rather than position as indicated by the interchangeable horizontal axes units in Fig. 3. In this case, the laser pulse is assumed to be Gaussian in time. Of course, multiple or varying surface features will distort the shape of this peak but this is true for both LIDAR and triangulation. The range artefacts generated by this peak distortion are different in the two measurement principles because of the difference in the distortion domain (spatial versus temporal).

There are also direct analogues in the scannerless techniques. Binary encoding and range-gated cameras are essentially the same technique. The binary projection patterns and gating patterns can be identical as shown in Fig. 2 with only a change of domain on the horizontal axis from position within the FoV to sub-frame gate timing. In binary encoding the binary pattern seen at each camera pixel across several video frames corresponds to a unique position in the projector FoV. (Other approaches use the black-white transition as the measurement point [16].) Simple triangulation geometry between the camera pixels and projector FoV provides the 3D measurement. In range-gated cameras, the measured binary pattern corresponds to a unique range bin. The equivalence of these techniques is shown in Fig. 4(a) and (b) where the only difference is the direction of the pattern laterally or with time (range).

Scannerless AM/cw is directly comparable to fringe projection in which a sinusoidal intensity pattern is projected laterally, similar to binary encoding. In both AM/cw and fringe projection the phase of the sinusoidal pattern is changed between frames and the reflected intensity pattern across several frames uniquely defines a phase shift at each pixel. In fringe projection the phase relationship with range is a function of the triangulation angle and for AM/cw the phase is proportional to range. Fig. 4(c) and (d) show the comparable sinusoidal patterns that differ only in direction – lateral for fringe projection and range (time) for AM/cw. The phase decoding equations for these two approaches are also generally the same [9]. Fig. 4 also shows the similarity between the modulated and binary approaches, though binary approaches are not limited by ambiguity interval.

The comparisons in this section demonstrate that the basic principles of triangulation and ToF are complementary in that they are essentially identical problems in a different domain, often with the same or similar processing algorithms. Of course the sensor components necessary for each technique can differ significantly and the limitations of the physical principles may differ in each domain. But problems and solutions in each domain can drive research direction for solving problems in the other domain.

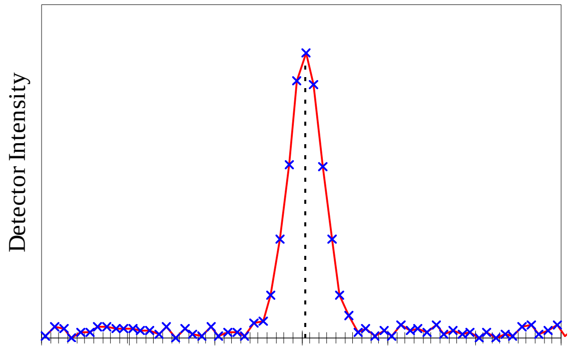

Fig. 3: Gaussian peak measurement.

3.3 Complementary Performance

Performance of triangulation, LIDARs, flying spot, and scannerless sensors are discussed in more detail in [9]. The basic results have already been mentioned in this paper but are briefly summarized below.

Flying spot pulsed LIDARs typically have range precisions on the order of centimetres to tens of centimetres but hold this precision over very long ranges of hundreds of meters to kilometres with only slow degradation. However, they are generally poorer at short range. Similarly, their voxel rates tend to be slower than other approaches and this can be further slowed by averaging multiple points to improve precision. Voxel rates can be particularly limited at close range because of the mass of the large optics (e.g., mirrors) required for longer range operation are slow to scan over the wider FoV required at shorter range. In addition, lateral precision (position orthogonal to range) is poor because all reflections from within a spot are associated with the centre of the beam and the spot size can be quite large for long range operation. The large spot also limits the resolution (smallest measurable feature).

Flying spot triangulation systems tend to improve quadratically in precision and speed as the range decreases and are generally comparable in speed to the fastest pulsed LIDARs, though much slower than AM/cw and scannerless approaches.

Flying spot AM/cw LIDARs are limited to much shorter operational ranges but can achieve millimetre precision at close range and at very high voxel rates. Unfortunately, the operational range tends to be on the order of triangulation limitations without achieving the range or lateral precision and resolution of

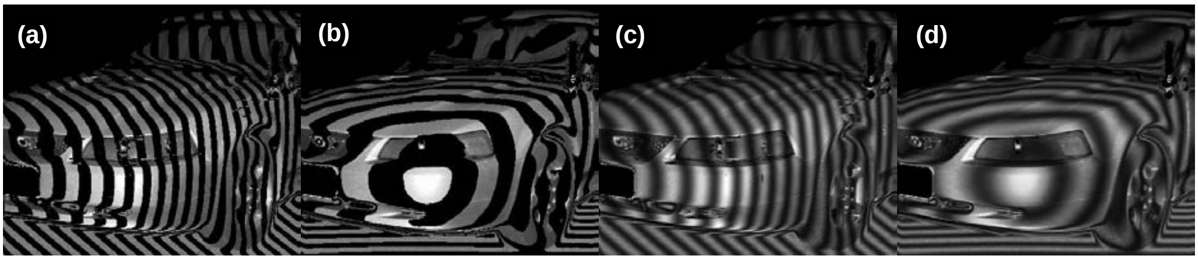

Fig. 4: Scannerless ranging: (a) binary encoding, (b) range-gating, (c) fringe projection, (d) AM/cw.

triangulation systems, leaving only the voxel rate and flexibly re-configuration as the unique advantages.

The scannerless approaches all have large voxel rates but the range and lateral precision and resolution tend to be worse than flying spot triangulation at close range, in addition to their reduced flexibility. The lack of moving parts also means they tend to be smaller, lighter, and require less power than flying spot scanners.

In summary, pulsed ToF is essentially the only principle that can work over long range and does a reasonably good job until a few tens of meters when speed and precision become issues. In contrast, triangulation and AM/cw are best at close range and are limited to a few tens of meters, with triangulation better for measurement precision and AM/cw better for voxel rates. The performances are then complementary because pulsed LIDAR is good for long range and poor for short range, and the other approaches are good for short range but poor for long range. This trade-off between ranging principles is not due to simple limitations of current technology that can later be overcome. The fundamental physics of photons, optics, efficiency, mechanics, and geometry mean that long and short range measurements inherently have complementary limitations [13,14].

4. HYBRID SOLUTION

4.1 Hybrid Design

The previous sections have demonstrated that there is no single sensor technology appropriate for all applications or for the entire volume of a single application that requires measurement from far to close ranges. A traditional solution to this problem is the use of multiple sensors. Such a solution provides extra cost, size, weight, power, and processing requirements. Often these factors are limited, particularly for space and robotic applications.

Another solution is to combine multiple approaches in a single hybrid sensor. For example, the Jigsaw program has combined a scannerless flash LADAR system with a flying spot scanning technique [23]. Such a hybrid approach combines the high data rate of the flash LADAR with the increased coverage provided by moving the smaller LADAR instantaneous FoV around a much larger field-of-regard as in flying spot systems. However, this hybrid scanning technique uses a fixed scanning pattern from rotating prisms and so does not gain the flexibility of a random access flying spot scanner. It also loses some of the benefit of scannerless systems associated with the lack of moving parts such as lower size, weight, and power requirements.

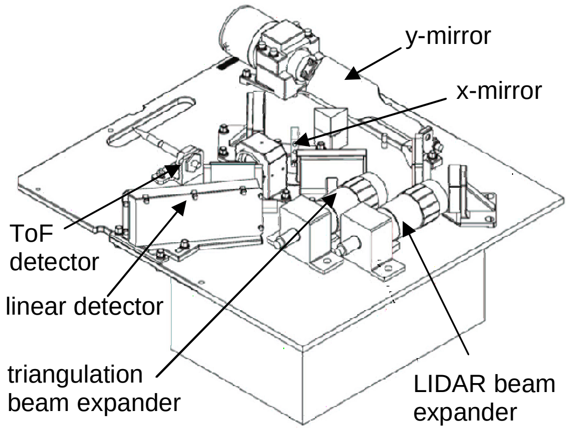

Fig. 5: TriDAR layout.

The hybrid approach chosen by Neptec is essentially the opposite of the Jigsaw combination. It combines multiple ranging principles into a single scanning mechanism rather than a single ranging principle in multiple scanning techniques. Neptec's hybrid sensor builds off of the success of the autosynchronous triangulation design developed and patented by the National Research Council of Canada and licensed by Neptec [4,7,24]. The hybridization adds a pulsed LIDAR unit into the same optical path as the triangulation for both projection and collection.

The combined triangulation and LIDAR (TriDAR) system share the same opto-mechanical system -- including galvanometers, mirrors, and collection optics. Additionally, the control electronics and measurement architecture largely overlap with the exception of the direct ranging measurement. The processing unit, upon which the intelligent applications can run in addition the scanning control, is also common. The thermal, structural, and communication interface are also common. Fig. 5 shows a layout schematic of the current TriDAR design.

Triangulation cannot provide the required long range measurements and ToF systems cannot provide both short range precision and measurement at long range. The TriDAR design provides mid-precision long range measurement and high-precision short range measurement with highly efficient overall size, weight, and power for these capabilities.

In addition to providing the optimum combination of ranging techniques for long and short range, the TriDAR design takes advantage of the autosynchronous scanning approach to keep both detectors (triangulation and ToF) viewing the projected lasers while maintaining a small instantaneous FoV of a few degrees. This instantaneous FoV can be scanned through a much larger FoR up to about 30º using dual-axes scanning mirrors driven by galvanometers. This scanning capability makes the TriDAR a random access flying spot scanner.

As discussed earlier, although flying spot scanners have benefits over other scanner types, particularly flexibility, they have the disadvantage of lower voxel rates than scannerless sensors. However, since the end applications often do not require all of the data produced by the scannerless sensors, the flexibility of flying spot scanners can be exploited to use feedback from the application itself to only scan points of interest and therefore maximize efficiency and "useful" data rates while minimizing processing time, and in some cases the removal of processing steps.

For example, tracking a target does not require a scan of the entire FoV except for initially locating the object [4,25]. After that, only points on the object are necessary which can be directed by the tracking output itself. Furthermore, the entire object does not have to be scanned in high-resolution, but only with sufficient number (and location) of points to provide the necessary tracking information.

It is this intelligent scanning application that has contributed in large part to the selection of the TriDAR design and on-board tracking capabilities as the sensor for autonomous rendezvous and docking of the Hubble Robotic Vehicle (HRV) to the Hubble Space Telescope (HST) for both short (<10 m) and long (10 – 150 m) range. This mission, should it continue, is designed to attach a de-orbit module to the HST. The TriDAR has also been selected for a Detail Test Objective (DTO) shuttle flight to demonstrate its tracking capabilities during docking and undocking with the International Space Station (ISS). Neptec has built a prototype TriDAR and demonstrated imaging at tens of meters as well as successful tracking of a scale model satellite.

4.2 TriDAR Potential

TheTriDAR dual measurement approach also offers great opportunities for additional performance improvements. While the LIDAR is intended for long range use and the triangulation system for short range, there is overlap in the mid-range from several meters to several tens of meters where both range measurement can provide useful information. The redundancy in both range and reflection (intensity) measurements provides opportunity for sensor fusion techniques to improve individual measurements. These fusion techniques can vary from simple weighted averaging of simultaneous range measurements to complex correlation and full-reflection analysis [26].

For instance, both triangulation and LIDAR suffer from edge effects due to split or distorted spot reflections, but exhibit the distorted edge in different manners. Correlation techniques between the two measurement may reliably indicate the location of an edge and analysis of the reflection signal (spatial for triangulation, temporal for LIDAR) may allow for better reconstruction of the edge feature.

Furthermore, triangulation does not suffer from the lateral imprecision and low resolution of the LIDAR since the triangulation principle relies on measurement of a feature position, in this case the peak of the Gaussian which is, by definition, associated with the centre of the laser beam. This lateral position measurement may be able to better position multiple LIDAR returns within the spot rather than simply associating them all with the centre of the LIDAR spot.

In terms of design efficiency, there may be additional room for improvement of the concept. The current design shown in Fig. 5 uses two sources at different wavelengths so that they do not interfere along the common optical path. While the triangulation measurement currently operates on a continuous laser beam, the principle can operate using a pulsed beam. In future designs this may allow for using a single source on the projection side and splitting the signal on the collection side between the detectors, thereby reducing size, weight, and power requirements. Although the beam size for long (LIDAR) and short (triangulation) ranges have conflicting requirements, a motorized beam expander may provide the necessary beam control as the range to object changes.

Another possible improvement is the range of operation. The TriDAR has small scanning mirrors only slightly bigger than the LCS design in order to maintain the scanning speed for short range operations. This means that the practical operational range using COTS LIDAR components is limited to the order 100 m or so. Custom design of the LIDAR components, such as the use of an optical amplifier has the potential to expand the operational range much further without significantly reducing the scanning capabilities for short range. At this range the LIDAR need only receive enough signal for "blob" detection for bearing and range rather than high resolution feature measurement or object pose estimation.

While 3D measurement technology has matured in performance and speed, the applications for most 3D sensors has been imaging. Triangulation is typically used for high-resolution virtualization of objects for a variety of eventual purposes such as video games, movies, reverse engineering, inspection, archiving of historic artefacts. LIDARs are most often used for airborne or ground-based imaging of regions such as geological surveys, forestry, bathymetry, urban planning, and automatic target recognition.

The TriDAR design and operational principle naturally lead towards the principle of intelligent scanning, a form of three-dimensional intelligence (3Di). Intelligent scanning implies the feedback of the application to drive the scanning to gather only the necessary data for the next measurement. The AR&D tracking and pose estimation application discussed earlier is one such application. Dynamic imaging, object recognition, collision avoidance, navigation, and in-situ part inspection are other examples of intelligent scanning applications. The TriDAR processing unit contains a CPU, DSPs, and FPGAs for both scan control and intelligent applications. Future designs may include optimization of the processing and electronics architecture for high-processing capabilities with smaller size, lighter weight, and lower power. 3Di applications running on-board can directly output the end-product information from the sensor, such as object pose estimation, rather than the raw 3D data. Thus the combined approach of intelligent scanning and 3Di can reduce the amount of raw data gathered as well as perform the data reduction and processing steps to output the end product following the paradigm of "less data, more information".

Finally, the very high-resolution triangulation at close range (up to several meters) can be used for other 3Di applications such as geomaterial characterization [27] and inspection [7] since the autosynchronous triangulation system has been designed to be a metrology instrument. Thus the same TriDAR can operate as a multifunction sensor robotic operations such as lander guidance, rover navigation, vehicle inspection, and exploration science. This flexible capability in a single sensor may be critical in future exploration missions where size, weight, and power limits are small.

5. CONCLUSION

This paper has examined the complementary nature of triangulation and ToF ranging principles as well as scanning techniques and performance. The conclusion of this analysis is that a hybrid sensor is the ideal methodology for a large class of 3Di applications. Neptec has built such a hybrid sensor prototype with demonstrated success and selection for several space missions. The potential for this design shows a multitude of applications, improvements, and future growth directions.

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