A COST-EFFECTIVE 3D IMAGING LIDAR SYSTEM

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ABSTRACT:

The proposed work deals with the design and construction of a new type of imaging lidar device which offers high performance in a cost-effective approach. Typical imaging lidars used in defence and security markets are high-end equipment, far from being considered cost-effective devices. Flash ladar systems are also too much expensive to cover some of the market demands, in several cases being the price its main restriction.

We present an imaging lidar approach which can provide a reduction in cost of up to 10 times in comparison to present commercial devices, enabling a wider use in existing applications while enabling novel ones. Just to mention some of the opportunities targeted, we can highlight robot guiding, remotely operated or self-guided vehicles, underwater sensing and guiding, landing aid subsystems for helicopter operation, or surveillance, among others.

1. INTRODUCTION

This work is centred in the design of a novel type of real-time 3D imaging camera conceived for outdoor and long range applications. Tentative performance values are in the range of 10 frames/s, with distances up to a few hundredths of meters and fields-of-view of some tenths of degrees. Specific values are provided in table 1.

Real-time lidar cameras with long range measurement capabilities are high-end equipment, which offers outstanding technical capabilities especially useful in a number of niche applications. However, not all markets can afford the cost of such devices. A cost-effective lidar camera could be of special interest in those applications where price restrictions don't justify the use of high-end lidar systems like the ones commercialized by ASC[1] or Princeton Lightwave [2]. A number of markets demand cost-efficient and affordable devices which present smart technical capabilities, in order to reduce investment and improve profitability to justify the introduction of the technology.

We propose a new concept of 3D imaging lidar camera that provides technical capabilities comparable to conventional flash ladar cameras in a cost-effective way. By using off-the-shelf optoelectronic components plus a proprietary and patented scanning approach, the total cost reduction can be up to 10 times cheaper in comparison with existing technologies.

2. EXPERIMENTAL SETUP

The design approach is based on pulsed time-of-flight measurement, where nanosecond laser pulses illuminate the target and precise time-counting circuits are used to determine the time between the on-going and back-reflected pulses.

Actually, we are working in two prototypes with different specifications. The first one is fully operative and this article is entirely based on it. However, some tentative data are also provided for the second prototype which is currently under its final stages of development. The working prototype consists of a pulsed Nd:YAG laser with an external second harmonic crystal, which emits 1ns pulses at a maximum repetition rate of 3KHz with an initial wavelength of 1064nm, which is turned onto 532nm after the crystal. The pulse energy delivered is 2µJ, so the peak power is set to around 2kW. A small portion of the laser pulse energy is captured by a PIN photodiode used for detecting the outgoing pulse. Signal is discriminated using the rising edge detection method, and the circuitry involves a low jitter comparator for threshold detection. This signal is used as start input for a high precision time-to-digital converter (TDC).

The main part of the pulse energy is used to illuminate the scene under measurement through a beam expander lens. Each pulse irradiates the whole surface at once, as in a conventional flash lidar system. A second group of lenses is used to image the scene onto our patented scanning system [3], so both the detector and the scene are optically conjugated. The scanning system does not present any mechanical wear or vibrations and is fully controllable by software. A complete photometric analysis of the setup and detailed ray-tracing simulations (not shown) were developed for a proper optomechanical design and construction of the system, including a TIR prism arrangement intended to reduce the optical path size and to enhance the compactness of the device. A third group of lenses focalizes light from the scanning system onto the detector.

The back-reflected pulse is measured by means of a Silicon Photomultiplier detector (SiPM) [4]. This is an extremely sensitive detector based on an array of Geiger mode APDs with single photon capability. In comparison with linear mode avalanche photodiodes, Geiger mode APDs offers high sensitivity, larger gain and faster response. The detector used has a gain around 10^6, 120ps of random jitter and $3mm^2$ of active area. The sensor used is a Hamamatsu MPPC S10362-33-100C, quite common in applications such as Positron Emission Tomography [5], fluorescence measurement, DNA sequencing or high energy physics [6]. Recently, some related work on the team responsible of this work has demonstrated its usefulness in atmospheric lidar applications, both in analog read-out mode [7] and in photon counting mode [8]. The detector read-out needed a special treatment in response to the strict timing constraints involved. A NINO ASIC [9] circuitry provided by CERN was chosen for accurate signal amplification and discrimination. The NINO circuitry provides an ultra-fast low power discrimination chip which delivers only 25ps of jitter. The read-out output feeds directly the TDC stop input after a conventional voltage shift conversion. The system was originally used as detection circuitry for read-out of multigap resistive plate chambers in the ALICE experiment. Fig. 1 shows the external shape of the designed prototype.

Figure 1. First prototype

The prototype dimensions are (WxDxH) 155x160x135 mm. Although these volumes are quite common in commercial lidar systems, the prototype currently under development will half them, making it especially interesting for embedded applications.

Fig. 2 shows the implemented optical setup. Note that the laser pulse illuminates the whole scene at once. This is the approach used in the first prototype, while in the second one some enhancements in order to improve energy efficiency by reducing the optical beam divergence while keeping the same FOV have been included. This approach enables a higher optical power concentration per surface unit, so a longer distance can be measured with the same emitted energy.

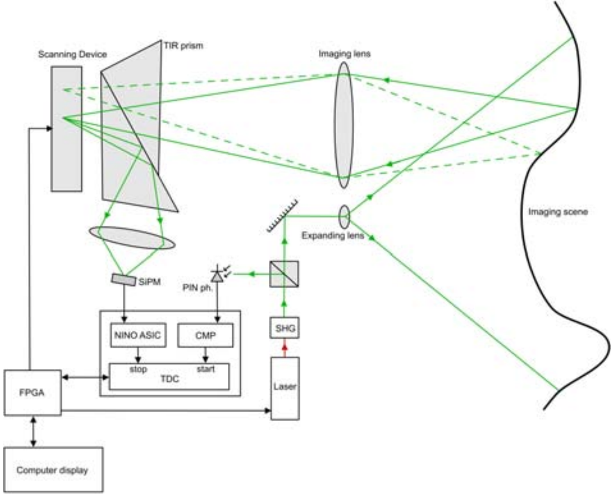

Figure 2. Optical setup

3. PERFORMANCE

Performance of both prototypes in terms of range, image spatial resolution and frame rate are configurable according to application needs. Table 1 shows three different configurations for three different application cases in both prototypes. Longer ranges require smaller field-of-view, while higher image spatial resolution requires lower frame rates. Such values can be configured, and depend on the optical configuration set.

Besides, our proprietary scanning system provides the possibility to change the image spatial resolution vs frame rate at will using a simple software reconfiguration [10]. In this case, the image spatial resolution can be increased while the frame rate value is reduced, and vice versa. Fig. 3 graphically shows this relationship considering the capabilities of the second prototype. This ability is inherent to our scanning device and cannot be found in any other existing lidar camera. In advanced applications, it becomes useful to tune the imaging properties to adapt the parameters according to external requirements.

Table 1. Performance example

Configuration	Parameter	First prototype performance	Second prototype performance
Short distance High spatial resolution Low frame rate	Measuring distance	10 m	100 m
	FOV	30º	70º
	Spatial resolution	255 x 191 px	430 x 330 px
	Frame rate	0.06 Hz	1 Hz
Middle distance Middle spatial resolution Middle frame rate	Measuring distance	20 m	500 m
	FOV	20º	10º
	Spatial resolution	63 x 47 px	195 x 115 px
	Frame rate	1 Hz	9 Hz
Long distance Low spatial resolution High frame rate	Measuring distance	30 m	1000 m
	FOV	8º	3º
	Spatial resolution	15 x 11 px	102 x 76 px
	Frame rate	15 Hz	25 Hz

Thus, the concept offers a versatility not attainable in present lidar imaging systems. Besides, an increase of available spatial resolution values up to camera-like ones under given conditions may be also highly desirable to overcome present limitations in spatial resolution existing in present flash lidar concepts. The variability of the scene conditions might require different measuring approaches in different moments. For instance, applications involving obstacle detection and identification in self-guided or remote operated vehicles could be enhanced if measurements with different speeds or resolutions depending on the circumstances could be optimized to adapt to different speeds of the vehicle, distances to the obstacles, movement and size of the obstacles, etc. Security and defence markets, due to the nature of its applications, are considered the most attractive for these novel imaging lidar devices.

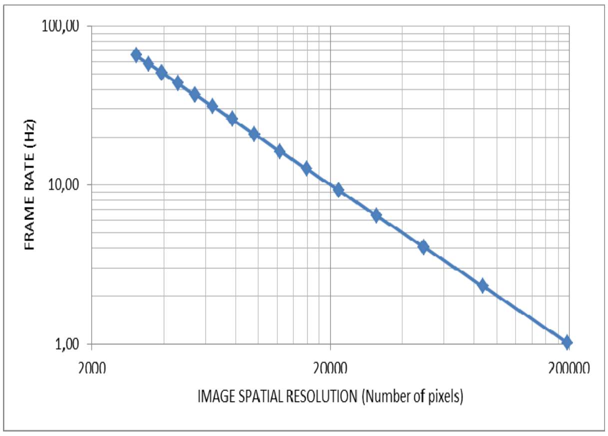

Figure 3. Relationship between image spatial resolution and frame rate. All values are attainable reconfiguring by software the same prototype

The measured experimental vertical resolution in the prototype system built is around ±2.5cm, regardless the range and scanning conditions involved. The sum of all electronic jitter and timing resolutions in the complete system has been reduced to 160ps in the existing prototype. It thus provides typical TOF vertical resolution, in special when small objects are measured in close ranges. In addition, background light is properly filtered so the device can work successfully either in indoor or outdoor applications, regardless the amount of background light present.

4. RESULTS

In order to test the validity of the measurement principle, a complex scene was set up in a laboratory environment, with a number of objects of different shapes placed at different distances. The objects have been placed at ranges between 1.2m, corresponding to the first object, up to the most distant wall set at 5m approximately. A photography of the scene is presented in Fig. 4. No processing at all has been performed on the images, which are shown as raw data directly obtained from the prototype.

Figure 4. Indoor test scene

The following figures show the measured scene through different scanning modes, from low to high resolution. Each of them has different measuring times depending on the amount of pixels resulting in different 3D video frame rates. In this case, the measuring time is strongly limited by the laser repetition rate. Note that this first prototype includes a 3KHz pulse rate laser. This parameter could be easily increased by using a faster laser source, therefore, the measuring time and also the frame rate will be significantly increased in the final system, and has been implemented in the second prototype.

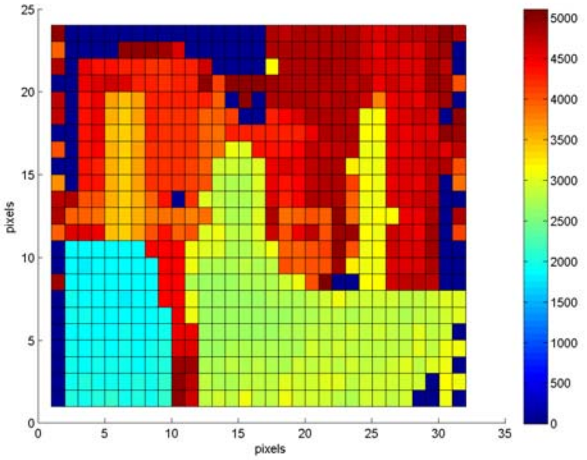

Figure 5. 0.7Kpixel @ 4.2 im/s

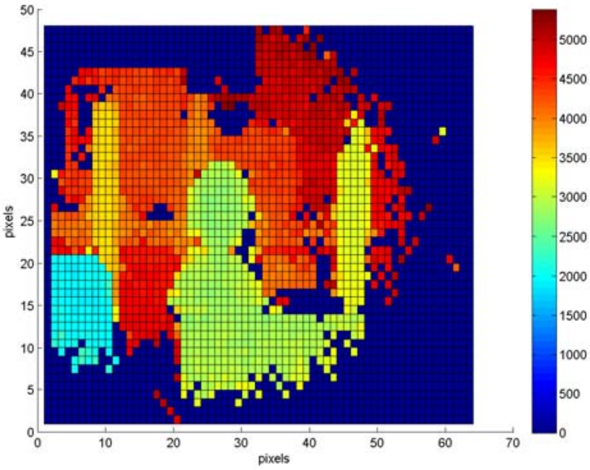

Figure 6. 3Kpixel @ 1 im/s

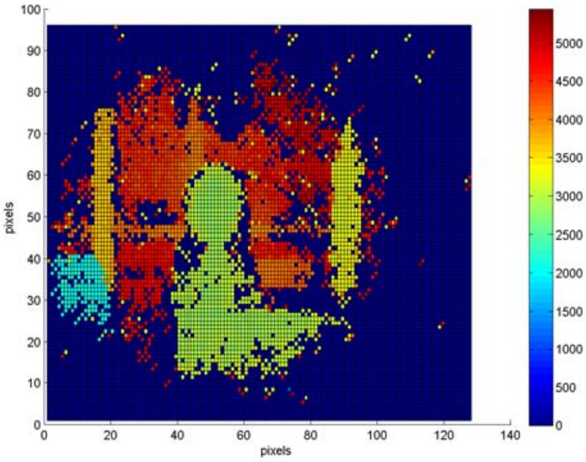

Figure 7. 12Kpixel @ 0.25 im/s

The reliability of the system when a strong background light is in the scene has also been evaluated. Fig. 8 shows an outdoor scene designed to evaluate the performance when direct sunlight is irradiating the surface. The results show that the performance of the system is not affected by such adverse conditions. Background light is well suppressed by using an optical band pass filter centered at 532±2nm. The resulting capture can be seen in Fig. 9.

Figure 8. Outdoor test scene

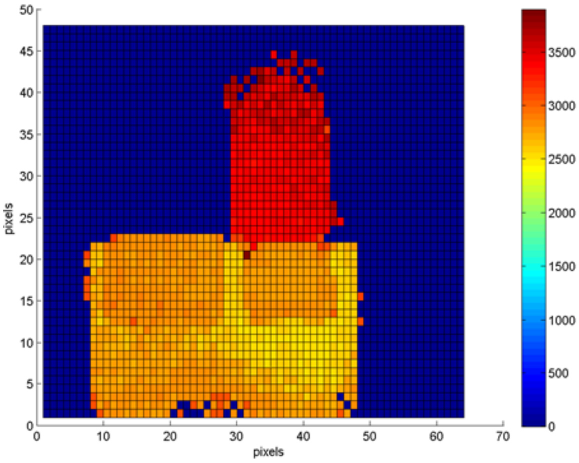

Figure 9. Measured outdoor scene

5. COST-EFFECTIVE APPROACH

The performance provided by the second prototype will be at the same level, even better, in comparison to existing lidar cameras. Nevertheless, its main advantage can be found in the cost of the device.

While standard real-time lidar cameras are in the range of 150-200K€, our lidar system is around 20-25K€. In the best case, it supposes a cost reduction up to 10 times. It should be mentioned that 75% of this cost corresponds to the laser source since pulsed and eye-safe lasers are expensive in all cases. This cost-effective approach is provided by the use of off-the-shelf components that are already available on the market and have been conceived for large volume applications. Such components are manufactured in large amounts so their cost is always cheap enough to keep the whole system cost-effective. This is also the case of the scanning system used, which is designed specifically for this device, but out of high-volume off-the-shelf components.

The second prototype will include a second full custom component which will be designed specifically. This is the TDC circuit implemented on an ASIC device with full-custom CMOS technology. It will provide all weather and degraded visual environment tolerance [11] (underwater and dust penetrating applications). However, the cost of this component is kept low by using multi-project ASIC fabrication provided by companies like CMP or Mosis.

6. CONCLUSIONS

A new 3D imaging lidar system has been designed, built and demonstrated. This system offers an innovative approach between technical performance and cost-effectiveness. The patented scanning technology combined with the use an off-the-shelf components enables a cost reduction up to 10 times cheaper compared with the existing systems. This cost effectiveness meets the actual market demands and also enables the use of the lidar technology in applications that where not possible before due to cost limitations. Larger volume applications can be tackled, for e.g., guided and remote operated vehicles, underwater 3D imaging for gas and oil industry, people and obstacle detection in railway and urban tams, advanced surveillance in security, UAV and UGV surveillance and the well-established applications in the defence market as well.

The patented scanning system provides a competitive mix of technical capabilities in terms of image spatial resolution, frame rate, FOV and range comparable to commercial flash ladars and real-time 3D cameras. Out-door operation at long distances and at real-time imaging combined with high point density are required capabilities to fulfil the requisites of the most demanding applications that additionally demands a reasonable device's cost.

7. ACKNOWLEDGEMENTS

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