Lidar imaging with on-the-fly adaptable spatial resolution

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ABSTRACT

We present our work in the design and construction of a novel type of lidar device capable of measuring 3D range images with an spatial resolution which can be reconfigured through an on-the-fly configuration approach, adjustable by software and on the image area, and which can reach the 2Mpixel value. A double-patented novel concept of scanning system enables to change dynamically the image resolution depending on external information provided by the image captured in a previous cycle or on other sensors like greyscale or hyperspectral 2D imagers. A prototype of an imaging lidar system which can modify its spatial resolution on demand from one image to the next according to the target nature and state has been developed, and indoor and outdoor sample images showing its performance are presented. Applications in object detection, tracking and identification through a real-time adaptable scanning system for each situation and target behaviour are currently being pursued in different areas.

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Keywords: time of flight, lidar, ladar, scanning, 3D imaging, adjustable spatial resolution, real-time imaging, frame rate.

1. INTRODUCTION

Advanced security and defence applications like object detection, tracking and identification require a delicate balance between frame rate (that is, the time required for a full frame acquisition), and the spatial resolution of the image. This is especially relevant in applications where the target is in movement, or where given areas in the image might require special attention in case of detection of activity. Often the requirements of the imaging system can be significantly different according to the shape of the target, its speed or its distance.

In classical scanning systems, the image frame rate is typically inversely proportional to the number of measured points due to its sequential measurement procedure. For slow moving objects a higher level of detail can be obtained by setting a high spatial resolution in the image (which can get to hundreds of measurement points). Conversely, fast frame rates can be configured when the object moves fast at expense of image point density. The detection range may be maintained high up to several hundreds of meters, and the field-of-view adapted to the requirements of the application.

For many years, galvanometric scanning mirrors have been the reference device when generating pulsed[1] lidar 3D images. The measurement was a sequence of fast, single point measuring steps. However, steering mirrors[2] are essentially mechanical devices which suffer from vibration and wear, present large volumes and important measuring times due to its sequential scanning nature. Its main advantages lie in the high beam collimation enabled by laser beams which enable to measure long distances easily thanks to the energy concentration at the measuring point they provide.

In these mechanical scanning devices, the image frame rate is always dependent on the number of measured points that compose an image due to the sequential nature of the measurement principle. Given a fixed laser repetition rate, the larger the spatial resolution, the smaller the image frame rate obtained. This implies that when a large image spatial resolution is required, an inadequate image frame rate is obtained since lasers have a limited pulse repetition rate. Although this is not a problem when static environments are measured, a too small frame rate is an important limiting factor when moving objects appear in the scene and need be considered. In that case, the device can't capture the moving object and erroneous data can be obtained.

In recent years, a new kind of lidar systems based on arrays of detectors[3] has emerged to overcome mechanical limitations and explore complementary applications. These devices do not need any scanning method since the whole image is captured at once. In this case, the scanning device is replaced by an array of sensors with TOF (time-of-flight) measuring capability in each detector[4].They are compact, and usually work based on the modulated TOF principle rather than on pulsed laser imaging. Their main drawback refers to the complexity of the microelectronic integration of such arrays in a single semiconductor die. This introduces a strong limitation in their spatial resolution, which, in the best case is typically set to around 16Kpixels[5]. Another relevant limiting factor of such devices is their measurable range of distances. As far as all the detectors within the array are measuring in parallel, simultaneously, the power of the illumination laser needs to be distributed among them. This implies a laser source which needs to expand to cover the whole FOV, so the energy available for each of the detectors decreases quadratically with distance. This physical effect is compensated by using more powerful lasers than those typically used with scanning devices in order to measure a given distance, and also introduces complexities in outdoor, daylight scenarios.

Contrary to sequential scanning systems, systems based on arrays of detectors can also provide excellent performance in their image frame rate thanks to its capability to measure in parallel multiple sample points. They give very good results when fast moving objects are in scene. Applications like object detection and tracking are feasible for these systems, although they tend to be prone to errors in varying outdoor environmental situations.

Additionally, arrays hardly go beyond the 20Kpixel value either in FMCW (Frequency Modulated Continuous Waveform) or pulsed TOF systems. In all these systems, the image spatial resolution is already fixed by the scanning system or by the length of the detector array. It's not possible to modify the point density in the image because this parameter is strongly linked to other parts of the system which are not easy to modify, e.g. the length of the sensor array or the mechanical parameters of the scanning devices. There is not the possibility to improve one parameter over the other according to different scanning criteria in a reconfigurable, active way.

2. ON-THE-FLY ADAPTABLE SCANNING EXPERIMENTAL SETUP

In advanced applications, it becomes useful to overcome this limitation between image frame rate and spatial resolution. Modifying the balance in order to optimize one or another parameter depending on the instant requirements of the application at each moment offers a versatility not attainable in present systems. Besides, an increase of available spatial resolution values up to camera-like ones (2Mpixels) under given conditions may be also highly desirable to overcome the present limitations of spatial resolution in flash lidar systems. 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 from obstacles, movement and size of the obstacles, etc. Security and defense markets, due to the nature of its applications, are considered the most attractive for these novel imaging lidar devices.

2.1 Lidar setup

A patented novel concept of scanning lidar device has been implemented in a novel prototype to establish the validity of the proposed scanning concept and test the limits of the system. It should be kept in mind that the prototype has been built as a proof of concept in order to test the feasibility of the scanning concept. The physical prototype of the device is presented in Figure 1. It 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 an expanding beam lens. Each pulse irradiates the whole surface at once, as in a conventional flash lidar system, although detection is based on pulse threshold detection instead of using the FMCW method. A second group of lenses is used to image the scene onto our patented scanning system, so both the detector and the scene are optically conjugated. The scanning system does not present any mechanical wear 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 complex 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.

Figure 1. Front view of the prototype of lidar setup. The upper optical group illuminates the scene using a diverging optics. The lower one is used to capture the back reflected light onto the optical scanning system.

An edge detection algorithm applied to the signal in the detector indicates the TDC circuit to finish time counting. In contrast with the start detector, special care has been taken on the detection side in order to optimize signal detection for small amounts of optical power received. For this reason, an extremely high sensitivity detector has been chosen. With these purpose, instead of the conventional avalanche photodiodes (APD) in Geiger mode for returned beam detection used in lidar systems, a silicon photomultiplier element (SiPM) has been used with the purpose of taking advantage of its extremely high sensitivity, larger gain and faster response. The detector used offers a gain around 10^6, 120ps of random jitter and $3mm^2$ of active area. The SiPM detector used in our setup is a Hamamatsu MPPC S10362-33-100C, quite common in applications such as Positron Emission Tomography[6] (PET imaging), fluorescence measurement, DNA sequencing or high energy physics[7]. Recently, some related work on the team responsible of this work has demonstrated its usefulness in atmospheric lidar applications, both in analog read-out[8] and in photon counting mode[9].

The detector read-out needed a special treatment in response to the strict timing constraints involved. A NINO ASIC[10] 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 read-out circuitry for read-out of multigap resistive plate chambers in ALICE experiment[11].

2.2 Performance

The proposed scanning system provides the capability to modify in real time the balance between frame rate and spatial resolution, which are inversely proportional parameters once the laser repetition rate is fixed. Using the optical scanning method proposed, the detection range and frame rate can be adjusted to reach very high values at the expense of reducing spatial resolution. The transition between scanning modes can be done from one frame to the other without any additional delay just by software. Examples of performance of three different configurations are presented in Table 1, showing the real experimental values obtained with the present experimental setup together with the experimental values expected for the second prototype of the system, currently under construction. The two main compromises in lidar imaging may be observed. Notice that given the source is fixed, the longer the measuring range, the smaller the lidar FOV. Accordingly, the larger the spatial resolution, the smaller the frame rate.

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. It 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 either in indoor or outdoor applications, regardless the amount of background light present.

Table 1. Three different possible configurations for measuring in three different conditions, each of them with a concrete balance between frame rate and spatial resolution. Specifications of the existent present prototype are shown besides the featured specifications of the up-scaled prototype, currently under construction.

Configuration	Parameter	Present performance setup	Future 2nd prototype value
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

3. EXPERIMENTAL 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 Figure 2. No processing at all has been performed on the images, which are shown as raw data directly obtained from the prototype.

Figure 2. Scene used for measurement in a laboratory environment. The image is composed of a number objects at different distances ranging from 1.2m to 5 m.

A number of measurements have been taken using the available prototype, which has not been optimized in terms of measuring time and spatial resolution but intended to proof the feasibility of the scanning technology proposed. Being a sequential scanning system using a pulsed laser, the image frame rate becomes directly linked to the laser repetition rate as each laser pulse is used to measure a single point in the final image. A single-shot approach is thus implemented, so the larger the desired spatial resolution, the larger is the measuring time and the smaller the frame rate. The existing prototype has been built using a laser with a pulse repetition rate limited to 3KHz, which is far from typical values considered in lidar applications. As mentioned, the objective of this study is to present an on-the-fly modifiable balance between frame rate and spatial resolution, rather than exceptional capabilities in terms of lidar imaging which can be attained with a different source. By substituting this laser with another with improved capabilities, the measured frame rate and spatial resolution will proportionally improve relative to the ones presented in this work, following the right column in Table 1.

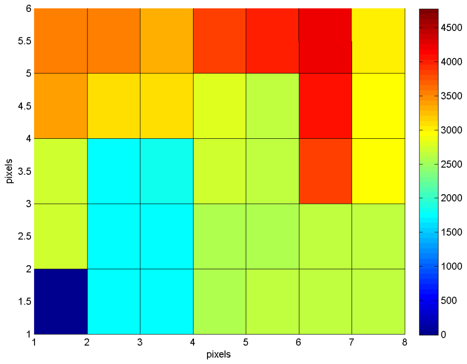

Figure 3. Lowest resolution image (35 pixels). Details are lost although frame rate is maxima.

Figure 3 shows a very low resolution image, with only 35 pixels available. Very few details can be appreciated since the pixel size is larger than with the details of the real scene. However, this configuration provides the maximum measurable range and the fastest frame rate of the system. This operating mode can be useful to identify if there are objects in movement or not within the field of view and the distance to each of them. It is not expected to be useful in order to capture details of the object shape. Figures 4, 5 and 6 show increased spatial resolution images reconfigured by software on the fly, with increased spatial resolutions of 0.16, 0.71, and 3Kpixels. Finer details can be appreciated in correlative images, such as the round shape of the doll's head, the edge of the distant table or the bottles in the scene. In larger spatial resolution images, the measured area doesn't cover the complete FOV scanned, as far as the laser power we are using is too small to obtain enough back reflected energy at each point. Images with larger spatial resolution may be obtained with the present system at the price of a larger energy concentration from the laser, which is attained by adjusting the illumination system in order to reduce the FOV of the laser. Figure 7 shows a 12 Kpixel image using the same setup with peripheral areas set to blue due to non-returned optical power. Figure 8 shows the maximum achievable spatial resolution in the image, which comes together with the minimum frame rate and FOV in the present setup, although a 48.7Kpixel image is obtained. The laser power is concentrated only around a small central area of the initial FOV. A more powerful laser with a better repetition rate, currently being built in the second prototype, would enable spatial resolutions up to the Mpixel level if required for the desired applications where frame rate is not the limiting factor. Table 2 shows a summary of the parameters of each of the images including the acquisition times involved for a single frame.

Finally, Figure 11 shows the plot of spatial resolution against acquisition time of each single frame. Unlike traditional image methods in lidar systems, our patented scanning system enables to adjust one parameter relative to the other by software, in order to set the proper balance between them depending on the scene and the requirements of the application. The criterion to find the best balance could be provided by different sources, from color or hyperspectral imagers to preliminary knowledge of the scene or the considered application.

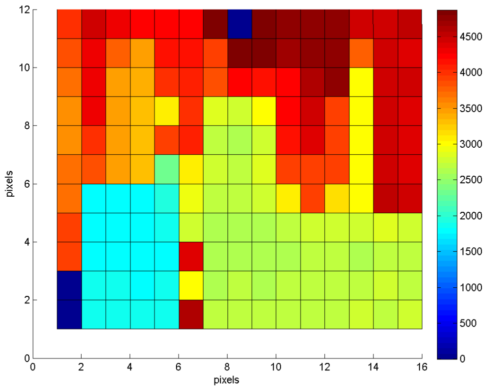

Figure 4. Spatial resolution has been four-folded relative to Figure 3 (165 pixels) using the same setup. Finer details, like the position of the bottles and the separation between the brown box and the white box, may already be observed.

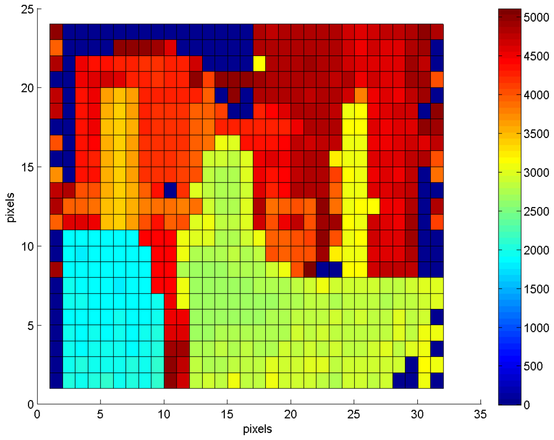

Figure 5. 0.7Kpixel image obtained using the same setup. Details like the bottle or the bottom-left box start to appear.

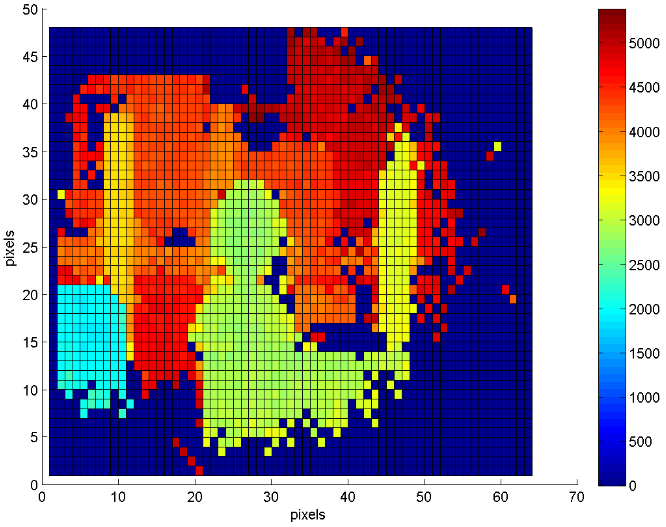

Figure 6. 3Kpixel image obtained using the same setup.

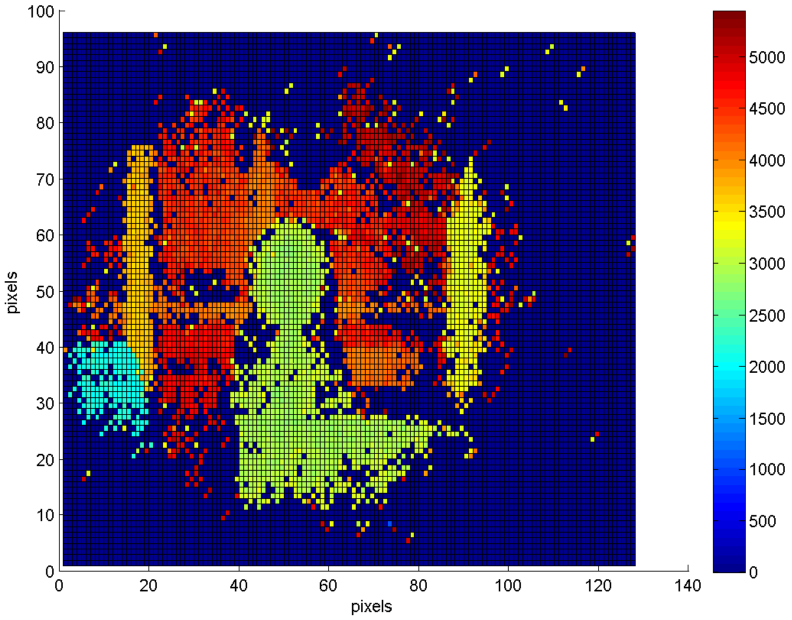

Figure 7. 12Kpixel image using the same setup, showing further details of the image. Blue regions correspond to regions of the image with not enough back-reflected energy.

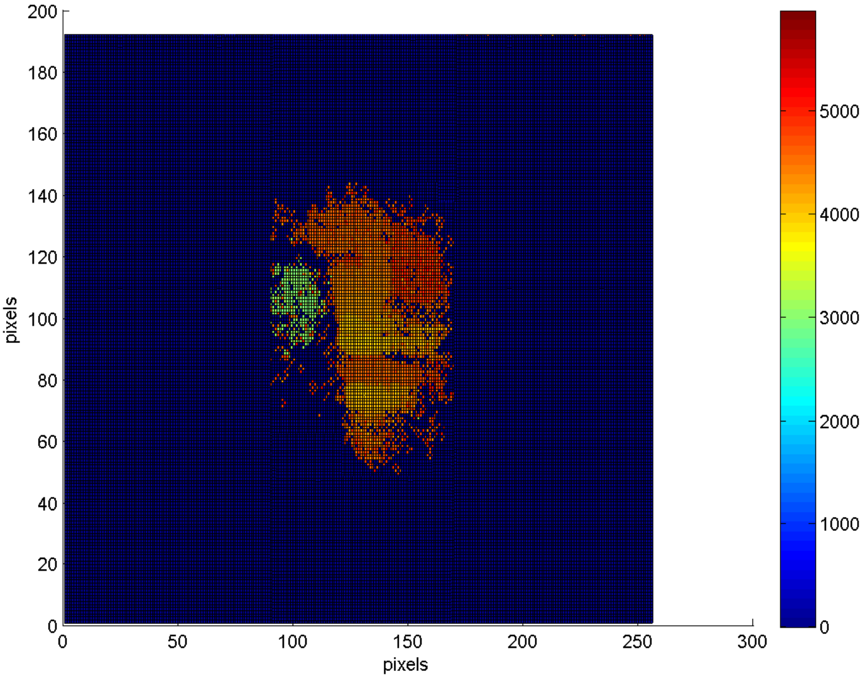

Figure 8. Maximum spatial resolution (49Kpixels) with laser beam concentrated around the center of the FOV. Blue regions correspond to undetected regions of the image.

The system is also reliable when a strong background light is in the scene. Figure 9 shows an outdoor scene designed to evaluate the performance when direct sun light is irradiating the surface. The results show that the system is not affected in such adverse conditions. The background light is well suppressed by using an optical band pass filter centred at 532±2nm. The resulting capture can be seen in figure 10.

Figure 9. Outdoor scene with strong sunlight conditions.

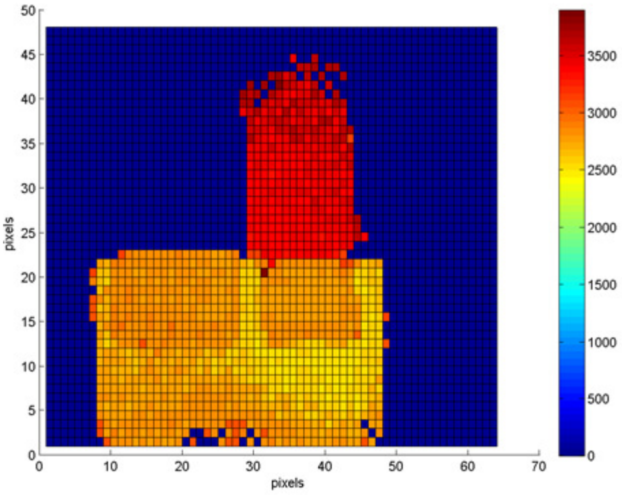

Figure 10. Image taken in outdoor environment with strong background sun light. This capture was taken at 12 of June of 2012 at 2:15 PM, coinciding with the maximum solar radiation days.

Table 2. Summary of the most relevant parameters for each of the previous images.

Figure	Resolution	Number of px	Measuring time	Frame rate	FOV
3	7x5 px	35 px	16 ms	62 Hz	30º
4	15x11 px	165 px	64 ms	15 Hz	30º
5	31x23 px	713 px	256 ms	4 Hz	30º
6	63x47 px	2961 px	1024 ms	1 Hz	30º
7	127x95 px	12065 px	4096 ms	0.24 Hz	20º
8	255x191 px	48705 px	16384 ms	0.06 Hz	14º
10	63x47 ps	2961 px	1024 ms	1 Hz	30º

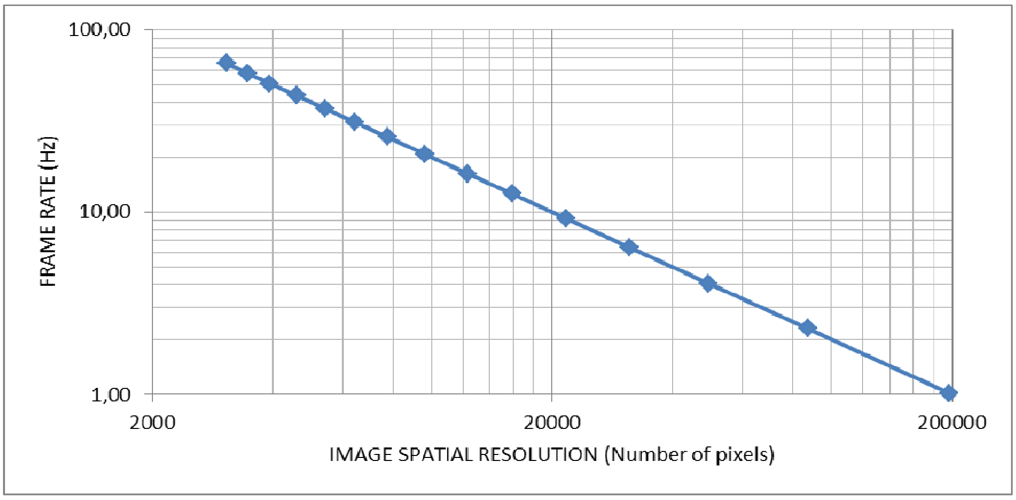

Figure 11. Relationship of frame rate and spatial resolution of the image in the present proof-of-concept prototype.

4. CONCLUSIONS

An imaging lidar system with balance between frame rate and spatial resolution controllable on the fly has been designed, built and demonstrated. A proof-of concept prototype with limited functionality has been constructed for testing the feasibility of the proposed concept.

The main capability of the system is to modify the image spatial resolution or frame rate according to external parameters obtained by different criteria on scanning strategy. We have presented results showing that the change in this balance can be performed on-the-fly, without any hardware modification and in real time. The margins for adjustment are extremely large, going from hundreds of Kpixels and less than one frames/s to a few pixels at 60 frames/s. A highly versatile and extended functionality lidar camera concept which combines a large number of image modes in a single device is obtained, offering a great potential to cover new advanced applications in the defense and security markets.

ACKNOWLEDGEMENTS

The authors wish to thank Spanish Ministry of Science and Innovation (MICINN) for project DPI2011-25525 which partially funded this research.

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