Evaluation of a 3D imaging vision system based on a single-pixel InGaAs detector and the Time-of-Flight principle for drones

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ABSTRACT

We present a case study for a time-of-flight (ToF) 3D imaging system using single-pixel imaging (SPI) approach based on compressive sensing (CS), accompanied by the Time-of-flight (ToF) principle applied to four reference points of the 2D image created and then mapped to the rest of the SPI generated virtual pixels. In this analysis we have developed a mathematical model of the system and evaluated three different scenarios considering different performance issues based on signal-to-noise ratio, different levels of background illumination, distance, spatial resolution, and material reflectivity presented by the objects in the scene. To be able to reduce the background photon shot noise and enable the correct functionality of the system also in harsh environments (in presence of micrometer size particles such as rain, snow, fog or smoke) we propose using near infra-red (NIR) active illumination with a peak wavelength of 1550 nm. The SPI principle is based here on an array of NIR emitting LEDs and the Thorlab FGA015 InGaAs single photodiode. For the system modelling and analysis, we considered the maximum background illumination intensity of up to 100 klux, different reflection coefficients of the target material to be detected, and measurement distances between 1 and 10 m. Using the ToF principle, we evaluated the direct ToF using both, pulsed laser NIR source as well as an array of NIR emitting LEDs combined with a single InGaAs photodiode on the one side, and an InGaAs single-photon avalanche diode (SPAD) on the other. Using the model developed, we estimated the spatial resolution (standard deviation from the distance measured) the proposed system might reach for each of the ToF methods analyzed and combining different system elements. Finally, we propose a SPI-ToF 3D imaging and ranging system for drone outdoors applications.

Keywords: InGaAs sensor, single-pixel imaging (SPI),time-of-flight (TOF),direct time-of-flight (dToF),indirect time-of-flight(iToF), Line sensor,2D/3D Image.

1. INTRODUCTION

Commercial CMOS vision systems offer a vast amount of signal processing and analog-to-digital conversion (ADC) on-a-chip. They are also very reliable, fairly cheap and compact. However, these systems exhibit several limitations if applied in ToF 3D imaging and ranging applications. For instance, based entirely on silicon, the systems based on this kind of solutions constantly have to deal with very high background photon shot noise, especially if used outdoors, due mainly to the silicon radiation sensitivity bandwidth ranging normally between 400 nm and 1100 nm wavelengths (embracing ultra-violet (UV), visible (VIS), and near infrared (NIR) parts of the spectra) at the most; exactly the main emission bandwidth of the Sun at ground level, and also the bandwidth where the maximum allowed light intensity of the active illumination source required for ToF principle based systems is mostly diminished due to the international IEC Eye Safety regulation IEC62471 for Class 3R lasers [1]. In addition, conventional RGB or RGB-depth sensors are limited under poor visibility conditions, as for example in rain, fog, smoke or snow impregnated scenarios that hinder the image acquisition or the estimation of the distance between the camera system and the different objects in the illuminated scene. For drone applications, depth information has been proven relevant in autonomous navigation applications [2]. Nevertheless, such sensing limitations prohibit the deployment of drones in scenarios with adverse conditions mentioned. Motivated by the above, we propose a vision system that can operate under extreme background illumination conditions. For this, we propose using a vision system working at longer wavelengths than those achievable by silicon based systems. The latter enables taking advantage of the bandwidth window yielding much higher atmospheric absorption and thus much lower background illumination, using active illumination sources with much higher irradiances allowed by the ESR, and the fact that using longer NIR wavelengths diminishes Rayleigh and other scattering mechanisms, and thus enables propagation of active illumination in rain, smoke, fog or snow. As there are no image sensors fabricated with materials such as InGaAs, sensitive to emitted radiation in the range around 1550 nm, that can allow the ToF sensor functionality normally pursued in CMOS based solutions, we propose using commercially available single InGaAs photodiodes accompanied by SPI principle of operation to generate 3D images at near video rates. For the latter, we present a mathematical model that considers different photon and electrical noise sources of the proposed system, a maximum 100 klux background light intensity, and consider three different sets of goal parameters: i) distance of objects in the illuminated scene varying between 1 m and 10 m; ii) different reflectivity indexes of the objects evaluated in the illuminated scene, and iii) spatial resolution, i.e. the standard deviation of the evaluated distances between the different objects in the illuminated scene and the vision system proposed, calculated considering the time that the emitted light pulse requires to reach the different objects in the scene, be reflected by them, and travel back to the detector system allocated aside the active illumination source. Thus, we propose a single-pixel imaging (SPI) [1] system working in combination with the principle of Indirect-Time-of-flight (iToF) [3, 4, 5]. We are confident that this vision system has the potential to be exploited in drone applications involving autonomous navigation.

For our proposed vision system, we use an InGaAs photodiode (PD), with quantum efficiency (QE) above 80% for 1550 nm wavelengths, and an array of NIR LEDs emitting in the NIR part of the spectra with a peak wavelength around 1460 nm. For the SPI-iToF vision system we additionally propose using a NIR diode laser (the system will follow the IEC Eye Safety regulation IEC62471 for Class 3R lasers [1]) for iToF.

For the evaluation of the proposed vision system, we defined a methodology for testing the devices and the implemented algorithms in the vision system at near video rate, and the generation of 2D and 3D images. The first analysis makes a comparative study considering the InGaAs Thorlab FGA015 diode. For the purposes of this work, we have focused on determining the minimum integration time of the diode to capture an image under different noise conditions and different object reflection coefficients at different distances. This parameter is decisive for calculating the video frame rate performance, measured in frames per second (fps). The second analysis is related to the required processing time of the single-pixel generated signals enabling the creation of 2D images. Due to the fact that the image generation system operates using the single-pixel principle, we use the OMP algorithm to recover and reconstruct 2D images. For the implementation of the OMP algorithm, an initial analysis is carried out to determine the minimum amount of patterns used for the generation of grayscale images with a compression factor of 2% for different resolutions (64×64, 64×16, 128×16, and 256×16 "virtual" pixels). We did an assessment of the orthogonal matching pursuit (OMP) algorithm running on two different hardware platforms, namely CPU and GPU, in order to determine the image processing time. The previously described analysis enables us to calculate the frame rate (fps) of two different resolutions of the generated images. A third analysis is related to the implementation of the ToF system for the generation of 3D images. This process will operate in parallel to the image capturing process. We consider the implementation of the continuous wave (CW) IToF [6] and IEC Eye Safety regulation IEC62471 standard applied to Class 3R lasers [1] in order to define the required performance specifications of the photodetector for the best performance at the level of distance measurement accuracy. The latter analysis enables defining the expected spatial resolution under different noise levels, and different reflection coefficients of the target materials.

2. MODELLING OF THE PROPOSED SPI-ITOF SYSTEM

Since the vision system proposed is SPI based [7], we provide a brief description of the main concepts involved in this sensing approach. Sequences of structured light (for example *Hadamard* patterns [7]) are projected on the objects in a scene, and the light reflected from them is focused onto a photodetector placed aside the active illumination source with no spatial information. The object is reconstructed from the electrical output signals generated by the photodetector to each applied illumination pattern using the OMP algorithm to recover the 2D image. As a first step, we select the most convenient photodetector for intensity measurements. In order to reduce the background light illumination, we chose an NIR-sensitive photodetector and placed a very narrow-band band-pass (1544 < λ < 1556 nm) filter in front of it, since the sun's spectral radiation content is small in this range. Regarding the properties of the objects embedded in the illuminated scene, we assume the usual *Lambert* reflection model shown in Fig. 1.

A key factor here is the assessment of the minimum integration time T_{int} required by the chosen photodiode under different working conditions, i.e. the time required to capture the photons emitted by the array of LEDs that get reflected by the objects in the scene, and finally reach the photodiode and provide an electrical signal above the background noise. For the determination of the integration time we use Eq. (1), which models the photon energy arriving at the single pixel [8]. Considering the use of a band-pass filter in front of the chosen photodiode, equation (1) depends on the spectral content 1544 nm < λ < 1556 nm, the detector quantum efficiency QE (λ) in this bandwidth, the length of the integration time T_{int} of the detector, and pixel´s effective photosensitive area A_{ph}, defined as $A_{W\times L}\cdot FF$, where $A_{W\times L}$ is the pixel (or photodetector) window and FF its fill-factor (FF). The distribution of detected energy E(N) will depend on the irradiance of the active light source (the array of chosen LEDs) and the ambient light conditions, as well as on the distance of the object to be detected and the optical parameters that define its reflective surface (see Fig. 1).

In equation (1), the parameter $\Phi_{e\lambda}$ is defined as the irradiation level of the active source, $E_{e\lambda\_sun}(\lambda)$ irradiation level of the sun illumination considered to be of 100 klux, the $f_{\#}$ number $f_{\#} = f_{foc} / d_{aperture}$ is the focal distance/opening distance, z is the measured distance, τ the lens transmittance, ρ the reflection index of the materials existent on the objects in the scene, and α_{FOV} the focal aperture angle [6] of the emitting LED array. Table 1 summarizes the values of the different quantities considered for simulation purposes.

$$E(N) = \int_{\lambda_1}^{\lambda_2} \frac{\rho \tau_{lends} QE(\lambda) T_{\text{int}} A_{ph} \lambda}{4hcf_{\#}^2} \left[\frac{\Phi_{e\lambda} T_{\text{int}} \delta(\lambda - \lambda_2)}{\pi z^2 \tan(\alpha_{FOV})^2} + E_{e\lambda\_sun} T_{\text{int}} \right] d\lambda \qquad (1)$$

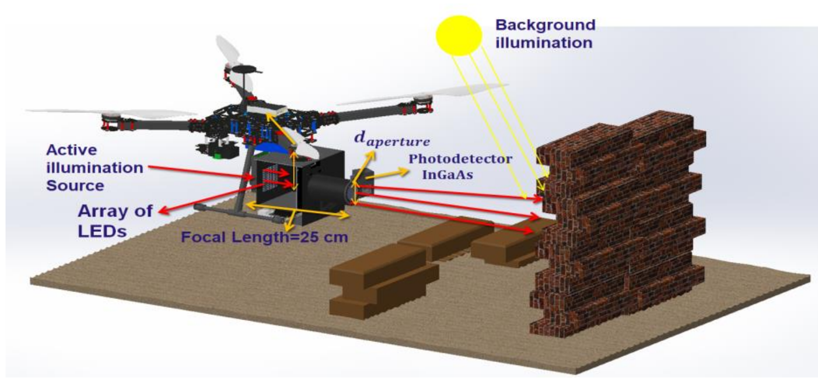


Figure 1. Scheme of measurement of energy level detected, the source of noise from the background lighting, distance, stages of the optical system are considered.

In order to calculate minimum integration time required to properly detect each of the emitted *Hadamard* patterns emitted, the analysis procedure is as follows:

1. Take the initial parameters of the optical system as listed in Table 1.
2. Calculate the number of overall number of photons $E(N)$ impinging the photodetector photoactive area using Eq. (1) and considering background illumination in the wavelength range defined by the narrwo band-pass filter added to the active illumination used.
3. Calculate the overall electrical noise floor in terms of the variance σ_{Noise_floor} calculated as the square-root of the sum of squares of the background illumination photon shot noise variance σ_{ph}, the variance representing the statistical variation in the amount of thermally generated electrons within the InGaAs photodetector or the dark shot noise σ_{dark}, and the read-noise σ_{read} generated by the readout electronics, as expressed by Eq. (2).

$$\sigma_{Noise\_floor} = \sqrt{(\sigma_{Ph})^2 + (\sigma_{dark})^2 + (\sigma_{read})^2} \tag{2}$$

4. Define the maximum distance reached $Z_{measurement}$ for the minimum level condition where the $E(N)$ is affected for the noise $\left|\left(E(N) - \sigma_{NOISE\_FLOOR}\right)\right| < \delta_{th}$
5. If $Z_{measurement} < Z_{\max}$ for a reflection index ρ the integrate time T_{int} is increased the skip to step 3. If $z_{measurement} \approx z_{\max}$ then $T_{\text{int}_i} = T_{\text{int}_{i-1}}$ condition of the stop.

After defining the algorithm for the calculation of the integration time, we evaluate the InGaAs diode Thorlabs FGA015, using the parameters listed in Table 1. This device will be used as a photodiode for the single-pixel system. The evaluation shows how the number of photons captured by the InGaAs Thorlabs FGA015 will be affected by the noise floor, a function of the distance measured and reflection index ρ, as shown in Fig. 2.

Table 1. Parameters used for the evaluation of the Thorlabs FGA015I nGaAs photodiode.

Parameter	Thorlabs FGA015 InGaAs photodiode
Photoactive area [mm^2]	0.0707
Power Source radiation (NIR LEDs) [W]	6.4
Maximum Distance Range [m]	10 m
Reflection index of the objects in the scene	0.2 - 0.5 - 0.8
Background illumination [klux]	100
Optical band-pass filter wavelength range [nm]	1544 – 1556
Field of view [°]	20
f-number	0.95
Fill Factor [%]	35

Fig. 2 shows the amount of photons reaching the *Thorlabs* FGA015 InGaAs photodetector for measurements performed at different distances, considering 20 %, 50 %, and 80 % reflection coefficients of the objects in the scene, respectively, and emitting optical power of 25.6 W in the NIR part of the spectra ($\lambda_{average}$ = 1550 nm). The graphs show the exact labelled distance where the electrical signal generated by the photodiode due to the detected radiation equals the noise floor of the same system. As it can be observed, lower reflectivity of the illuminated objects causes the noise floor to be reached within a shorter distance, 2.8 m for 20 % reflectivity, 5 m for 50 % reflectivity, and 8 m for almost completely reflective objects.

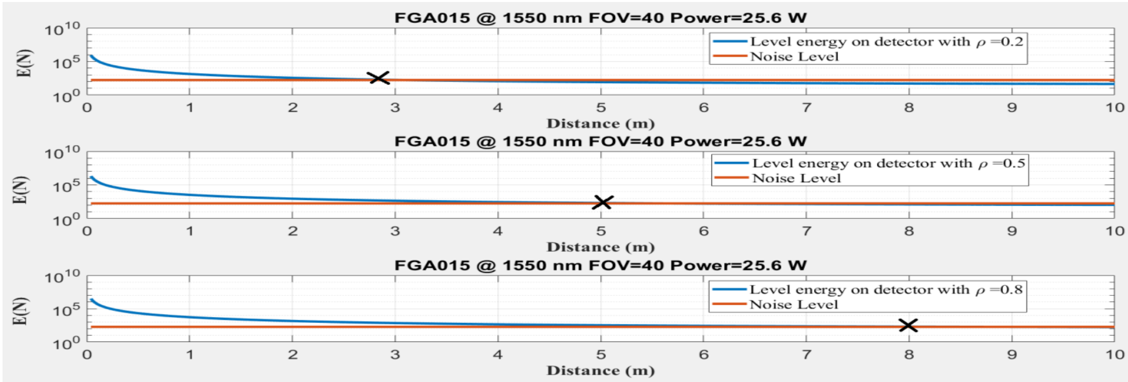


Figure 2. Behavior of the *Thorlabs* FGA015 InGaAs photodiode in function of numbers photons detected, and the noise floor, for the integration time proposed, considering different reflection indices and the distances measured.

3. IMAGE PROCESSING TIME ANALYSIS

We propose using parallel kernel approach to implement the Batch Orthogonal Matching Pursuit (OMP) algorithm [9], divided in three operations: the first is dot product with a computational complexity of O(MN); the second is the sort algorithm with a computational complexity of O(N); and the last is the Least Square algorithm with the highest implementation complexity. With the goal to reduce the execution time as much as possible, we propose using a GPU platform with four parallel kernels that must be implemented for each of the above operations. The latter will allow for a SPI processing time of below 41.6 ms, i.e. a frame rate of above 24 fps, as it can be extracted from Table 2. Additional analysis regarding the implementation of the OMP algorithm on GPU and CPU architectures, respectively, showed that using a 4-kernel GPU allows reducing the processing time by a factor of 3 and even 4 in some cases if compared to the same implementation running on a CPU platform.

Table 2. Comparative study of different SPI image resolutions, regarding the amount of *Hadamard* illumination patterns used for their generation, the time required to process the electrical responses of the photodiode to each of the illumination patterns used, and the amount of frames per second generated in this way to produce a video stream. The patterns can be projected with a maximum frequency of 15 kHz.

Image Size	Number of illumination patterns required	Pattern projection time [ms]	Time to process the images using the Batch-OMP algorithm on a GPU [ms]	Frame/s
64×64	128	8.53	30.08	24
64×16	32	2.13	7.85	79
128×16	64	4.27	15.5	44
256×16	128	8.53	29.6	25

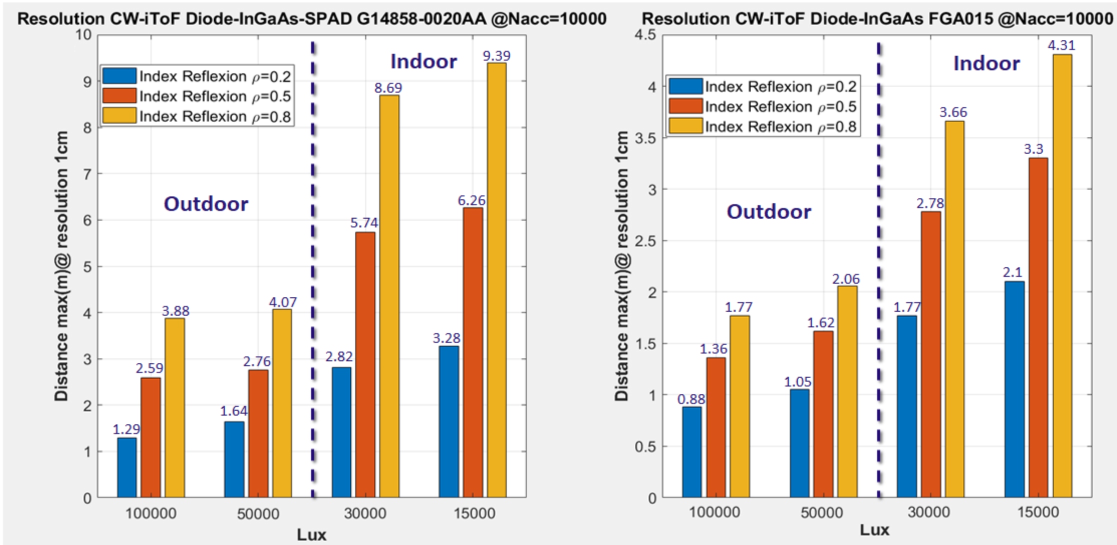
4. EVALUATION OF INDIRECT TIME-OF-FLIGHT(ITOF) MEASUREMENT METHODS

For the reconstruction of a 3D image, we use the indirect distance estimation method based on continuous-wave indirect time-of-flight (CW-iToF [2-3]) that estimates the phase shift between the emitted sinusoidal illumination pattern and the reflected and detected one. The approach proposed is to estimate the depth of different points in the virtual image at four separate control points, and then use this estimated distances to generate a complete 3D image by applying shape comparison method with measured distance mapping. The sinusoidal phase shift contains the information regarding the distance between the photodetector and the different objects in the scene. To evaluate the resolution capacity of the CW-iToF method, we established a maximum measurement distance of d_{max} = 10 m and we defined different the conditions of the outdoors background illumination intensity ranging between 50 and 100 klux on the one hand, and indoor conditions with background illumination between 15 and 30 klux. We considered the reflectivity coefficient of the object in the illuminated scene to be 0.2, 0.5, and 0.8, respectively.

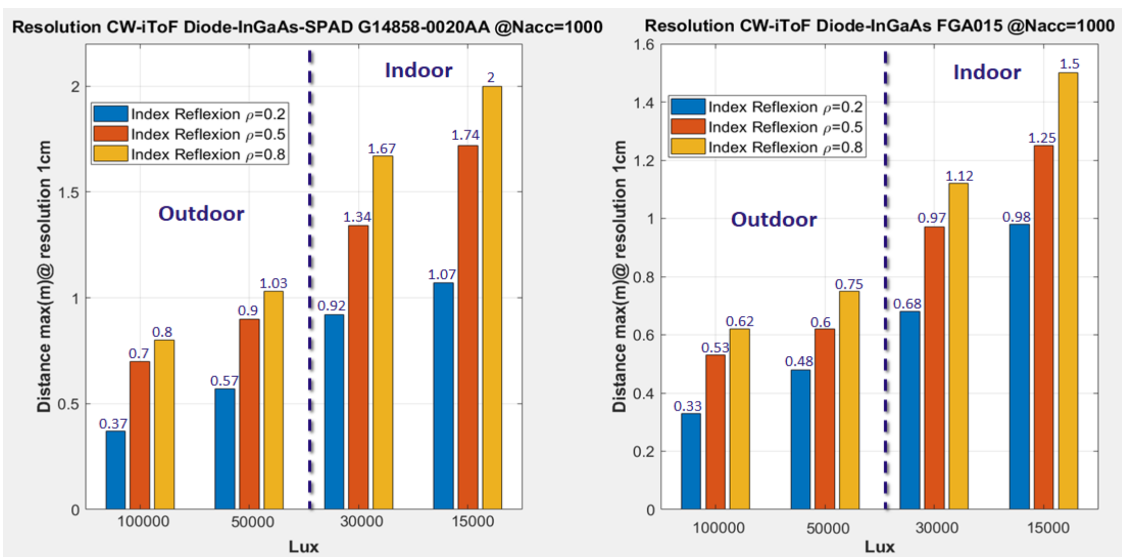
We evaluated the system using 1,000-period continuous-wave NIR LED illumination at first, and then expanding the number of accumulations (and improving the signal averaging feature) to 10,000 signal periods. The minimum amount of accumulations required is defined by the target spatial resolution of the system, the background illumination photon shot-noise, the distance of the target objects to the photodetector, and the reflection index of the materials covering these objects. We are aiming at the target spatial resolution of below 1 cm. To calculate the achieved spatial resolution, i.e. the standard deviation $\sigma_{CW\text{-}iToF}$ of the measured distance using the iToF method, we use Eq. (3) [6], where d_{max} corresponds to the maximum measurement distance, A_R corresponds to the number of photons detected in the detector window, B corresponds to background noise, $F(x) = \sqrt{x}\sin c(x)$, where x=T_{TAP}/ T_p is a scaling factor that depends on the pulsed time T_p and sample time T_{TAP}.

$$\sigma_{CW-iToF} = \frac{d_{\max}}{A_R}\sqrt{\frac{A_R + 2B}{N_{acc}}}\frac{1}{2\pi F(x)} \tag{3}$$

The results obtained from the evaluation of the indirect distance estimation method are shown in Fig. 3 for the maximum measured distance (in meters) with a standard deviation (spatial resolution) of below 1 cm, estimated under different operating conditions. For the underwent evaluation, we considered the *Thorlabs* FGA015 InGaAs photodiode [9] and an InGaAs SPAD diode, *Hamamatsu* G14858-0020AA [10], respectively, to perform a comparative evaluation of the maximum distance measured under the defined outdoor and indoor conditions, respectively, considering different reflection indexes, and using 10,000 (see Fig. 3(a)) and 1,000 (see Fig. 3(b)) period accumulations in each case. The same evaluation was performed applying pulsed illumination, using 1,000 and 10,000 NIR (with a wavelength of 1550 nm) laser pulses of a 65 ns length with the *Thorlabs* L1550P5DFB [12] NIR pulsed laser. The results were very similar to those reported in Fig. 3.



(a)



(b)

Figure 3. Maximum distance resolution (standard deviation in distance measurements) achieved using the CW-iToF method considering different reflection indices of the objects and the InGaAs SPAD *Hamamatsu* G14858-0020AA [10] MPPC left, and the *Thorlabs* FGA015 InGaAs photodiode [9] right for: (a) 10,000 illumination CW period accumulations and different background illumination levels; and (b) 1,000 illumination CW period accumulations and the same different background illumination levels.

Under indoor illumination conditions, the InGaAs SPAD diode [10] enables measuring distances of between 3 and 9 m if the spatial resolution of below 1 cm is targeted, whilst the InGaAs PIN photodiode [9] was able to measure distances ranging between 2 and 4 m under the same circumstances. Under outdoor background illumination conditions, the measured distance range achieving spatial resolutions of below 1 cm was of between 1 and 4 m if using the InGaAs SPAD diode [10] and considering different reflection coefficients of the objects in the scene, and of between 0.8 and 1.7 m in case the InGaAs PIN photodiode [9] is used.

5. HYBRID SPI-ITOF 3D IMAGING SYSTEM PROPOSED

Based on the analysis described in the previous sections, we propose a hybrid SPI-iToF system shown in Fig. 4, aimed at generation of 2D / 3D images in a video stream. The system consists of two stages. The first stage is dedicated to generating 2D single-pixel images using the *Thorlabs* FGA015 InGaAs PIN photodiode [9] and an array of NIR LEDs used for active illumination. Additionally, the system includes a LED control driver used to project illumination patterns on the objects in the illuminated scene, and an analog-to-digital (ADC) converter of the photodiode output signals. The second stage operates in parallel to the first one, and is responsible of defining four control points immersed in the virtually obtained SPI 2D image, measuring the distance of the different objects in the illuminated scene to these points using the indirect time-of-flight approach. Here, for distance measurement using iToF, a *Thorlabs* L1550P5DFB [12] pulsed laser, emitting at 1550 nm wavelengths, is to be used together with four *Thorlabs* FGA015 InGaAs [9] separate photodiodes.

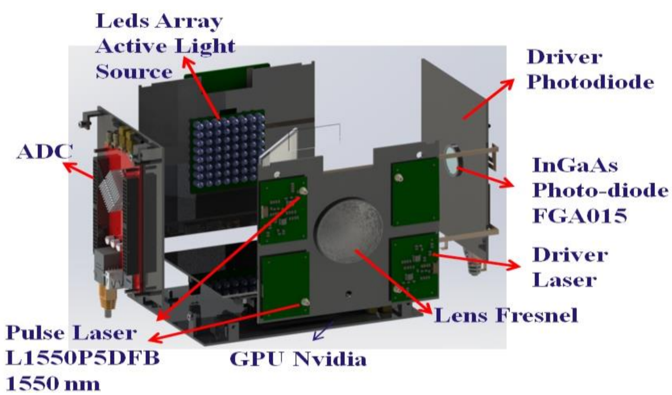


Figure 4. The proposed hybrid system consisting of two stages: the first stage is dedicated to generating 2D single-pixel images using the Thorlabs FGA015 InGaAs PIN photodiode [9] and an array of NIR LEDs used for active illumination; the second stage operates in parallel to the first one, and is responsible of defining four control points immersed in the virtually obtained SPI 2D image, measuring the distance of the different objects in the illuminated scene to these points using the indirect time-of-flight approach.

We envisage that the hybrid system proposed in this work has the potential to be applied for drone navigation. Due to the advances in visual sensing, stereo cameras and RGB-D cameras have become a standard sensing mechanism for drone navigation. These particular type of sensors offer two advantages: 1) chromatic information of the scene enables the construction of 3D maps of the environment where the drone navigate; 2) the depth information recovered by the stereo or infrared pattern in RGB-D cameras can be exploited to recover a map with scale, hence enabling 6-D pose estimation with metric [12]. On the other hand, if depth information is available then it can be combined with monochromatic visual information for map building and camera localization, this can be exploited for autonomous drone navigation in GPS-denied environments as shown in [13]. In this sense, our proposed vision system could be coupled with conventional monochromatic cameras given the fact that our system has the capacity to recover depth information. Furthermore, a greater advantage is that the 3D image reconstruction can be carried out in adverse environments such as foggy or rainy environments, scenarios where conventional chromatic vision sensors would face visibility problems. In contrast to RGB-D cameras, functioning under the infrared pattern projection method, our vision system aims at working in outdoor scenarios where the 3D reconstructed image can be used for sense-and-avoid [14].

CONCLUSION

In this paper, we have presented a theoretical analysis of the design of an SPI-iToF hybrid 2D/3D imaging system capable of generating a video stream enabling decision making in continuous time. To analyze the system, we have proposed a methodology divided in three stages. The first stage focused on the selection of components based on background noise and distance resolution conditions. In this assessment, we determined that it is possible to use the *Thorlab* FGA015 PIN photodiode to capture SPI 2D images of objects placed at distances of up to 8 m in outdoor illumination conditions of up to 100 klux, for reflection coefficients of 0.8, and up to 3 m for reflection coefficient of 0.2. We are confident that the vision system has the potential to be exploited in drone applications in both indoor and outdoor environments. In the second stage, we have developed an algorithm for SPI 2D image generation. This algorithm exploits a parallel architecture aiming at an image reconstruction time of between 20 and 30 ms, thus enabling a frame-rate of the emitted video stream of above 24 fps. In the last stage, we have evaluated relevant iToF methods to estimate distances with spatial resolutions (standard deviation of the measured distance) of below 1 cm of objects of up to 4 m for outdoor conditions, and up to more than 9 m in indoors.

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