Microelectronic Single-Photon 3D Imaging Arrays
for low-light high-speed Safety and Security Applications

Final Report - PUBLISHABLE

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1. FINAL PUBLISHABLE SUMMARY REPORT

1.1 EXECUTIVE SUMMARY

The MiSPIA objective was to develop imagers for high frame-rates and single-photon sensitivity cameras for 2D “imaging” and 3D “ranging” of rapidly changing scenes, in light starved environments. The MiSPIA focus was on two clearly identified photonics applications, namely:

- high frame-rate short-range (<50m) 3D ranging for automotive pre-crash safety systems;
- wide-spectrum long-range (200m-1km) 3D ranging for security surveillance.

The MiSPIA products are two complete camera systems compliant with the specifications set at the beginning of the project and based on new microelectronic sensor chips, capable of single-photon sensitivity in the visible and near infrared wavelength range, and programmable electronics and graphical user interface for user-friendly acquisition of movies of 2D and 3D scenes. The MiSPIA outcomes impact not just advanced video systems in safety and security applications, but also adjacent markets, like molecular imaging, fluorescence lifetime imaging, biological analysis, confocal microscopy, adaptive optics, diffusive optical tomography, and ghost imaging, just to mention a few.

The MiSPIA technology is based on solid-state Single-Photon Avalanche Diodes (SPAD), able not only to count single photons (“photon counting”), but also to accurately measure their arrival time (“photon timing”). The two different MiSPIA imagers consist of arrays of smart-pixels able to provide full images of the scene. Each smart-pixel contains a SPAD detector and an in-pixel intelligence for processing, at pixel-level, either the 2D intensity-data (by counting the number of detected photons) or the 3D depth-ranging information (by measuring the Time-Of-Flight of each detected photon) of the scene under investigation. The MiSPIA fabrication processing are a cost-effective CMOS technology, for monolithic planar fabrication of front-illuminated (FrontSPAD) imagers, and a more advanced wafer-bonding processing of two wafers (one with detectors and one with read-out electronics), for back-illuminated (BackSPAD) innovative camera sensors.

The MiSPIA consortium consists of 7 partners, among leading European research groups in the fields of SPAD detector arrays and single-photon instrumentation (partner POLIMI), CMOS sensors fabrication and advanced SOI processes (FRAUNHOFER), design and fabrication of microlens arrays (HWU), single-photon detection modules and cameras (MPD), safety applications in the automotive field (CFR), security surveillance (EMZA), and management of European projects (CFc):

- POLIMI - Politecnico di Milano (Italy), Coordinator, Prof. Franco Zappa (franco.zappa@polimi.it);
- FRAUNHOFER - Fraunhofer-Gesellschaft zur Foerderung der Angewandten Forschung E.V (Germany), Mr. Werner Brockherde (werner.brockherde@ims.fraunhofer.de);
- HWU - Heriot-Watt University (United Kingdom), Prof. M.R. Taghizadeh (m.taghizadeh@hw.ac.uk);
- MPD - Micro Photon Devices S.R.L. (Italy), Dr. Simone Tisa (stisa@micro-photon-devices.com);
- CFR - Centro Ricerche FIAT S.C.P.A. (Italy), Ing. Nereo Pallaro (nereo.pallaro@crf.it);
- EMZA - EMZA Visual Sense LTD (Israel), Dr. Zeev Smilansky (zeev@emza-vs.com);
- CFC - CF Consulting S.R.L., Mrs Carla Finocchiaro (carla.finocchiaro@cf-c.it).

The MiSPIA overall cost is € 3.400.166, with € 2.632.854 funding from the European Union, within the Collaborative project in “Information and Communication Technology”, ICT-2009.3.7, in “Photonics”, of the FP7 Framework. MiSPIA leverages a massive infrastructure worth over 150 M€ existing at the MiSPIA partners’ premises that allowed them to request no equipment funding. The MiSPIA project lasted three years and a half, from June 1st, 2010, to December 31st, 2013.

1.2 PROJECT PUBLIC WEBSITE

The MiSPIA webpage is www.mispia.eu, with information on results and publications.
1.3 PROJECT CONTEXT AND OBJECTIVES

Objective 1 - SPAD smart-pixels with “in-pixel intelligence”

Objective 1 aimed at developing the basic building block of the imaging arrays, i.e. the smart-pixels suitable for 2D imaging and 3D depth ranging, based on Single-Photon Avalanche Diodes (SPADs) with beyond state-of-the-art performances. Here are the proposed smart-pixels: 2D “photon-counting” smart-pixel, able to count individual photons in well-defined time-slots, for providing intensity information of the scene under observation; 3D “direct TOF” smart-pixel, able to perform accurate “photon timing” of the incoming photon, by means of an in-pixel Time-to-Digital Converter (TDC), measuring the photon’s time-of-flight (TOF); 3D “pulsed-light indirect TOF” smart-pixel, able to extract distance information from photons counted within time-slots synchronous with active illumination pulses; 3D “continuous-wave modulated indirect TOF” smart-pixel, able to measure phase delays between sinusoidal illumination and optical “echos”.

The design was led by partner POLIMI, the fabrication of array sensor chips by FRAUNHOFER, the development of the preliminary illuminator for short–range tests by MPD and for microlenses by HWU. Objective 1 was fully completed in the first year, resulting in the new state-of-the-art in CMOS SPADs so far reported, in terms of single-photon sensitivity over the 300nm-900nm range, very large active area (up to 500 µm diameter), very low noise (0.08 noise counts/s/µm²), high dynamic range (130 dB at 100 fps), un-cooled operation and cost-effectiveness.

Objective 2 - Front-side illuminated array chips (FrontSPAD)

Objective 2 aimed at fabricating the sensor chips to be integrated in the final 3D camera system, based on the smart-pixels selected from the best performing device (from Objective 1). For the two 3D ranging applications, namely short-range automotive Safety and long-range Security surveillance, POLIMI designed two different 3D imagers to be manufactured in the FRAUNHOFER planar front-side illuminated (FrontSPAD) fully standard 0.35 µm CMOS technology. A first imager aims at short distance ranging, up to 50 m, for the automotive safety application. It provides 64x32 pixels for 2D imaging and 3D ranging through indirect TOF technique, based on active illumination of the scene by means of pulsed-light (PL-iTOF) or continuous-wave (CW-iTOF) modulation. The imager provides 2048 pixel images and movies up to 100,000 fps in 2D mode and up to 33,000 fps in 3D mode, with tens of cm distance resolution. A second imager aims at medium and long distance ranging, with depth ranges of 50 m up to some km distance, for security surveillance applications. It provides 32x32 pixels for 2D imaging and 3D ranging through direct TOF technique, based on active illumination of the scene by means of picosecond pulsed laser. The imager provides 1024 SPADs and 1024 Time-to-Digital Converters (TDCs) for providing images and movies up to 100,000 fps in 2D mode and still 100,000 fps in 3D mode at 5 cm single-shot precision, or at 200 fps with 0.1 mm distance resolution. Also other array chips, both linear (32x1, 32x32, and 60x1 pixels) and matrix (32x16 and 16x4 pixels), were developed for other applications in microscopy, biological imaging, spectrometry and diffusive optical tomography.

The complete functionality of all arrays and of the different in-pixel 3D processing electronics (iTOF and dTOF) was characterized and tested by POLIMI and MPD. Electrical and optical tests fully validated their microelectronic design and detection performance. The new imagers represent the best-in-class imagers among CMOS SPAD arrays, for both excellent sensitivity (55% photon detection efficiency at 400 nm, higher than 30% between 300 nm and 650 nm and still 5% at 850 nm) and noise (<80cps at room temperature and 5V above breakdown) performance, very good photon timing (300 ps photon TOF resolution), and readout speed (up to 100,000 frames/s).

Objective 3 - 3D ranging modules based on FrontSPAD arrays

Objective 3 aimed at the design and assembly of two different final 3D ranging modules and different illuminators for short (up to 40 m), medium (up to 150 m) and long (up to 4 km) distance ranges, for the applications of partners CRF and EMZA. The two cameras developed by MPD employ the FrontSPAD
chips developed for Objective 2, namely the **short-range 2D/3D camera with the 64x32 iTOF imager** and a **long-range 2D/3D camera with the 32x32 dTOF chip**. Each ranging system is composed by the 2D/3D camera (containing the microelectronic imaging chip, an FPGA board and a power-supply board) and the corresponding illuminator. Each camera is connected via an USB 2.0 link to a remote computer, for easily setting acquisition parameters, for downloading 2D and 3D videos, and for further off-chip user-specific processing and actuation. The FPGA board controls the chip and perform some pre-processing of the 3D depth-information, before uploading it to the external electronics. The power-supply board enables the module to be biased just through the USB link, with no need of other power supply.

The housing of the two cameras is very compact, 6 cm x 6 cm x 10 cm and provide a standard C-mount plug to easily connect commercially available photo objectives, to ease the customization of the 2D/3D detection to different scenes and field-of-views. The graphic user interface developed by MPD through Matlab tools allow an easy setting of the overall functions of the system and also to perform post-processing on the acquired images and movies.

Two **modular short-distance illuminators** were designed by POLIMI, conceived and developed to be reconfigurable, in order to allow easy optimization of active illumination of the iTOF 2D/3D vision system, also in environments other than the automotive one. One is based on LEDs and the other one on solid-state commercially available lasers. The latter provides a large 40°x20° field-of-view and is low-power and eye-safe, since low power illumination is enough, thanks to the single-photon sensitivity of the MiSPIA SPAD imagers. The illuminators remarkably compare with other higher-power illumination systems, developed so far by other 3D vision systems developers, with reach shorter distance range.

### Objective 4 - Back-side illuminated array chips (BackSPAD)

Objective 4 aimed at fabricating an even more advanced sensor chips compared to the FrontSPAD, based on a more complex, non-planar CMOS fabrication technology, based on back-side illumination of a silicon-on-insulator (SOI) wafer containing only custom SPADs, flipped and wafer-bonded on a standard CMOS wafer containing the acquisition and read-out electronics (see Objective 5). Two major improvements were planned: **higher pixel density**, since BackSPAD detectors are placed on top of the corresponding smart-pixel electronics, instead of being placed side-by-side (as in planar FrontSPAD structure); **enhanced spectral sensitivity** in the near-infrared, up to 1μm-wavelength, thanks to thicker active volume within the SOI detector wafer and to the back-side illumination of the active area.

The first SOI BackSPAD chips fabricated by FRAUNHOFER in the second year showed good performance, though with higher noise (dark-count rate) due to the SOI wafer compared to the bulk CMOS wafer on the FrontSPAD approach (Objective 2). A final POLIMI design of complete BackSPAD SPADs and arrays was completed in the third year and processed.

### Objective 5 - Assembly and test of the BackSPAD imager

Objective 5 aimed at fabricating the wafer containing only the CMOS imager electronics (instead SPADs lie on an SOI wafer, see Objective 4), to wafer bond the two wafers together, to dice the chips and to provide standalone BackSPAD sensor chips. The architecture and the full design of the imager electronics in the standard CMOS technology was completed by POLIMI in the second year of the MiSPIA project. The final BackSPAD imager was meant to be tested and compare to the FrontSPAD imagers, but no integration into a final camera was planned in the proposal. The electrical characterization of the electronics proved the proper operation of in-pixel electronics and global addressing and read-out electronics, proving the correctness of the design.

### Objective 6 - 3D camera integration in short-range Safety applications

Objective 6 aimed at the system integration of a complete 2D imaging and 3D ranging system into a real automotive vehicle, for the automotive safety implementation in short-distance applications in the range of some tens of meters, and in performing on-field tests in automotive scenarios. The main activity
was to develop all required optics, mechanics and tools and to equip two vehicles with the 2/3D camera based on the 64x32 iTOF SPAD imager and CW/PL-modulated laser illuminator (Objective 3).

A first vehicle, a FIAT Multipla, was assembled by partner POLIMI, for preliminary tests and customization of the firmware of the 3D camera (FPGA code and Matlab code for frames acquisition) and the pc-software for graphical user interface adjustments. A second complete vehicle, a ALFA ROMEO Giulietta, was equipped by partner CRF for detailed tests. All final tests were performed in labs, with different objects and static and dynamic scenes, in order to assess the performance of the camera system in both 2D imaging and 3D ranging modes. Then detailed tests were performed outdoor both in private driving tracks and in normal streets and traffic situations, to validate the ensemble of illuminator and 2D/3D camera.

Overall the tests validated the operation and confirmed the robustness of the system. Also the aliasing problem, typical of iTOF phase-resolved 3D ranging systems, was counteracted and finally resolved, thanks to the adoption of a double modulation frequency pattern, able to cancel aliasing, to increase the full-scale distance range and to improve depth-measurements precision.

Some issues highlighted under thick fog and rainy conditions was due to low illuminator light, which got drastically attenuated, and faint collected signal, which was not enough to provide high-quality 3D maps. For such extreme conditions, a more powerful illumination can be adopted (it is sufficient to double the present one), with an optimization of the illuminator installation in the vehicle (with proper optical window in the windscreen, with no thermal barrier or in the car's beamlights), and a reduction of the field-of-view (instead of the very broad 40°x20° employed in the reported tests).

**Objective 7 – 3D camera integration in long-range Security applications**

Objective 7 aimed at the system integration of the second 2D/3D system into representative scenarios for security applications, like monitoring or surveillance, and in performing on-field tests in medium-distance and long-range environments. The main activity was to couple the 2/3D camera based on the 32x32 dTOF SPAD imager with two optical set-ups, based on proper pulsed lasers, with pulse width shorter than 100 ps and collimated optics, to shine the target under acquisition.

One first medium-distance optical set-up was developed by partner POLIMI, employing a four wave mixing laser and a photographic 200x objective for acquisition of 3D movies up to tens of meters; the resolution of the camera was augmented via a fast and simple scanning system, in order to test the overall adaptability of the system to more complex scenes and detailed targets. A second long-distance optical set-up was designed by partner HWU, exploiting a confocal illumination/detection optics, with multi-spot illumination through a Diffusive Optical Element (DOE). Such illuminator is capable of shining 32x32 spots onto the target and to imagine them back onto the 32x32 pixels of the camera, thus minimizing illumination power and optimizing light collection of far-away objects.

**Dissemination and Exploitation activities**

MiSPiA dissemination activities (through scientific papers, technical conferences, commercial workshop, common laymen advertisement via newsletters, leaflets and webpage) triggered the interest of different potential users working on completely different research developments and commercial applications. In fact, cost-effectiveness, low-power requirements, state-of-the-art detection performance, and easy configurability of MiSPiA’s chips and cameras dictate the success of MiSPiA outcomes into all those equipment requiring ultra-high photosensitivity (down to the single-photon level), very short-integration time (as short as few microseconds), high-performance photon-timing (with sub-nanosecond time-gating and ps level precision) for acquiring very fast and fast optical events.

Eventually MiSPiA exploitation activities involved wide communities and markets, in Safety (e.g. environmental surveillance, food and agriculture quality and safety assessment, etc.) and Security (biometrics, surveillance systems, etc.) applications, but also in microscopy, biology, adaptive-optics, gaming, and 2D night vision and 3D ranging/lidar in light starving conditions.
Overview of MiSPiA results

In the MiSPiA project many successful outcomes were proved, important not only to successfully crown MiSPiA objectives, but also to definitely exploit them toward novel fields.

1- a set of **new state-of-the-art CMOS SPAD detectors and arrays** (Objective 1), with Dark-Counting Rate DCR<80cps at 5V excess bias for 30µm SPADs at room-temperature; Photon Detection Efficiency PDE of 55% at 400nm, >30% in the 300-600nm range, 10% at 750nm and still 5% at 850nm; Time-of-Flight (TOF) precision better than 40psFWHM; SPAD diameters up to 500µm (never reported so far). MiSPiA SPADs are best-in-class not only among CMOS SPADs, but also impressively compare with leading-edge custom-process (both planar and reach-through) SPADs.

2 – a set of **3D ranging chips for “direct TOF” and photon-timing** (Objective 2) with best-detection performance so far reported, based on smart-pixels with 30µm SPADs and in-pixel time-to-digital converters (TDCs) for TOF measurement of individual single photons: both linear arrays and 1048 pixels imagers, acquiring 2D images and 3D movies at 100,000fps with 5cm single-shot depth-precision while 0.9mm at 200fps, with 6bit photon-counting dynamics and <100cps/pixel noise, 10bit photon-timing with 212psrms resolution and 320 ns full-scale range. These chips simultaneously provide single-photon counting 2D images and 3D depth-resolved maps, with ps-width pulsed lasers, running at tens of MHz. Apart from classical 3D ranging and as monolithic detectors for lidar, these MiSPiA dTOF chips are the enabling technology for forth-coming “look-around the corner” and “first-photon imaging” challenging scenarios. Eventually, right now these MiSPiA dTOF chips are being exploited in time-correlated single-photon timing (TCSPC) acquisitions of very fast (tens of ps) time-resolved optical waveforms, fluoroscences, and spectra in a broad range of biological essays, microscopy, optical tomography, spectrometry.

3 – a set of **3D ranging chips for “indirect TOF” and photon-counting** (Objective 2) with among the best cutting-edge performance among SPAD imagers, based on smart-pixels with 30µm SPADs and digital counters for phase-resolved detection of either pulsed-light (PL) or continuous-wave (CW) actively illuminate scenes: linear arrays or matrixes, 2048 pixels acquiring 2D images at 100,000fps and 3D maps movies at 33,000fps, with 9bit photon-counting dynamics and <100cps/pixel. These chips simultaneously provide 2D imaging, through single-photon counting of no-actively illuminated objects, and 3D ranging, via cost-effective low-power LED or solid-state laser active illumination, running with either pulses of hundreds of ps or sinusoidal modulated light at few MHz. Apart from 3D ranging, these MiSPiA iTOF chips are being used in time-gated acquisitions of fast (sub-ns range) optical waveforms of fluorescence and diffusive specimen in different applications of fluorescence life-time imaging (FLIM and FRET), optical tomography (DOT), fluorescence correlation spectroscopy (FCS), and proteomics.

4 – two **compact and modular low-power fully-programmable active illuminators** (Object 3), to be coupled with 3D iTOF cameras for short-ranges up to 50m, based on commercially-available LEDs or solid-state lasers, able to switch between two operating mode, namely pulsed-light (PL) mode, with flashes lasting few hundreds of ns, or continuous-wave (CW) modulation, at MHz rates. The developed illuminators are adjustable (in both pulse-width and modulation frequency) to different depth ranges, from few meters (e.g. for gaming of smart-TV applications) to some tens of meters (e.g. for automotive or robotic applications), in order to exploit at best the performances out of the camera for very different scenes (e.g. in moving conditions, through semi-opaque shields of camouflages), of objects (e.g. their reflectivity, material composition, colour), of background (e.g. dusk/sun light, visible/near-infrared spectra, constant/burst stray light flashes), desired (cm range) resolution and signal-to-noise ratio, to be traded-off with frame-rate.

5 – one **reconfigurable user-friendly compact camera module** (Object 3) for 2D/3D acquisitions of pictures and movies by any (linear array or imager, iTOF or dTOF based) MiSPiA CMOS SPAD chip, to be remotely controlled by a remote pc through USB 2.0 link and a graphical user interface (GUI). All signals, clock, and buses to/from the chip are managed by an on-board FPGA, able to store high-throughput streams of data into a SRAM. All chip’s low-voltage power supplies, SPAD high-voltage (25V)
bias, FPGA/SRAM devices are provided by internal DC-DC switching power board, operated by the single +5V USB plug. The Matlab GUI allows easy control of all acquisition parameters (e.g. chip settings, either real-time, free-running or time-gated, 2D and/or 3D modes), handy image and video display, thus easing further off-line data-processing.

6 - two different cost-effective CMOS technologies for SPAD manufacturing, in a robust and reliable 0.35µm node, to fabricate either fully-planar single-chip, front-illuminated CMOS FrontSPAD imagers (Objective 2) or advanced two-chip wafer-to-wafer bonded, back-illuminated SOI-based BackSPAD imagers (Objective 4). The FrontSPAD technology is completely validated and tested, and resulted in the development of previously listed products 1, 2 and 3. The BackSPAD technology consists of: i) well-assessed electronic design and fabrication of CMOS read-out integrated-circuitry (roic); ii) custom-based design and fabrication of Silicon-on-insulator (SOI) arrays of SPADs with trench-isolation and “through-vias”; iii) designed masks, alignment procedures, fabrication steps for planarization and solid-state inter-diffusion (SLID) between two (SOI over CMOS) wafer-to-wafer bonded chips; iv) full-assembly procedure and manufacturing of the SOI SPAD array and the CMOS roic electronics into a monolithic BackSPAD imager.

7 – tests and characterization in short-range safety automotive scenarios (Object 6), under different experimental conditions, indoor and outdoor, in static and dynamic scenarios, in private driving test tracks and public every-day standard traffic conditions, in either daylight, twilight or night-time. The expertise acquired during tests allowed to develop better in-sights on 3D vision in automotive field and enabled the definition of pros and cons of optical vision systems compare to other technologies, and of single-photon counting-based optical techniques versus standard analogue ones based on linear-mode single-pixel photodetectors or CMOS video cameras.

Details of MiSPiA products

The MiSPiA project achieved so far many successful scientific and technological results. Most of these products will eventually move to concrete new business and markets. Due to the broad spectrum of MiSPiA outcomes, from technologies, to devices, components and 2D/3D camera systems, the exploitation activities will promote, deploy and feed a broad set of products, as detailed in the followings.

MiSPiA technologies

Concerning technologies, here are the MiSPiA products that are available and can be exploited.

- **Standard CMOS processing of CMOS SPAD detectors** in a 0.35 µm node for the fabrication of state-of-the-art CMOS single-photon avalanche diode detectors, within isolated and independent n-doped wells, developed to allow complete integration together with on-chip electronics in order to form monolithic, stand-alone, smart-pixels, and suitable for the development of arrays of smart-pixels. See Fig. 1

![Fig. 1: 0.35µm high-voltage CMOS SPAD technology FRAUNHOFER (left), employed in the FrontSPAD MiSPiA detectors and imagers. Photographs of a processed 8” wafer with FrontSPAD devices and imagers (right).](image-url)
• **Advanced SOI processing of custom SPAD detectors** for the fabrication of high-performance SPAD detectors with recipes that can be either fully-custom or CMOS-compatible. The SOI allows the development of individual SPADs and arrays of SPADs (with no surrounding electronics, though) optimized for performances and fill-factor. See Fig. 2.

![Cross-section of the MiSPIA SOI wafer (top), containing the SPADs, put on top of a standard CMOS wafer (bottom), containing the electronics and read-out circuitry, employed in the BackSPAD MiSPIA imagers.](image1)

**Fig. 2:** Cross-section of the MiSPIA SOI wafer (top), containing the SPADs, put on top of a standard CMOS wafer (bottom), containing the electronics and read-out circuitry, employed in the BackSPAD MiSPIA imagers.

• **Wafer-to-wafer bonding**, for the assembly of the SOI SPAD wafers with the standard CMOS electronics wafers as depicted in Fig. 2. The technology employs Cu and Zn microplating and soldering with Solid-Liquid-Inter-Diffusion “SLID” process, as shown in Fig. 3. After wafer bonding the SOI wafer is thinned down to a few micron thickness. This technology has been developed in MiSPIA for the BackSPADs, but with some modifications it may be used also for other wafer bonding applications. The wafer bonding technology as well as the SPAD process technology in bulk CMOS and SOI will be available for product development and production after the end of the project. See Fig. 3.

![Wafer-to-wafer bonding processing employed in the BackSPAD MiSPIA imagers (left) and microphotographs (center and right) of some steps in the processing.](image2)

**Fig. 3:** Wafer-to-wafer bonding processing employed in the BackSPAD MiSPIA imagers (left) and microphotographs (center and right) of some steps in the processing.
**Diffractive and refractive microlens fabrication and assembly**, which is a mature technology with a proven track record, and is used to enhance the proportion of incident light coupled into the active area of the detector, is being exploited through the HWU spin-out company. See Fig. 4.

![Two different assembly techniques, lens-up and lens-down, developed in the MiSPiA project, for diffractive microlenses.](image)

**Image processing**

The iTOF MiSPiA cameras can operate both in 2D imaging and 3D mode. In 2D mode, each frame provides the pixel by pixel intensity of the objects in the scene, with no illumination, i.e. in a “passive” acquisition. Instead in 3D mode, each frame provides the pixel by pixel information about the overall signal reflected by the objects after “active” illumination and also the phase-difference in detected light compared to emitted light, i.e. the distance information (see the first three pictures of Fig. 5). Thanks to these three different images (intensity, reflectivity and ranging) provided simultaneously by the MiSPiA camera, it is possible to improve the resolution and the 3D accuracy through algorithms. For example in Security applications, to discern persons from animals.

![A person walking in a underground parking. From up to down: (left) Total Intensity Image (2D active + passive light), 3D acquisition after the median filter and segmented image, (right) reflected active light, 3D measurement after the floor removal and 3D information superimposed to the image.](image)
The first three images of Fig. 5 show frames as acquired by the MiSpiA camera: 2D acquisition in standard “passive” mode (no illumination) in a grayscale map; Reflected light acquisition, with just the active illumination’s reflected light; 3D acquisition with a simple spatial filtering.

Then, in order to improve image understanding, these frames are merged together into one single image. The 2D image is used to define the image grey-levels (i.e. the colour saturation) while the 3D image provides the colour information (close by objects are red while far away ones are green). The Reflected light acquisition is used to mask the 3D information: where the reflected light is not enough, the 3D measurement suffers of a very high noise and the provided information is misleading; therefore, pixels with not sufficient an SNR are not coloured (they maintain only the grayscale). Then floor is removed and the segmentation of objects is performed (fourth and fifth pictures in Fig. 5). The last step consists in the superimposition of rectangles defining the edge of recognized objects and the computation of geometrical characteristics of objects (e.g. dimensions, distance and speed), as shown in the last picture of Fig. 5.

**Algorithmic subsystem**

The algorithms applied to the MiSPIA sensors are built over EMZA’s proprietary Reduced Recognition Architecture (RRA) and algorithms. This solution, following years of research, calls for dividing the analysis into three stages: pixel level, geometric level and motion/higher level.

For analysing the data streaming out of MiSPIA sensors, we have adapted the algorithms to the output of the various MiSPIA sensors, both passive (for 2D imaging) and active (with illumination for 3D ranging). For the 3D ranging imager (with illumination and TOF analysis), the main task is to compute from few frames the expected Time To Impact (TTI). This has to be performed reliably, while considering the relatively high noise inherent to single pixel detection. While these algorithms have inherent novelty in them, we do not see them as an independent product that can be sold, but as part of a complete sensor solution.

**MiSPIA devices**

The MiSPIA microelectronic chips that will be exploited are the followings.

- **CMOS chips containing individual SPAD detectors**, to be used together with off-chip electronics for custom-specific applications. In fact the state-of-the-art performance of MiSPIA SPADs (reaching also 500 µm diameter) with only 100 kcps dark counting rate) are indeed a business success *per se*. Hence this exploitation can deploy these CMOS SPADs to OEM, small high-tech enterprises and also big companies, already playing in the market of very sensitive optical detection. See Fig. 7.

![Fig. 6: Example of one chip, containing individual SPAD detectors 50 µm, 30 µm, 20 µm, 10 µm (top left) and 500 µm, 200 µm, 100 µm and 50 µm diameters.](image)
CMOS chips containing **individual SPAD smart-pixels**, i.e. one SPAD detector together with the analog sensing front-end and the in-pixel digital electronics for either counting the detected photons or measuring their arrival time. Targeted applications range from the measurement of faint optical DC- or slowly varying optical signals within counting time-slots as short as hundreds of nanoseconds or few microseconds (usually called **photon-counting**) to the precise acquisition of high-speed time-resolved optical waveforms (named **photon-timing**, or **time-correlated photon counting**, or **time-of-flight** measurements). See Fig. 8.

**Fig. 7:** Dependence of Dark Counting Rate (left) on excess bias and SPAD diameter. Note the low 100 kcps value also for the larger, 500 µm SPADs. The uniformity of MiSPIA SPADs (right) reaches up to 95%, with just a dozen of SPADs out of 2048.

**Fig. 8:** "Photon-counting" (top) and "photon-timing" (bottom) MiSPIA architectures (left) and layout (right) of smart-pixels, containing both SPAD detector and in-pixel processing electronics.
CMOS chips containing **1D linear SPAD arrays**, i.e. orderly mono-dimensional arrangements of SPAD smart-pixels, with surrounding global electronics for synchronization, common gating and data-read-out. These arrays are the best candidates when high-performance (e.g. large SPAD diameter, above 100 µm), few pixels (e.g. up to 32 or 64), “fancy” layout (e.g. not just linear, but also multiple quad-cells, cylindrical symmetry, few lines, etc.) arrays are a must, in order to provide fully-parallel multi-channel monolithic systems able to discriminate photon-arrival position (e.g. in wavelength-resolving spectrometers), signal correlations, interferometry, quantum communications, etc. See Fig. 9.

![Figure 9: Chips of 1D linear SPAD arrays of 2x32 pixels with SPAD diameters of 50µm (top) and 100 µm (bottom). For both the output is a digital bus providing the number of photons detected in the corresponding pixel, during the user-selectable integration time.](image)

CMOS chips containing **2D SPAD imagers**, i.e. squared (2D) layouts of “photon-counting” SPAD smart-pixels with global shutter electronics, row-by-column digital read-out, hardware and software gating of region-of-interests and parallel settings. These imagers are based on smart-pixels optimized for fill-factor (e.g. medium SPAD diameter, up to 100 µm) and for counting photons in two-three independent in-pixel counters, all properly driven by global synchronisms. These arrays are targeted for those imaging applications requiring single-photon sensitivity, (moderately) high pixel count (of some $10^3$ pixels), for gated and phase-resolved light “intensity” acquisitions at high frame-rates, up to some $10^5$ fps (frames per seconds), i.e. frame time slots of few µs. See Fig. 10.

![Figure 10: Chips of 2D SPAD imagers of 64x32 "photon-counting" smart-pixels with 30 µm SPAD diameters.](image)
CMOS chips containing **3D SPAD ranging imagers**, i.e. squared (2D) layouts of “photon-timing” SPAD smart-pixels, each able to measure the time elapsed from a global common “start” synchronism to the “stop” signaled by the photon arrival therein, that is able to provide the digital information of the time-of-flight. These arrays can provide the information of the “distance” of an object (hence the name “3D”), based on the return trip time of a pulsed light excitation of the scene. The time-resolution of 300 ps and INL linearity of 200 ps rms provide a sharp time-stamping performance for those applications dealing with very fast optical signals. In 3D ranging, these performance turn into a single-shot depth resolution of 10 cm. See Fig. 11 and Fig. 12.

**Fig. 11:** Timing performances (top) of the “photon-timing” smart-pixels, with Time-to-Digital Converter in each, with 300 ps channel width (LSB) and about 200 ps rms precision. Accuracy in terms of DNL and INL (bottom), corresponding respectively to 2 mm and 5 mm rms in depth.

**Fig. 12:** Chips for 3D ranging with 32x32 and 32x16 “photon-timing” smart-pixels with two SPAD diameters.

### MiSPiA components

Concerning components, the MiSPiA components that will be exploited are the followings:

- **LED illuminator for continuous-wave modulation** and short-range (7m) 3D iTOF ranging. The illuminator is composed by 36 LEDs with emission peaked at 850nm, 40 nm wide. The peak wavelength is consistent with the requirements of the MiSPiA project (NIR), as the angle of half intensity (the MiSPiA camera must cover a horizontal FOV of 40°). The prototype illuminator receives the synchronization signal with the required frequency, up to 20 MHz. The maximum optical output power is about 1 W. See Fig. 13.
Fig. 13: LED illuminator for short-range continuous-wave modulation, up to 20 MHz, employing 36 LED of 25 mW each, for an overall peak power of 1 W, able to reach a maximum distance of 7 m.

- **Laser illuminator for continuous-wave and pulsed-light modulation** and medium-range (up to 40m) 3D iTOF ranging. The illumination is based on laser diodes with emission spectrum centered on 808 nm, 2 nm wide. The maximum peak power is 200 mW per diode and the emission angles are 12°/40° (V/H). The illuminator has a modular design, with driver boards hosting 3 laser diodes each, in order to match the power requirements of the particular application. See Fig. 14 and Fig. 15.

Fig. 14: Laser illuminators for short-range continuous-wave (up to 20 MHz) and pulsed-light (from 180 ns to 800 ns) pulsed-light modulation, employing 15 lasers at 808 nm of 200 mW each, for an overall peak power of 3 W, able to reach a maximum distance of 50 m with a 40°x20° field-of-view, together with the MiSPIA camera.

- **Diffractive and refractive microlens fabrication and assembly**, which is a mature technology with a proven track record, and is used to enhance the proportion of incident light coupled into the active area of the detector, is being exploited actively through the HWU spin-out company Alba Photonics Ltd (http://www.alba-photonics.co.uk). See Fig. 16.
Microelectronic Single-Photon 3D Imaging Arrays
for low-light high-speed Safety and Security Applications

Final Report - PUBLISHABLE

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Fig. 15: Distance precisions (top) and computed distance (bottom) by the 3D iTOF system in an indoor parking (46m long), at three CW-iTOF frequencies: 4.17MHz (left) with 36m unambiguous range; 12.5MHz (center), with 12m unambiguous range; 8.3MHz (right), with 18m unambiguous range. Note different ranges of the colour scales.

Fig. 16: Microlenses array, mounted on top of a 2D imager (left) and a 3D imager (right), with the lens-up approach.

• **Algorithms for image processing**

For the passive (2D) imagers, the main task of the algorithms is to perform intruder detection. This translates to being able to distinguish between “regular” and “irregular” pixels. We base this analysis on comparison of current pixel intensity with its “historical” levels, using a low complexity computational platform. This allows even a noise system, observing a dynamic scene (i.e. with wind, moving branches etc) to distinguish between regular background and illumination changes to a physical object moving in the scene. See Fig. 17.

For the active (3D) imagers, the main task is to estimate distance, and in particular distance changes, and predict time of impact (TOI) of objects. This on the background of a very noisy scene with only a small number of pixels and avoiding distance aliasing. See Fig. 18 and Fig. 19.
Fig. 17: Example of a screen-shot showing a 3D image, with the computation of distances, velocities and dimensions of some region-of-interest in the scene under observation.

Fig. 18: Correct 3D ranging acquisition with the two modulation frequencies algorithm.

Fig. 19: Screenshot of the user interface when a 3D depth-resolved movie of a girl is being acquired.
MiSPiA 2D/3D camera systems

Concerning the MiSPiA detection systems, for either 1D array detection, 2D imaging cameras or 3D ranging cameras, the products that will be exploited are the followings.

- **1D detection module for multi-channel “photon-counting” and “photon-timing”**, based on 16x1, 32x1, 32x2, and 60x1 linear arrays of smart-pixels, each containing three up/down counters and a Time-to-Digital (TDC) converter, with a readout rate of 10ns per pixels, thus topping at over 6Mfps for the smaller array. See Fig. 20 and Fig. 21.

![Board assembly of the MiSPiA chip containing one 1D linear array of 2x32 smart-pixels with 50 µm SPAD smart-pixels and differential drivers for direct timing output to external electronics (left), typical timing performance of a pixel with 5V excess bias at λ=850 nm (right). All the pixels of the array have a FWHM of about 110 ps.](image)

- **2D camera for “photon-counting” imaging**, based on a 64x32 array of smart-pixels, each containing three up/down counters, with minimum integration time of 32µs, maximum frame-rate of 30kfps when all the three counters are read. Frame rate tops at 100kfps when only one counter is used. Not only imaging of standard objects (see Fig. 22), but also more complex imaging of fluorescence, live-cells and diffusive media have been exploited (see Fig. 23).

![Micrograph of the 60x1 arrays with 100 µm round SPADs and 150 µm pitch.](image)
Microelectronic Single-Photon 3D Imaging Arrays
for low-light high-speed Safety and Security Applications

Fig. 22: MiSPIA 2D camera (left) and example of 2D acquisition at 2048 pixels (64x32 iTOF).

Fig. 23: Transfected Cell (left) acquired by the 64x32 iTOF camera, able to measure pixel-by-pixel the fluorescence lifetime for GFP (blue line) and GFP in FRET (green line). A change of the decay fluorescence occurs because of energy transfer.

- **3D camera for “photon-counting” ranging**, through either continuous-wave or pulsed-light illumination of the scene and indirect iTOF phase-resolved estimation of the 3D distance information of the object in the scene. The camera comes with a LED illuminator, for covering short distances up to 7m, or with a laser illuminator (see Fig. 24) for reaching medium-distances up to 50 m (see Fig. 25).
Fig. 24: MiSPIA 3D iTOF camera based on “photon-counting” chips (left): principle of operation of the continuous-wave and pulsed-light modulation techniques (top) and example of a 3D movie acquisition at 9m range and with 2 cm depth resolution (right).

Fig. 25: Frames from a 3D movie at 200fps in a chaotic street, with moving cars and pedestrians. Frames were taken at about 1s from each other, i.e. one frame out of about 200.

- **3D camera for “photon-timing” ranging**, through direct dTOF measurement of the time-of-flight of photons launched by a laser illuminator toward the scene of interest and detected back by each camera pixel. The imager is based on either a 32x32 (30µm SPADs) smart-pixels, each containing a Time-to-Digital (TDC) converter. The array is read-out at 100kfps, but multiple laser pulse for each frame can be launched (only the first pulse detected in each frame will the recorded). See Fig. 26 and Fig. 27. Apart from 3D ranging, the TOF camera can be used for any time-resolved movie acquisitions, like Diffusive Optical Tomography (see Fig. 28), spectroscopy, microscopy.
Fig. 26: MiSPIA 3D camera based on “photon-timing” chips: principle of operation of the direct Time-of-Flight dTOF technique (top) and photograph of the boards of the camera prototype.

Fig. 27: Target acquired by the dTOF camera, scanning the scene in 50 steps, for a total of 250ms overall acquisition time.

Fig. 28: 2D acquisition for detecting an inclusion in an opaque diffusive media (yogurt).
1.5 POTENTIAL IMPACT AND MAIN DISSEMINATION ACTIVITIES AND EXPLOITATION OF RESULTS

The MiSPIA 2D imaging and 3D ranging chips and cameras provide real-time 2D movies with single-photon sensitivity in the visible and near infrared (300nm - 900nm) ranges the 3D ranging movies at high frame-rates with on-chip processing and 2D photon-counting in linear or matrix array layouts. Significant results and validations were demonstrated during this third year of the MiSPIA project, in both short-range (up to 50m) automotive environments and medium-range security monitoring. Overall the MiSPIA project proved successful in all aspects, from technology processing developments, microelectronic chips deployment, detection camera and illumination module system integration, end-user applications.

Furthermore, MiSPIA dissemination activities (through scientific papers, technical conferences, commercial workshop, common laymen advertisement via newsletters, leaflets and webpage) triggered the interest of different potential users working on completely different research developments and commercial applications. In fact, cost-effectiveness, low-power requirements, state-of-the-art detection performance, and easy configurability of MiSPIA’s chips and cameras dictate the success of MiSPIA outcomes into all those equipment requiring ultra-high photosensitivity (down to the single-photon level), very short-integration time (as short as few microseconds), high-performance photon-timing (with sub-nanosecond time-gating and ps level precision) for acquiring very faint and fast optical events.

Eventually MiSPIA exploitation activities involve wide communities and markets, in Safety (e.g. environmental surveillance, product safety analysis, food and agriculture quality and safety assessment, etc.) and Security (biometrics, surveillance systems, dangerous agents monitoring, fire hazards, etc.) applications, but also in microscopy, biology, adaptive-optics, gaming, and 2D night vision and 3D ranging/lidar in light starving conditions.

Individual SPADs and detection modules

CMOS SPAD chips with 20–500 µm diameter, low DCR and high uniformity

*Partners involved: MPD - POLIMI - FRAUNHOFER*

Detection modules with individual CMOS SPAD pixels

*Partner involved: MPD - POLIMI*

For MPD the MiSPIA outcome of a single pixel CMOS SPAD with different detector diameters (ranging from 30um up to 500um) and low DCR, is a very good fit in our product range; in fact the enhanced PDE of CMOS SPAD in the Blue and UV range (300-450nm) fills nicely the performance degradation of our custom SPAD modules, namely PDM.

Fig. 29: Present SPAD detection module (single pixel) sold by MPD, model PDM open-air (top) and PDF (bottom) fiber-coupled.
Fig. 30: Photon Detection Efficiency of MiSPIA CMOS SPADs compared to other state-of-the-art SPADs, made in custom processing. Note the extremely high PDE in the near ultraviolet, thanks to the proprietary processing of partner FRAUNHOFER.

Not only, but the expected timing accuracy of the new CMOS SPAD in the sub-100ps FWHM range will also allow MPD to overcome the degradation of our current module timing accuracy in that wavelength region, giving us an even stronger advantage against our competitors. MPD intention is therefore to use the CMOS SPAD chip with the integrated existing AQC electronics, either mounted on a Peltier cooler (as in our current products) or not, packaged in a TO-8 and then assembled in a new PDM-B&UV (PDM blue and UV enhanced) module. The likely markets in which we do expect to offer and sell this new PDM-B&UV modules shall be similar to our existing ones, with some slight changes due to the improved PDE in the UV range; therefore our customers base will be represented by biomedical, biophysical, biochemistry, quantum communication, cryptography and astronomy research groups from universities or national research institutes as well as industries using photonics methodologies. We do expect these new SPADs to perform well in a variety of cutting-edge applications including: Particle Sizing, Confocal Microscopy, Ultra-Sensitive Fluorescence, Luminescence, Time-correlated single photon counting, Single Molecule Detection, Astronomic Observations & Adaptive Optics, Optical Range Finding, LIDAR & LADAR, Quantum Cryptography & Quantum Optics, Single-photon source characterization, Optical testing of integrated circuits.

Considering that MPD sells around few hundreds PDM modules per year, we reckon that this new product will inherit the quality, robustness and reliability of our existing PDM production limiting the changes to the cost and packaging saving that would make sense to introduce into it. The expected sales volume shall be in the order of 50-100 units/year, generating a turnover return in the region of few hundreds thousands of euros/year. As it has always been, MPD was not too keen in selling SPADs chips as stand-alone modules. In fact this kind of sales not only requires slightly different production processes and certifications, that are not in our DNA yet and that we could only consider to undertake in case of a very large volume business opportunity (at least hundreds of thousands of pieces/year), but also a business model which will be fairly new to us (typically this sales imply a price/chip very low, which means a very much different type of cash flow that we are used to). In any case we do not see any real market of this kind in the short term; hence we rather leave this kind of opportunity as something that might happen in the long term future.

Besides this, there might always be the possibility of selling individual chip to selected partners for selected research applications that might lead to the birth of new methodologies, new applications or new interesting products. In this latter case, not only the price per chip but also the future prospects shall be high enough to justify the business.
Fig. 31: Layout of a chip containing a smart pixel for photon counting iTOF with 135 µm x 135 µm squared SPAD, 1.25 mm x 1.25 mm overall size (left) and a chip with two pixel for photon-timing (dTOF), 30 µm and 500 µm diameter SPAD, 1.90 mm x 1.90 mm size (right).

**Individual Smart-pixels**

**CMOS smart-pixels with digital output bus for photon-counting**

*Partners involved: POLIMI - FRAUNHOFER - MPD*

**CMOS smart-pixels with digital output bus for photon-timing**

*Partners involved: POLIMI - FRAUNHOFER - MPD*

**Compact detection heads employing individual CMOS smart-pixels**

*Partners involved: MPD - POLIMI*

Although we do expect the performances of smart CMOS SPAD pixel to be very similar to the PDM-B&UV just described, the much higher electronics integration level shall open up a scenario of significant cost reduction in the manufacturing costs of the module besides a slight rise of the non-recurrent costs of manufacturing of the chip. The smart CMOS SPAD pixel will integrate the SPAD detector, in-pixel analog quenching electronics and digital photon counting and timing electronics to provide MPD with a viable solution for some OEM sales channels.

It is still unclear if the chip will be sold fully encapsulated in a suitable package or as a small PCB with the chip mounted on top of some extra electronics to make the customer interface easier. In any case, both options could stay open and might end up selling into two different market channels. One possible interesting deployment of this smart CMOS SPAD pixel could be their usage as lab-on-a-chip (LOC) devices that integrate one laboratory function on a single chip of only few square millimeters in size. SPAD LOCs typical application could be: Drug discovery, genomics, diagnostics, proteomics, IVD & POC, high throughput screening, providing advantages like:

- faster analysis and response times due to short diffusion distances, high surface to volume ratios
better process control because of a faster response of the system
lower fabrication costs, for cost-effective disposable chips, fabricated in mass production

Lab-on-a-chip technology may soon become an important part of efforts to improve global health, particularly through the development of point-of-care, drug discovery, biotech and ecology testing devices. Some researchers believe that LOC technology may be the key to powerful new diagnostic instruments.

The lab-on-chip segment is part of the global biochip market which was valued at $2.6 billion in 2010 and is expected to reach $5.6 billion by 2015; growing at a CAGR of 16.7%. This growth is attributed to increasing applications in cancer diagnostics and expression profiling, the boom in personalized medicine, and government funding. Although DNA microarrays represent the largest segment of this market and will continue to be the largest contributor for another number of years, this segment will be closely followed by lab-on-chip (LOC) in the coming years due to its wide applications and increased adoption by various biotechnology, pharmaceutical companies, and research laboratories.

Asiatic market will account for a bulk of future biochip market growth due to its high growth potential and huge demand from emerging economies such as India and China, the large pool of heterogeneous patient population, and increasing R&D investment in these countries.

The top players in the biochip market are Affymetrix, Inc., Illumina, Inc., and Fluidigm Corporation.

### 1D linear arrays and modules

**1D linear SPAD array chips for spectroscopy applications**

*Partners involved: POLIMI – FRAUNHOFER - MPD*

**Detection modules with 60 photon-counting and timing channels**

*Partners involved: MPD - POLIMI*

Life science instruments are used extensively in research and development activities, laboratories being one of the major users. Their market is growing at a rapid rate due to the continuous requirement of these instruments in pharmaceutical and biotechnology industries. Besides, advances in life science research and technology innovations require quality instruments with high throughput capacity. The ever increasing demand for higher throughput fits nicely with the MiSPIA outcome of liner arrays of CMOS SPAD detectors (1x8, 1x16, 1x32, up to 1x60).

The reasons for which MPD is quite interested in exploiting the demand of linear arrays are many and of different kinds, but for sure the ones that matters more to its end users are the possibility to:

- increase the sampling rate with consequent reduction of the test duration (which is a significant benefit when these tests are performed directly on humans);
- augment of the test area which impacts again into a saving of time or in the possibility to put under investigation a much bigger zone in the same time frame;
- acquire multiple wavelength at the same type, improving the effective investigation power of all the spectroscopy methodologies.

Besides these, another huge advantage of linear SPAD arrays, above all when these are smart array, i.e. arrays in which each pixel has got built in the single-photon counting and timing electronics, is the cost saving of the module which shall become significantly smaller than making an equivalent modular device made of the same number of individual pixels. From this point of view, the uniformity of the performances across the pixels highlighted by the MiSPIA chips shall make this type of liner array a very cost effective solution.
Fig. 32: Microphotographs of some pixels of the two 1D linear SPAD arrays of 60 pixels, 150 μm pitch: circular SPAD with 100μm diameters (top) squared SPAD with 135 μm sides (bottom).

The implementation of the timing electronics inside the pixel will make the deployment of very nice, compact and cost effective multichannel devices possible for time-resolved spectroscopy, which is, in physics and physical chemistry, the study of dynamic processes in materials or chemical compounds by means of spectroscopic techniques. Most often, processes are studied after the illumination of a material occurs, but in principle, the technique can be applied to any process that leads to a change in properties of a material.

The global Life Science instrumentation market, mentioned above, was estimated to be $30.2 billion in the year 2011 and is expected to grow at a CAGR of 8.4% from 2011 to 2016 to reach $45.2 billion. Spectrometry segment has the largest share (33.8%) followed by chromatography (22%) in 2011.

The U.S. holds the major share in this market across technologies; it is closely followed by Europe. The market is driven by high growth from Asian and the LATAM countries, where demand is on a rise due to increased outsourcing activities in the life technology field. Singapore is a major region for life science instruments, as many companies are establishing a manufacturing base in Singapore, due to the tax incentives. As the market is vast there are many players in the market, the major players in this market include Affymetrix Inc. (U.S.), Illumina Inc. (U.S.), Agilent Technologies Inc. (U.S.), Roche Diagnostics Inc. (Switzerland), Bio-Rad Laboratories (U.S.), GE Healthcare (Sweden), Life Technologies (U.S.), Caliper Life Sciences (U.S.), Shimadzu Corporation (Japan), Abbott Laboratories (U.S.), Hitachi High-technologies Corporation (Japan), and Siemens Healthcare Diagnostics (Germany).
2D imagers and cameras

64x32 CMOS SPAD chips for 2D imaging

*Partners involved: POLIMI - FRAUNHOFER - MPD*

Camera modules for 2D imaging

*Partners involved: MPD - POLIMI*

MiSPiA outcome of a new CMOS SPAD chip with 64x32 smart-pixels able to perform “photon counting” of the incoming photons (also during user-defined gate windows, if needed) and allowing the on-chip background noise subtraction, will enhance the 2D imaging capabilities of our existing Single Photon Counting Camera (SPC\(^2\)) product, currently fitted with a 32x32 CMOS SPAD chip.

In fact this new chip shall overcome two of the major limiting factors of MPD existing 2D camera: high pixel DCR, in the order of few thousands of counts per second for the best pixels (which counts typically for 50% of the total); poor pixel performance stability across the array. This new improved SPC\(^2\) version (SPC\(^2\)i) will inherit the case and most of the electronics from the existing module which will be modified only to address the new bigger CMOS SPAD chip with 64x32 smart-pixels, instead of the actual 32x32.

These 2D cameras shall address the needs of Life sciences (biotechnology and medicine) applications: these applications will be interested in the SPC\(^2\)i SPAD CMOS cameras especially for their combination of low noise, high sensitivity, and high frame rates. In particular, microscopy techniques such as super resolution microscopy and structured illumination must record many single images in order to provide the user with a result image. In super-resolution microscopy independent fluorescent flash generation is emitted by corresponding indicator molecules, so images with non-sharp light blobs are recorded. These are generated by single molecules, and these blobs and their centre of mass are evaluated by algorithms and their position is stored. Many images are recorded and their positions are accumulated to generate one resultant image, showing a higher resolution than the microscope optics can accommodate.

The first application used EMCCD cameras at low resolution with a small ROI to achieve an acceptable frame rate. Based on these setups, total recording time for one image took a few minutes. The SPC\(^2\)i image sensor allows for a larger area and maintains a major improvement in reduced recording time because of much higher frame rates. Similar advantages exist for structured illumination microscopy, where many images with superimposed patterns are also recorded to remove stray light and increase resolution above the optical limit of the microscope.

![Fig. 33: Present 2D SPAD camera sold by MPD, model SPC\(^2\), based on a previous generation 32x32 SPAD pixels array.](image-url)
Both microscopy areas require low readout noise, excellent quantum efficiency, and high frame rates. There are also new techniques in DNA analysis that analyse weak fluorescence signals, yet require high throughput, and other applications that require high frame rates and high dynamic, for example, slide scanners in digital pathology.

Considering all these researches are mainly conducted by either universities or research groups from all over the world, it is hard to forecast a potential OEM application in which the MiSPiA 2D SPAD chip shall be required as a standalone chip, hence it is most likely that, as MPD, we will concentrate in selling the SPC2i as a ready-to-go module, that through its own set of DLLs will allow any programmer to adjust its behaviour and performances accordingly to his specific needs.

Following this assumption, MPD believes the SPC2i customer's base to be fairly similar to the one usually buying its single pixel modules, which, considering also the quite significant selling price, shall impact the expected number of sales to be in the region of up to few tenths of units per year.

### 3D ranging imagers and cameras, based on indirect TOF

#### 64x32 CMOS SPAD chips for 3D ranging via phase-resolved indirect TOF

*Partners involved: POLIMI - FRAUNHOFER - MPD*

#### SPAD camera for high frame-rate 3D indirect iTOF ranging

*Partners involved: MPD - POLIMI*

### Active illuminator based on solid-state modulated lasers

*Partner involved: POLIMI*

MiSPiA outcome of a new CMOS SPAD chip with 64x32 smart-pixels able to perform accurate “photon timing” of the incoming photon, i.e. to measure the elapsed time from laser excitation and photon detection via a high-frequency clock counter and gated counting, will allow MPD to supply the market with a 3D ranging camera through phase-detection indirect TOF (iTOF), namely SPC3i.

The single-photon iTOF camera coming off MiSPiA development employs a single “universal” smart-pixels able to perform both “pulsed laser” iTOF ranging and “continuous wave modulation” iTOF ranging. Both approaches are based on the “photon counting” of back reflected photons within well-defined time-slots, synchronous with the burst illumination or the CW modulation. Such “indirect” TOF measurements based on the “digital” count of single photons will positively compare with the standard “analog” approach, impaired by “analog” noise and limitation in SNR and sensitivity.

Besides the iTOF camera, MPD, in partnership with PoliMI, will develop the illuminator for the 3D ranging module, for short range (up to 50m) single wavelength and multiple discrete wavelength applications (multi-spectral approach). It will be based on pulsed or CW-modulated semiconductor laser sources and the necessary collection and routing optics in order to make it widely usable for the majority of applications.

This new SPC3i and the illuminator will be made such as it shall be possible to assemble them together as an individual module or keep and sell them separated as standalone units.

Once again the SPC3i will be based on our existing SPC2i electronics and mechanics modified to allow the interface and combination with the external illuminator.

These new SPC3i cameras shall find its markets in the following applications, some similar to the ones previously described for the SPC2i, with some more enhanced functionality due to the extra 3D capability:
Microscopy: the SPC\textsuperscript{3i} shall provide these applications with a real single-photon imager able to operate at high frame rate. Also the inherent capability of non-destructive accumulation and gated operation of MiSPI\textsuperscript{3}A iTOF 3D detectors further enhance the potential of using pulsed laser illumination and synchronous acquisitions.

Biology: for Multi-spot Fluorescence Correlation Spectroscopy or Photon Migration studies the new SPC\textsuperscript{3i} capability can be employed to investigate not only long (microseconds range) but also short (nanoseconds range) multi-spot FCS fluorescence applications. Moreover, gated operation of MiSPI\textsuperscript{3}A array chips allows the exploitation of pulsed laser illumination for conveniently Photon Migration studies.

Astrophysics: the SPC\textsuperscript{3i} shall nicely fit in adaptive optics systems of the next generation ground-based telescopes. MiSPI\textsuperscript{3}A 3D imager can provide substantial benefits over CCD-based system thanks to higher speed and sensitivity. The number of sub-apertures in the telescope pupil is in the range of few hundreds, thus the pixel count of SPAD array is not a show-stopper.

Entertainment Industry: its demanding requirements for dynamics in TVs, personal computers, and 3D metrology for automobiles could represent potential application areas in which the SPC\textsuperscript{3i} device shall be tested. The television broadcast and film industry is interested in the high dynamics, hence the SPC\textsuperscript{3i} advantage of low power consumption, high dynamic range, single photon sensitivity (which turns into a very low illuminating power requirements), high video-rate and lightweight shall make it the ideal sensors for portable devices.

Except for this latter case, it is still valid what we said about the SPC\textsuperscript{3i} or that it is quite difficult to foresee potential OEM applications in which the MiSPI\textsuperscript{3}A 3D iTOF SPAD chip can be sold as a standalone chip, hence it is most likely that, as MPD, we will concentrate in selling the SPC\textsuperscript{3i} as a ready-to-go module (with or without the illuminator), with its set of DLLs to be programmed accordingly to the customer needs.

Once again, the perception is that the SPC3i will still sell to our typical customer’s base which means that the expected number of sales will be in the region of few tenths of units per year. Rather different is the last scenario, for which, besides the difficult challenge of winning the business competitions off other technologies, the potential are at the moment beyond our DNA, comprehension and capabilities.

3D ranging imagers and cameras, based on direct TOF

32x32 CMOS SPAD array chips, for 3D ranging via direct dTOF and in-pixel Time-to-Digital Conversion

*Partners involved: POLIMI - FRAUNHOFER*

SPAD camera for high spatial resolution 3D dTOF ranging

*Partners involved: POLIMI - MPD*

In this case the smart-pixel coming off the MiSPI\textsuperscript{3}A development is able to perform accurate “photon timing” of the incoming photon, i.e. to measure the elapsed time from laser excitation and photon detection via a sophisticated Time-to-Digital Converter (TDC), namely SPC3d.

Such “real” and “direct” TOF measurement will reach the extreme limit of LIDAR techniques, at the utmost advantage of having all array detectors and pre-processing integrated into a single-chip manufactured in a fully-standard CMOS technology. The SPAD much superior sensitivity compared to standard CMOS photodiodes and APS and the timing resolution at tens of picoseconds will enable the implementation of dTOF techniques with higher range measurement accuracy (centimetre) and higher frame rate (above 100fps).
As for the SPC³i camera, MPD will partner with PoliMi to develop the illuminator for the 3D ranging module, in this second case the long-range (200-1,000m), multi-spectral 3D ranging module will be operated at up to 4 different “colours” (possibly more), ranging from the visible to the near infrared wavelength bands, thanks to the broad spectral sensitivity of the proposed MiSPIA modules. The goal is to add further information on the nature of the target for ease distributed target recognitions.

Therefore the new SPC³d and the illuminator will be made such us it shall be possible to assemble them together as an individual module or keep and sell them separated as standalone units.

It shall be possible to share some of the electronics and mechanics with the SPC³i, modified to allow the interface with the different CMOS SPAD chip and illuminator.

The advantages of low power, high dynamic range, single photon sensitivity, high video-rate and lightweight make the SPC³d cameras ideal sensors for:

- **Astrophysics:** laser-guide-star-based system presently suffers from the so-called “spot-elongation” issue which could be overcome by the use of pulsed laser, in order to track pulses as they propagate through the atmosphere. This requires detectors that, in addition to the aforementioned performance of sensitivity and speed, allow also non-destructive accumulation of several short “active” slots per each frame, such as the proposed MiSPIA dTOF 3D detectors.

- **3D Flash LIDAR:** situational awareness, object identification, day-night-rain-fog imaging, aviation take-off and landing, mid-air refuelling, terrain mapping, autonomous navigation, smart intersection monitoring and control, unmanned ground vehicles, unmanned air systems and vehicles, machine vision, hazard material detection and handling and underwater 3D imaging.

- **Space:** manned and unmanned or automated space activity where situational awareness, relative guidance and safe docking are crucial functions. With NASA’s exploration initiative to return to lunar exploration and eventual human exploration of Mars, there is an increased need for 3D sensors that provide adequate determination of trajectory, landing hazards and identification of safe landing sites during the critical landing sequence. Determining real-time spacecraft trajectory, speed and orientation to the planet surface, as well as evaluating potential hazards at the landing site required for precision landing are all functions 3D Flash LIDAR cameras are uniquely capable of performing, making them ideal as hazard avoidance sensors for Entry, Descent and Landing (EDL).

- **LIDAR Cameras for Potential Aerial (UAV/UAS or Manned) Applications:** i.e. Autonomous Refuelling, Brownout Landing, Collision Avoidance, Countermeasures, Helicopter Landing, Landing Zone Evaluation, Laser Tracker, Mapping, Situational Awareness, Surveillance, Wire Detection, all of which all benefit from the SPC3d specs of high frame rate, high sensitivity, no motion distortion, no calibration required, small size, low weight and power.

For the SPC³d it is quite foreseeable the sales of both fully functional modules and standalone 3D dTOF CMOS SPAD chips; the former to the usual research groups and universities requiring imaging of time-resolved photons with high time precision, well below 1ns and possibly tens of picoseconds (e.g. advanced molecular research at UCLA, University California Los Angeles or in quantum communication and ghost imaging at MIT, Massachusetts Institute of Technology), whilst the latter to potential OEMs industrial customer like PMDTec, SELEX-Galileo, and FOI, the Swedish Defence Research Agency (examining for single-photon time-of-flight remote sensing, with interest in operation in the visible and near ultraviolet wavelength ranges for defence and homeland security interests).

Therefore with respect to economical and commercial prospect we shall distinguish two different scenarios. The first one refers to specific niche applications of the product for high-end application and environments which can turn into production volumes of the order of some hundreds units/year. The second scenario considers possible high-volume applications, in particular referring to consumer market for which we can refer as large volume production, in the order of 100 k-1 M units/year, with lower margin. In this latter case, though hardly evaluable at this level because it strongly depends on the complexity of the final 3D ranging modules, the turnover impact could be much higher and roughly estimated in the order of 10 M€/year.
2. USE AND DISSEMINATION OF FOREGROUND

2.A (PUBLIC) USE AND DISSEMINATION OF FOREGROUND

This section describes the dissemination measures, including the list of scientific publications relating to foreground developed within the MiSPIA project. Its content can be made available to the public domain thus demonstrating the added-value and positive impact of the project on the European Union. MiSPIA partners participated to national and international events, such as conferences or workshops, organized by external bodies, in order to promote and amplify the project’s outcomes. Both scientific conferences and dedicated workshops were considered relevant to the project development and promotion and to consolidate the interests of targets groups. Overall, the dissemination performed by the MiSPIA during its 43 months of activity was adequate and in line with the dissemination plan. In fact, after the first two years mainly devoted to conceiving the MiSPIA components and to developing the imagers and the cameras, in the third and last period there was an increase in the activity of dissemination, thus reaching a world-wide level of publication and awareness.

The following Tables A1 list all scientific publications relating to the foreground of the MiSPIA project. More specifically, Table A1a lists the peer reviewed publications, starting with the most important ones. Table A1b lists all other scientific publications presented to conferences and published in the pertinent Proceedings. Eventually Table A1c lists the scientific publications submitted to peer reviewed Journals, after the end of the MiSPIA project and under evaluation.

Table A2 lists all dissemination activities (publications, conferences, workshops, web sites/applications, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, posters). These tables are cumulative, which means that they show all publications and activities from the beginning until after the end of the project.

Many Dissemination activities were planned and carried out with the final goal to promote the project activities and outputs. The different tools used by MiSPIA consortium included:

1. Logo - The Consortium defined a logo at project starts, epitomizing the aspects that are addressed by MiSPIA. The logo was used in all dissemination material to characterise the project and to give to it an unique identification.

2. Web-site ( www.mispia.eu ) - A web-site was developed during the first months to support both external dissemination and interaction between partners. It includes the presentation of the project aims and its methodology, deliverables and available results. A restricted access section gives the opportunity to access drafts of documents for partners to provide input to the development process.

3. Leaflets - Three documents was created and updated for easy download from the website. The leaflets are made available to all partners for circulation within their own faculties, universities and research centres, in order to promote the project as widely as possible.

4. E-newsletter - Four releases of E-Newsletters were released and circulated to different environments to push the MiSPIA concepts outcomes.

5. Presentations - Several presentations were shown during international and national conferences, workshops, exhibitions, and invited talks were given.

6. Posters - shown during national and international conferences and in booths during exhibitions and fairs.

7. Mailing list - created at the beginning of the project to address a broad audience.

8. Papers and publications - Many papers in Journals and conference proceedings were published by MiSPIA partners during the project, always acknowledging the EC funding.
9. Technical Data-sheets - They were created to distribute technical specifications of the developed MiSPiA 2D and 3D cameras and chips to an expert community of potential end-users or system integrators.

10. Media tools - MiSPiA project actively promoted three press releases and also a Facebook page.
    
All these materials are presented in the following pages.

**Logo**

![MiSPiA Logo](image)

**Website**

A key part of the MiSPiA project was the creation of a website from which researchers and enterprises and all other relevant stakeholders can find information concerning the 3D ranging imagers and high-sensitivity single-photon 2D imagers: high frame-rate, short-range 3D ranging systems for automotive safety systems and long-range 3D ranging systems for security surveillance. The project website ([www.mispia.eu](http://www.mispia.eu)), was periodically updated, implemented and maintained. The scope of the website was twofold: to present and disseminate information about MiSPiA and its funding by EC to scientific community and general public (public area); and to be an instrument for information exchange and sharing among partners and towards the EC (public and reserved areas).
### TABLE A1A: SCIENTIFIC (**PEER REVIEWED**) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES

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Microelectronic Single-Photon 3D Imaging Arrays for low-light high-speed Safety and Security Applications

Final Report - PUBLISHABLE

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<th>Place of Publication</th>
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**TABLE A1B: SCIENTIFIC PUBLICATIONS PRESENTED AT CONFERENCES AND PUBLISHED IN THE PROCEEDINGS**

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<td>A. Tosi, G. M. Padovini, F. Zappa, S. Tisa, D. Durini, S. Weyers, W.</td>
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<td>Advanced Optical Technologies</td>
<td>Volume 1, De Gruyter, USA, 2012, Pages: 171-180</td>
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<td>Advances in time-of-flight and time-correlated single-photon-counting devices</td>
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<td>F. Zappa, A. Tosi</td>
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## TABLE A1C: SCIENTIFIC PAPERS SUBMITTED TO PEER REVIEWED JOURNALS AND UNDER EVALUATION

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<td>Workshop</td>
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<td>MiSPiA Project: Representatives from Israeli Ministry of Defence</td>
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<td>Photonics Europe 2012: &quot;Single-Photon counting and timing for 2D imaging and 3D ranging&quot;</td>
<td>16/04/2012 – 19/04/2012</td>
<td>Innovation Village, Brussels, (Belgium)</td>
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<td>24/04/2012</td>
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### Microelectronic Single-Photon 3D Imaging Arrays
for low-light high-speed Safety and Security Applications

**Final Report - PUBLISHABLE**

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"MiSPIA“ – project no. 257646 - 42 / 46 - PUBLISHABLE
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<td>Proc. SPIE 8631, Quantum Sensing and Nanophotonic Devices X: &quot;Large-area CMOS SPADs with very low dark counting rate&quot;</td>
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<td>All (Europa, America and Asia)</td>
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<td>33</td>
<td>Paper presentation</td>
<td>P1 POLIMI P3 HWU</td>
<td>Proc. SPIE: &quot;Monolithic time-to-digital converter chips for time-correlated single-photon counting and fluorescence lifetime measurements&quot;</td>
<td>02/02/2013 – 07/02/2013</td>
<td>San Francisco (USA)</td>
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<td>500</td>
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<tr>
<td>34</td>
<td>Paper presentation</td>
<td>P1 POLIMI P4 MPD</td>
<td>Photon Counting Applications IV; and Quantum Optics and Quantum Information Transfer and Processing: &quot;Figures of merit for CMOS SPADs and arrays&quot;</td>
<td>15/04/2013</td>
<td>Czech Republic (Prague)</td>
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<td>35</td>
<td>Paper presentation</td>
<td>P1 POLIMI P4 MPD</td>
<td>Advanced Photon Counting Techniques VII: &quot;MiSPiA: microelectronic single-photon 3D imaging arrays for low-light high-speed safety and security applications&quot;</td>
<td>29/04/2013 – 03/05/2013</td>
<td>Baltimore (USA)</td>
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<td>Workshop</td>
<td>P6 EMZA</td>
<td>MiSPiA Military Usages</td>
<td>07/05/2013</td>
<td></td>
<td>Israel</td>
<td>Representatives from Israeli ministry of defence</td>
<td>10</td>
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<td>37</td>
<td>Discussion</td>
<td>P6 EMZA</td>
<td>MiSPiA Usage for Gas and Oil plants</td>
<td>10/09/2013</td>
<td></td>
<td>Israel</td>
<td>Industry</td>
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<td>38</td>
<td>Paper presentation</td>
<td>P1 POLIMI P4 MPD</td>
<td>2013 IEEE Nordic Mediterranean Workshop on Time-to-Digital Converters (NoMe TDC): &quot;CMOS single photon sensor with in-pixel TDC for time-of-flight applications&quot;</td>
<td>03/10/2013</td>
<td>Perugia (Italy)</td>
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<td>39</td>
<td>Discussion</td>
<td>P6 EMZA</td>
<td>MiSPiA Military Usages</td>
<td>10/12/2013</td>
<td></td>
<td>Israel</td>
<td>Industry</td>
<td>10</td>
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</table>
Leaflet

Three different releases of the official MiSPiA project leaflets were released, as shown in Deliverables D.9.3.4, D.9.4.4 and D.9.6.

E-Newsletters

Four different releases of the official MiSPiA project e-newsletters were released, as shown in Deliverables D.9.3.4, D.9.4.4 and D.9.6.

Posters

Two posters were prepared to be shown in workshops, conferences, meeting to both scientific, industrial and laymen audience, as shown in Deliverables D.9.3.4, D.9.4.4 and D.9.6.

Mailing list

The instrument used in order to inform and reach a specific interested community is the MiSPiA mailing list. It was started at the beginning of the project, by identifying some target groups. In the following years, the original mailing list was updated with specific contacts based on the project needs and in order to extend the number and the type of target groups.

The target groups identified and included in the mailing list are:

- Industries and SMEs, in order to increase the dissemination of results, making awareness of the new products and potential exploitation with different users;
- Chambers of Commerce and Ministry, in order to explain the results towards different markets;
- National Contact Points, in order to inform them about the expected novel outcomes and their targeted applications and potential use.
- Scientific Communities (such as European Polytechnics and Universities), in order to disseminate new technology and project results.

Papers and publications

During the duration of the project, technical and scientific dissemination of the project was also guaranteed by means of several peer-reviewed publications in specific journals and printed in international conferences proceedings. In addition to scientific and technical dissemination, in order to target the industries and enterprises, articles in specific industrial journal papers were published.

The complete list of publications in reported in Tables A1a, A1b, and A1c. The complete list of events like conferences, exhibitions and meetings is shown in Table B2.

Technical Data-sheets

Some technical data-sheets of the “hardware” outcomes of the MiSPiA project were produced, in order to advertise the 2D/3D cameras based on the two developed techniques to a broad technical audience. These compact and easy to read instructions are the main way to most directly interact with potential end-users, customers, system integrators, willing to get in touch with the MiSPiA technologies and “play” with real demonstrators. Detailed information can be found in Deliverables D.9.3.4, D.9.4.4 and D.9.6.
Microelectronic Single-Photon 3D Imaging Arrays
for low-light high-speed Safety and Security Applications

Final Report - PUBLISHABLE

Links in websites

The MiSPIA website has been publicized, thanks to the links which has been added in some partners websites. Links to the website has been present in the partner organisation websites. Detailed information can be found in Deliverables D.9.3.4, D.9.4.4 and D.9.6.

Media

MiSPIA website and MiSPIA Facebook page played an important role to reach wider public, as described in the above paragraphs. Other powerful tools used for reaching the wider public were press releases. Detailed information can be found in Deliverables D.9.3.4, D.9.4.4 and D.9.6.

Facebook Page

A MiSPIA Facebook Page was created in order to ensure a wider dissemination of the project concepts and on-going activities by this widespread social network. The page contains some information and pictures about the project and it is linked to MiSPIA website. The Facebook page was periodically updated, through many uploads of various dissemination materials like the new E-newsletters, new brochures and new pictures and photographs. The MiSPIA Facebook Page is shown in following figures.

Fig. 34: MiSPIA project Facebook page, with logo and detailed information.
Fig. 35: MiSPIA project Facebook page, with albums, divided among outcomes, press-releases, performance, technologies developed within the MiSPIA project.