3rd PROJECT PERIODIC REPORT

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1. PUBLISHABLE SUMMARY

1.1 PROJECT CONTEXT

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* (200fps) *short-range* (<50m) *3D ranging* for automotive pre-crash safety systems;
- *wide-spectrum* (300-900nm) *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, ghost imaging, and sub-Rayleigh 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), time-correlated single-photon detection modules and cameras (MPD), safety applications in the automotive field (CRF), security surveillance monitoring (EMZA), and management and dissemination of European projects (CFc). Here are the contact person:

- **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);
- **CRF** - 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. (Italy), 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 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/µm^2), 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 **a 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 even shorter distance range and narrower field-of-view.

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 impaired by a higher noise (dark-count rate) due to the lower lattice quality of 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 processed in the third year, but suffered many delays and manufacturing issues due to malfunctioning equipment. Eventually only preliminary BackSPAD detectors were completed and satisfactory tested, while full SPAD arrays went damaged due to a unwelcome oxidation over the whole wafer surface. Since the issue was neither due to design errors nor to technological limitations, but to fabrication instability of a dry etching tool, the SOI BackSPAD fabrication is postponed beyond the deadline of the project.

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. Anyway, issues met in a fabrication step of the SOI wafer (see Objective 4) impacted on the completion of this Objective 5. In fact, even with major delays during manufacturing, the CMOS wafer with the electronics was successfully completed at the real end of the project. 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. However the unavailability of the SOI wafer did not allow the complete wafer-to-wafer bonding and final assembly of the two halves of the BackSPAD ensemble. Therefore no further test and validation was possible on the whole BackSPAD concept, apart from assessing good performance of individual SOI SPADs (Objective 4) and correct operation of CMOS electronics (Objective 5).

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 preliminary 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), 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 (full-width at half maximum) 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.

1.3 MAIN RESULTS ACHIEVED IN THE THIRD YEAR

In this third year, 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 $40ps_{FWHM}$; 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 $212ps_{rms}$ resolution and 320 ns full-scale range. These chips simultaneously provide single-photon counting 2D images and 3D depth-resolved maps, with of 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, fluorescences, 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 micro (bio)array 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. At the end of the MiSPiA project, all four steps but the fifth one are completed and validated. Due to a temporary (though impairing) malfunctioning of an oxidation tool, during the fabrication of the final SOI SPAD wafer, all wafers get damaged, hence final full-assembly was cancelled. Individual steps (bonding and SLID procedures) are tested and chips (single SOI SPADs, CMOS roic) are available, but no validation of the BackSPAD imager as a whole was possible before MiSPiA end.

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.

1.4 EXPECTED RESULTS AND POTENTIAL IMPACT AND USE

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.

1.5 PROJECT PUBLIC WEBSITE

The MiSPiA **webpage** is www.mispia.eu, with information on results and publications.