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Development and demonstration of cutting-edge technologies for time-domain diffuse optics

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***Abstract*— Several technological advancements are changing the time-domain diffuse optics perspectives, boosting the achievable performances and opening the way to unprecedented applications: extreme throughput detection chains, large collection area sensors and time-gating. These advancements, in particular those achieved at Politecnico di Milano, will be discussed.**

***Keywords*— time-domain diffuse optics, solid-state detector, diffusive media**

I. Introduction

Time-domain diffuse optics (TD-DO) is a technique for non-invasive analysis of diffusive samples (such as biological tissues). It relies on the injection of short pulses of light in the sample and in the collection of the temporal distribution of re-emitted photons (distribution of time-of-flight, DTOF). Such an approach is considered highly informative since it permits (with a single acquisition) to disentangle absorption (μ_a) from reduced scattering coefficients (μ_s') as well as to determine from the re-emission time the average depth probed by photons (if working in the so-called reflectance geometry). Therefore, TD-DO is considered to have the highest informative content, thus its widespread diffusion could possibly revolutionize the field but currently the technological limitations (in terms of dimensions, costs, and achievable performances) are setting a limit. In the last decade, however, a great effort has been made to minimize the dimensions while improving the performances of the main components of the TD-DO systems: laser sources, detectors as well as timing electronics. In this work, technical advancements on the detector side needed to reach the limit of the TD technique (i.e., large collection area detector, extreme throughput, and fast-gating) will be discussed.

II. Large Area Detectors

As enlightened in Ref [1], one of the needed conditions to approach the ultimate limits of the TD-DO technique is a large sensitive area to increase the light harvesting capability of the system, thus enabling the detection of a huge number of late photons. The introduction of Silicon PhotoMultipliers (SiPMs) (active area of about 1 mm^2) sets a milestone for diffuse optics. Indeed, the advantages of solid-state detectors (compactness, ruggedness, insensibility to electromagnetics field, lower biasing voltage) coupled to the relatively large area and the possibility to put the detector in contact with the sample represented a revolution for TD-DO. In this way, indeed, SiPMs improved significantly the light harvesting capability with respect to other solid state detectors. It is worth noting that photocathode-based detectors can exhibit sensitive areas of several square millimeters, but practically they cannot be put in contact with the sample. In this case, optical fibers are needed to drive the light from the collection point to the detector, thus limiting both the collection area and the numerical aperture, causing a loss of more than one order of magnitude of useful signal and demoting the achievable performances.

During recent years, Politecnico di Milano has lead the development of progressively increasing SiPM area, reaching unforeseeable results: from around 9 mm^2 up to slightly less than 1 cm^2 sensitive area. Despite the not-ideal instrument response function, good results in terms of recovery of optical properties of homogenous media were obtained in all cases, thus enabling the exploration of new applications such as, for example, measurements of various locations of human body with very large source-detector distance as well acquisitions on fruits in transmittance geometry [2]–[4].

III. Extreme Throughput

Large area detectors increased of order of magnitude the number of collected photons, but this improvement could have been frustrated if the standard single photon statistics limit (i.e., count-rate set to ~5% of the laser repetition rate) is applied to avoid DTOF distortion (pile-up effect) [5]. For this reason, the possibility to work well beyond the single photon statistics (up to more than 99% of the laser repetition rate) was investigated both in-silico and on phantom [6]. The possibility to both retrieve optical properties of homogeneous media as well as to detect absorption perturbations buried in depth was demonstrated, provided that suitable pile-up correction algorithm is applied in post-processing [7]. The possibility to significantly increase the throughput (much more than one order of magnitude), allows one or to decrease the integration time to have faster measurements keeping the number of collected photons per measurement as constant (e.g., to detect fast dynamics or decrease the duration of a whole scan during optical mammography) or to improve the measurement Signal-to-Noise Ratio (SNR) by increasing the number of acquired photons. For the former case, in Ref [8] we demonstrated the possibility to detect the heartbeat typical pattern in the brachioradialis muscle while performing an arterial occlusion (see Fig. 1) and also in the resting state on the forehead of a volunteer. Moreover, in the same work, approaching the 0.5 billions counts per second (by summing up all the 256 time-to-digital converters) it was

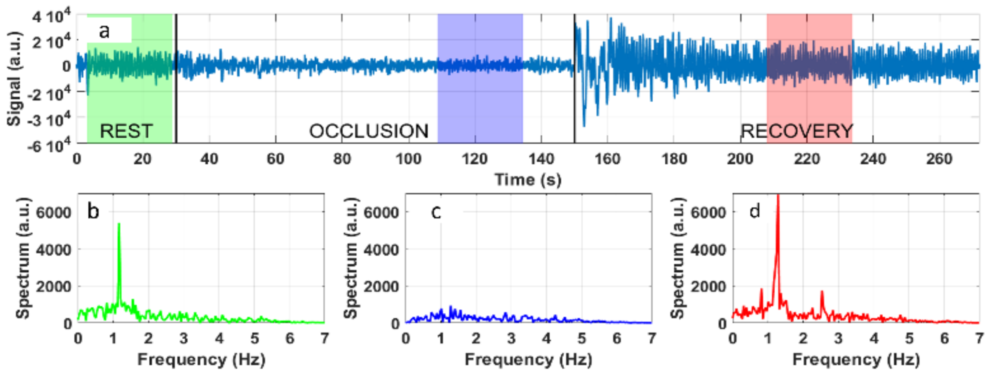

Fig. 1. Arterial occlusion measurement taken from paper [8]. Signal obtained after the band pass filtering the recorded data -a-. For each phase (resting -b-, occlusion -c- and recovery -d-) of the occlusion, the spectral components of the signal were computed with FFT analysis on about 25 s.

possible to image an optical perturbation (introducing an absorption perturbation of about 0.17 cm^{-1} over 1 cm^3 in a homogeneous medium featuring μ_a= 0.1 cm^{-1} and μ_s'= 10 cm^{-1}) down to a depth of 35 mm with short integration time, while, if using standard 1 s acquisitions, the remarkable depth of more than 40 mm could be reached.

IV. FAST GATING CAPABILITY

Another conditions to reach the ultimate limits of the TD-DO technique, is the use of the fast-gating capability (i.e., the possibility to turn on the detector in few hundreds of ps). In this way, it is possible to acquire only portions of the DTOF corresponding to late photons thus bringing information about deep structures [1]. If coupled to short (even null) source-detector distance, once the huge peak of early photons is rejected, this approach ensures an improved visibility of optical perturbations as well as a higher spatial resolution. Till 2020, the fast-gated technique was possible only using small area (100 µm diameter) fiber-coupled single-photon avalanche diodes, thus coming back to the small light harvesting capability described in Sect. II. In 2021, it was introduced in diffuse optics the possibility to fast-gate a SiPM with a large active area (up to 8.6 mm^2) [9]. The light harvesting capability was shown to be 2–5 orders of magnitude higher than that of gated SPADs, thus enabling to obtain a penetration depth of 37.5 mm inside a liquid phantom with realistic optical properties, overcoming the performances achieved by all other fast-gated detectors previously validated for TD-DO applications.

In 2023, with the start of the fastMOT project [10], the fast-gating principle is going to be applied also to superconducting single photon detectors (SSPDs). The project's aim is to build a new multifunctional optical tomograph based on a light sensor with 10,000 pixels (with overall mm diameter, thus going toward large area SSPDs) targeting a 100x improvement of SNR compared to existing light sensors.

V. CONCLUSIONS

TD-DO was always considered as the most demanding in terms of instrument cost and complexity even though it brings the higher information content when using the reflectance geometry. To push the technique to extreme performance (e.g., highest penetration depth), several advancements had to be implemented such as large area (to improve light harvesting capability), high-throughput (not to frustrate the achievable signal and exploit at the best the large sensitive area) and fast-gating capability (to collect only late photons and improve contrast and spatial resolution). In all this research directions, Politecnico di Milano pioneered important advancements opening the way to a new applications (e.g., detection of heart-beat) and scenarios (e.g., wearable devices and home-care monitoring).

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