IPP Seminar

Summaries of the thesis

January 2020

Laboratoire ICube
UMR 7357

23, rue du Loess
67037 STRASBOURG

300, boulevard Sébastien Brant
67412 ILLKIRCH

INSA

24 Boulevard de la Victoire
67084 STRASBOURG

Overview

13:30	14:00	**INTRODUCTION OF SYLVAIN LECLER** **AG IPP / B141**

After in C429, 10 min presentation + 5 min questions

Presentation			
Time		**PhD student,** Title of the thesis**, Director,** *Co-director, Supervisors*	**Page**
14:15	14:30	**Vaibhav NAIN** Study of the thermo-mechanical behavior of large-scale parts manufactured by depositing material in form of powder or metal wire **M. CARIN (LIMATB)**, *T. ENGEL, D. BOISSELIER*	3
14:30	14:45	**Alireza MORSALI** Distributed Acoustic Sensor **P. PFEIFFER**, *S. LECLER, P. PELLETIER*	5
14:45	15:00	**Yuzhou SUN** Nano-multi-facets element applied in the field of photonics **M. FLURY**, *T. ENGEL*	6
15:00	15:15	**Ke ZHANG** Surface optical elements in transmissive and reflective mode: from diffractive structures to metasurfaces **P. GERARD**, *P. TWARDOWSKI*	7
15:15	15:30	**Sébastien MARBACH** Super-Resolved Local Spectroscopy Assisted by Microsphere **M. FLURY**, *P. MONTGOMERY, D. MONTANER*	8
		BREAK 15 min	
15:45	16:00	**Anastisiia SHPIRUK** Mechanical investigations of new generation of ultra-thin polymer hydrogels **C. GAUTHIER (ICS),** *A. RUBIN (ICS), P. MONTGOMERY, F. ANSTOTZ*	10
16:00	16:15	**Agathe MARMIN** Real-time quantitative elastography with digital holography **S. GIOUX**, *S. FACCA, A. NAHAS*	11
16:15	16:30	**Enagnon (Fabrice) AGUENOUNON** Real time processing and visualization in multispectral quantitative optical imaging: Application to surgical guidance. **S. GIOUX**, *W. UHRING*	13
16:30	16:45	**Silvère SEGAUD** Widefield quantitative multispectral imaging in real-time for image-guided surgery **S. GIOUX**	15
16:45	17:00	**Luca BARATELLI** Design and validation of a diffuse optical characterization platform for tissue mimicking phantoms **S. GIOUX,** *M. FLURY*	17

Study of the thermo-mechanical behavior of large-scale parts manufactured by depositing material in form of powder or metal wire

PhD student: Vaibhav NAIN

Director: Muriel CARIN
Advisor: Thierry ENGEL, Didier BOISSELIER
Laboratory and/or enterprise(s) associated: IRDL, ICube, IREPA LASER

Keywords: DED-CLAD®, LMD, ALE, Modeling, Simulation, Heat Source, Additive manufacturing, Material Activation

Summary

The Directed Energy Deposition - Construction Laser Additive and Direct (DED-CLAD®) technique is a free-form metal deposition process, which allows generating near-net shape structures through the interaction of a powder stream and a laser beam. The DED-CLAD® system consists of the laser optics system with a continuous coaxial powder nozzle that brings laser and powder particles which fell in the melt-pool created by laser. The melted powder then solidify to form a deposited clad bead, as the laser advances. The process schematics is shown in Figure 1. This repeated cycle of rapid heating/melting/solidification/cooling process leads to deformation (inaccurate dimensions) and residual stresses in the build part. Therefore, it is essential to develop a Numerical Model that can predict deformation and residual stresses, and then with compensation methods Numerical Model can minimise/avoid deformation and residual stresses in the actual parts.

To develop a Numerical Thermo-Mechanical model, first step is to accurately model temperature field (Thermal Model) in the part. *So, in the present work, three different numerical thermal model for DED-CLAD® are presented named as Quiet/Active, Arbitrary Lagrangian Eulerian (ALE) free surface motion (horizontal) and Arbitrary Lagrangian Eulerian free surface motion (vertical) that allows a detailed study of the temperature evolution in the build part.*

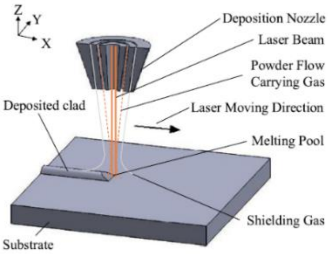


Figure 1: DED-CLAD® Process Scheme depicting material deposition and laser movement

1. *Quiet/Active* Material Addition Numerical Thermal Model

For a given simulation step, the translating laser heat flux is applied on the top surface of the domains representing material currently deposited. As the laser beam advances, an analytical expression accordingly switches thermo-physical properties from gas to the material properties.

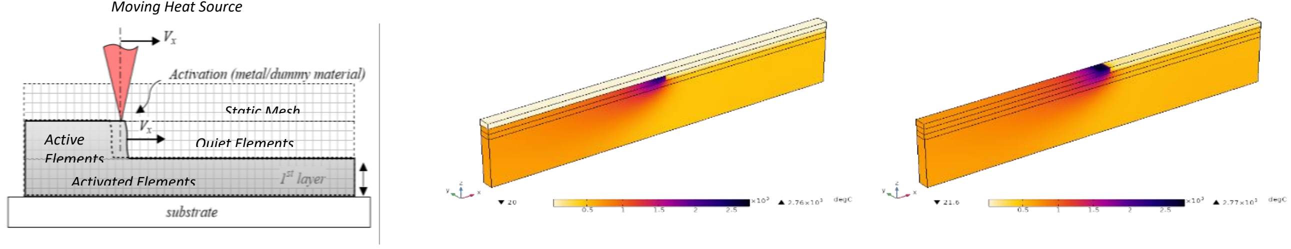


Figure 2: (a) Quiet/Active Method (Idea), (b) Numerical Layer fabrication (Second), (c) Numerical Layer fabrication (Third)

The above simulation is shown only for 3 layers and for a straight laser scan (Start and end position is same for all layers) *i.e.* direction for laser movement is same for layer 1, 2 and 3.

2. *ALE Horizontal* Material Addition Numerical Thermal Model

In this Numerical Model, at each successive time step, the solid domain is stretched towards laser scan direction and is initialised at melting temperature. So, this model does not use any heat source, but this can be altered and a heat source can be used to increase accuracy. Build dimensions and scan strategy is shown in Figure 5

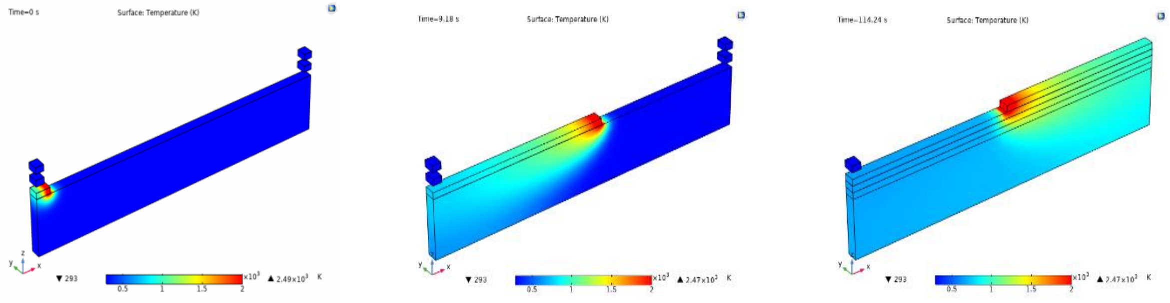


Figure 3: ALE Horizontal (a) Starting of thermal Analysis (b) Numerical Layer fabrication (1st), (c) Numerical Layer fabrication (4th)

3. *ALE Vertical* Material Addition Numerical Thermal Model

At each successive time step, top face of substrate is stretched vertically (magnitude of build height), and simultaneously moves in laser scan direction. After it finishes one layer, layer 1 top face is stretched in laser head direction and simultaneously follows laser scan movement. Build dimensions and scan strategy is shown in Figure 5.

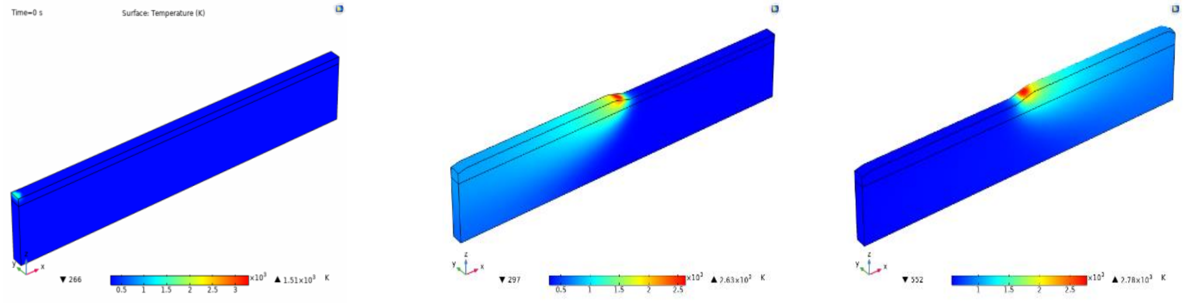


Figure 4: ALE Vertical (a) Starting of thermal Analysis (b) Numerical Layer fabrication (1st), (c) Numerical Layer fabrication (4th)

Model Validation

All 3 Numerical Thermal models have been validated with experiment data available from the literature (Thermocouple: Temperature measurement) and melt-pool dimensions as shown below.

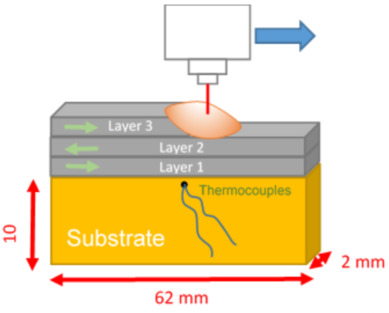
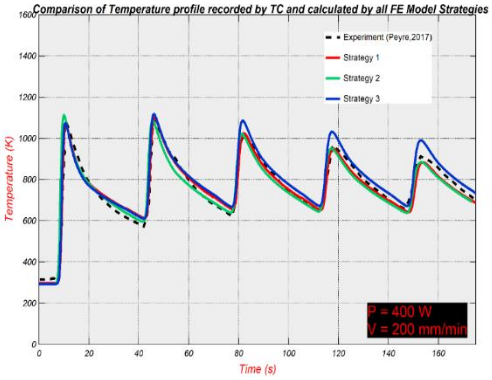
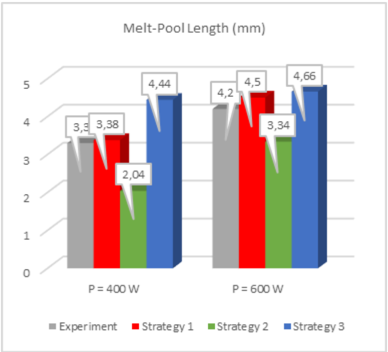


Figure 5: Building Strategy and Build Dimensions





Numerical Model Methodology

The methodology in the above proposed 3 numerical model simplifies the melt-pool fluid and powder dynamics to reduce computational cost and focuses on the thermal fields. The models discretize the continuous physical process of laser metal deposition into a combination of simulation steps, in which, laser travel is considered sequential step-by-step.

Future Work

More experiments are needed with different process parameters and for different material to validate the Numerical Thermal Model. After the validation of Thermal Model, have to start the Development of Mechanical model so that a complete Numerical Thermo-Mechanical.

Distributed Acoustic Sensor

PhD student: Alireza MORSALI

Directors: Pierre PFEIFFER
Co-supervisors: Sylvain LECLER
Laboratory and/or enterprise(s) associated: ICube, IPP, Company: OSMOS Group

Keywords: backscattering, distributed fiber optic sensing, fiber optic reflectometry, fiber optic interferometry

Summary:

In the recent years, fiber optic distributed sensing technologies have been developed very quickly. The systems of fiber optic distributed sensing that are based on advanced photonics technologies have been successfully developed and implemented for temperature and strain measurements in Structural Health Monitoring (SHM) purposes. Their applications in different fields such as power plants, buildings, dams, oil and gas pipelines, submarines' power supply cables, oil, or geothermic wells survey are already demonstrated. Distributed fiber optic sensing techniques replace thousands of classical gages by an optical fiber having a 10-micrometer diameter core. Techniques like optical reflectometry, fiber Bragg gratings, Brillouin, Raman or Rayleigh effects, or a combination of them can be implemented in these systems. One of the most applicable measurements using optical fiber is distributed acoustic sensing. The aim of this doctoral program is to study a new distributed acoustic sensing (DAS) technique that could operate over distance up to 50 km. The principle of the optical fiber sensor would be a combination of optical time domain reflectometry, interferometry, Bragg grating, and an intensity-based sensing method, which is already developed in OSMOS group, partner of this CIFRE PhD work. The two other bottlenecks of the system are the required calibrations for absolute measurements and the coating functionalization in order to enhance the transmission of the external vibrations to the core of optical fiber optimally without diming its protective role.

Nano-multi-facets Element Applied in the Field of Photonics

PhD student: Yuzhou SUN

Directors: Manuel FLURY
Advisor: Thierry ENGEL
Laboratory and/or enterprise(s) associated: ICube

Keywords: faceted structure, angular spectrum method, 3D electromagnetic simulation

Summary:

Laser beam shaping is nowadays an important activity in the field of photonics, because many industrial applications require very good uniformity in illumination with white light or power lasers containing low coherence. Applications where this need is found are for example laser machining, optical metrology or optical photolithography. Of course, there are many different possible solutions such as diffractive optics or complex refractive configurations. However, the performances of these components are very sensitive with the properties of laser beams (wavefront quality, monochromaticity, coherence, etc.). The Photonic Instrumentation and Processes group of the ICube UMR 7357 Laboratory of the University of Strasbourg has a very long experience in the field of laser beam shaping with various concrete realizations. In the literature, diffractive and refractive approaches have shown their limits. But there is a need for sources with poor or undefined coherence, such as white LEDs or power laser sources. We have shown in a previous thesis that it is possible to use a completely different concept based on the inclination of small facets on a surface [1]. Numerous simulations with a photometric approach have shown the possibility to shape light using this principle. A demonstrator was made using the 3D printer technology offered by Luximprint in the Netherlands. This is a completely different approach from the common approach to beam shaping [2,3].

In this thesis, the objective will be to reduce the size of the facets: this will allow to imagine smaller components applied to more general case. We will be able to focus on even more sophisticated beam shaping with sources such as small white diodes.
We will work as follows:
-a state of the art on electromagnetic computing means adapted to the problem (Angular Spectrum Method, Finite element method, Finite Difference Time Domain with Lumerical, etc..),
-Electromagnetic tools adapted to the structure created in the previous PhD defended by Lihong Liu,
-the implementation of suitable algorithms to solve the inverse problem using the previous work,
-the realization of micro-faceted structures,
-the proof of concept on simple laser diodes, white light source or high beam shaping with a dynamic spatial light modulator.

References:

[1] L. Liu, T. Engel, M. Flury, Simulation and Optimization of Faceted Structure for Illumination, Proceeding of SPIE, Vol. 9889, 2016, p. 98891A.
[2] L. Lihong, T. Engel, M. Flury, M. De Visser, Faceted structure: a design for desired illumination and manufacture using 3D Printing, OSA Continuum, 2018, 1(1), p. 26-39.
[3] M. Flury, L. Lihong, T. Engel, M. De Visser, White light beam shaping with optical elements containing facets and manufactured by 3D Printing, EOSAM 2018, Octobre 2018, invited conference, Delft (Pays Bas).

Surface optical elements in transmissive and reflective mode: from diffractive structures to metasurfaces

PhD student: Ke ZHANG

Director: Philippe GERARD
Advisor: Patrice TWARDOWSKI
Laboratory and/or enterprise(s) associated: ICube

Keywords: diffractive optical element, electromagnetic simulation

Summary:

Metamaterials permit to generate new effective optical properties. Based on sub-wavelength structurations and possible local resonances, they permit to control the induced phase shifts. Considering this phase response, a diffractive optical element (DOE) can be considered as an simplified archetype of metasurface asking for a rigorous design. Our research group has specific skills in the use and development of rigorous calculation methods applied to electromagnetism. These methods permit the modeling of micro-optical components taking into account the reflected light, the polarization and the wide-angle propagation. These tools are compatible with the study of DOEs or metamaterials. These methods are named Radiation Spectrum Method (RSM) [1], Finite Difference Time Domain (FDTD) [2-3]. We also use their coupling and work on their parallelization.

In this thesis, we will develop an iterative algorithm for the design of « sandwich » DOEs. We will use the RSM 3D (limited to free space) to propagate the field from the DOE plane to the reconstruction plane. In a so called « sandwich » configuration, we need two DOEs. For example, the first one is illuminated by a forward plane wave whereas the second one is illuminated by a backward plane wave. Of that way, light arriving on the reconstruction plane, located between the two DOEs, is composed of both forward and backward waves. Depending the investigated cases, we will meet either with classical depth profiles for the DOE or profiles involving sub-wavelength periods in the case of metamaterials. For this last case, we will modify the iterative algorithm using the FDTD as a propagator in the thickness of the element. We will investigate the possible use of this « sandwich » configuration. Finally, these elements will be manufactured and characterized.

References:

[1] P. Gérard, P. Benech, D. Khalil, R. Rimet, S. Tedjini, “Towards a full vectorial and modal technique for the analysis of integrated optics structures: the Radiation Spectrum Method (RSM)”, Optics Communications, Vol 140, july 1997, pp 128-145.
[2] V. Raulot, P. Gérard, B. Serio, M. Flury, B. Kress, P. Meyrueis, “Modeling of the angular tolerancing of an effective medium diffractive lens using combined finite difference time domain and radiation spectrum method algorithms”, Optics Express, vol. 18, n°. 17, August 2010, p 17974-17982.
[3] V. Raulot, P. Gérard, B. Serio, M. Flury, P. Meyrueis, “Comparison of the behavior of subwavelength lens in TE and TM polarization allowing some non-standard functions”, Optics Letters, Vol. 36, n°7, april 2011, pp 1194-1196.

Super-Resolved Local Spectroscopy Assisted by Microsphere

PhD student: Sébastien MARBACH

Supervisor: Manuel FLURY – Co-supervisor: Paul MONTGOMERY
Advisor: Denis MONTANER
Laboratory and/or enterprise(s) associated: ICube

Keywords: White Light Interferometry, FF-OCT, Optical Instrumentation, Local Spectroscopy, Super-resolution, Microsphere

Summary:

To describe material physical properties, the topography is often a key information. White light interferometry is a common way to obtain the sample topography, and even the tomography, if the element is transparent. Indeed, according to the acquisition and processing step, it is possible to measure roughness with step height under λ/2 (in reflection) and a few nm accuracies thanks to PSM (Phase shifting microscopy). To overcome the height limitation, CSI (Coherence Scanning Interferometry) has been developed [1,2]. It allows 3D measurement at depth of a few micrometers. WLSI (White Light Scanning Interferometry) is a well appreciated method due to its contactless, and rapidity (full-field imaging) capabilities. However, the structure of new micro and nano materials requires an improvement in lateral resolution to be measured. Another demand is to obtain information on the sample composition locally through optical measurement. That is the reason why the present work is focused on super-resolution and local spectroscopy.

Lateral resolution is limited in optics due to the nature of the light. Indeed, an aberration-free microscope allows the observation of elements whose size are at least half of the used wavelength. To improve it, some new methods have been developed, like fluorescence microscopy (PALM, STORM, 4Pi, …), Structured Illumination Microscopy (SIM), and recently microsphere assisted microscopy.

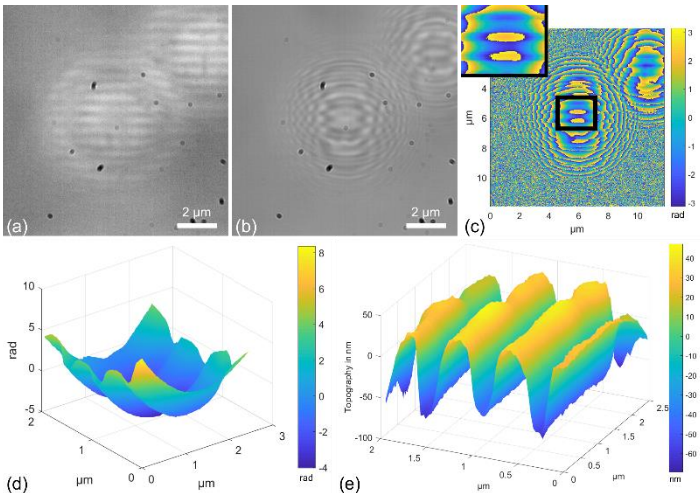


Figure 2: PSM measurement made through a 25-µm diameter microsphere. First the virtual image produced by the microsphere deposit on the sample is focused (a). The optical path difference introduced by the microsphere in the object arm is adjusted by adapting the reference arm (b). Once the fringes appear a classic PSM acquisition allow to acquire the information in 3D (c,d). The curvature introduced by the microsphere is finally removed numerically (e).

The latter compared to the formers, present advantages to be a label-free method, simpler to use, and to provide full-field imaging with a lateral resolution which can reach λ/5. To obtain an information in the 3 dimensions of the space at a nanometric scale, microsphere assisted microscopy can be combined with interferometry. For instance, Wang et al. combine microsphere with CSI measurement [3], whereas Perrin et al. combine microsphere with PSM to measure sub-diffracted-sized element in 3D [4]. An example of PSM measurement made through a 25-µm diameter microsphere with the Leitz-Linnik is illustrated figure 1.

Local spectroscopy method has also been studied. Indeed traditionally, spectrometer, or ellipsometer, are used to obtain spectral information. However, the spectrum obtained is an averaged answer on a surface of some mm². Some other methods, like IR-SNOM, or hyperspectral microscopy has been developed, but they are still expensive, difficult to use, and time consuming. Recently, local spectrum in the visible range in surface [5,6], and even in depth [7] under certain experimental condition, has been obtained with CSI measurement. The acquisition procedure is identical, but the processing is different. Indeed, from the stack of interferometric images, the signal is extracted and treated locally, pixel by pixel. A Fourier transform is then applied on the signal, and the influence from the spectral answer of the setup (determined through a calibration step) is removed. An example of reflectivity measured on 4 different samples: Al,Ag,Ti,Si in surface is illustrated figure 2.

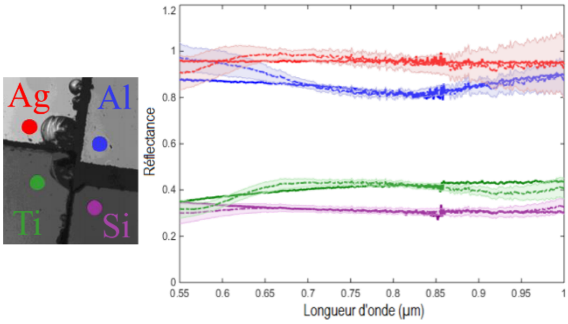


Figure 3: Reflectivity obtained with WLI compared to one obtained with classic spectrometer for Al, Ag, Ti, Si [6].

3D measurement assisted by microsphere and local spectroscopy are based on interferometry. That is the reason why a white light interferometer, with a Köhler Illumination, has been developed (see figure 3). A Linnik configuration was chosen to be able to adapt the optical path difference between the reference and object arm, and so eventually compensate optical path difference introduced by microsphere. Since the local spectroscopic measurement are very sensitive to noise, the setup is currently updated with a high accuracy piezo system, and with a 16-bits sCMOS cooled camera to increase the signal to noise ratio, and so the result of measurement.

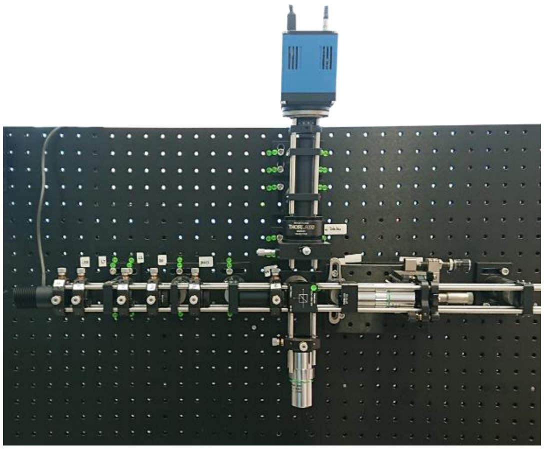


Figure 4: Vertically home-made white light interferometer

References:

[1] P. de Groot, Adv. Opt. Photon. 7, 1 (2015)
[2] P. C. Montgomery, F. Anstotz, J. Montagna, D. Montaner, L. Pramatarova and E. Pecheva, J. Phys.: Conf. Ser. 253, 012017 (2010)
[3] F. Wang, L. Liu, P. Yu, Z. Liu, H.Yu, Y. Wang and W.J. Lu, Sci Rep 6, 24703 (2016)
[4] S. Perrin, A. Leong-Hoï, S. Lecler, P. Pfeiffer, I. Kassamakov, A. Nolvi, E. Hæggström, and P.C. Montgomery, Appl. Opt. 56, 7249-7255 (2017)
[5] A. Dubois, J. Moreau and C. Boccara, Opt. Expr. 16, 17082 (2008)
[6] R. Claveau, P. C. Montgomery and M. Flury, Phys. Stat. Sol. 2017, 1700157 (2017)
[7] R. Claveau, P. C. Montgomery, M. Flury and D. Montaner, Opt. Exp. 25, 20216 (2017)

Mechanical investigations of new generation of ultra-thin polymer hydrogels

PhD student: Anastasiia SHPIRUK

Directors: Christian GAUTHIER
Supervisors: Anne RUBIN
Collaboration with Paul Montgomery, Freddy ANSTOTZ
Laboratory and/or enterprise(s) associated: ICS (MIM Group), ICube

Keywords: microbubble inflation, ultrathin polymer film, interference microscopy.

Summary:

The mechanical behavior of ultrathin polymer films under different environmental conditions is one of the current key questions as it deals with confinement effects. We are interested in investigations of mechanical properties such as strain, stress, creep compliance and yielding of Polystyrene (PS) and Poly(vinyl acetate) (PVAC) polymer films of a few tens of nm thickness near their glass transition temperature.
Experiments are carried out using the microbubble inflation method [1], which consists of inflating a polymer film suspended over an array of 5 µm diameter holes. Interference microscopy is used to measure the change in deformation over several hours (see Fig.1 for example) [2].

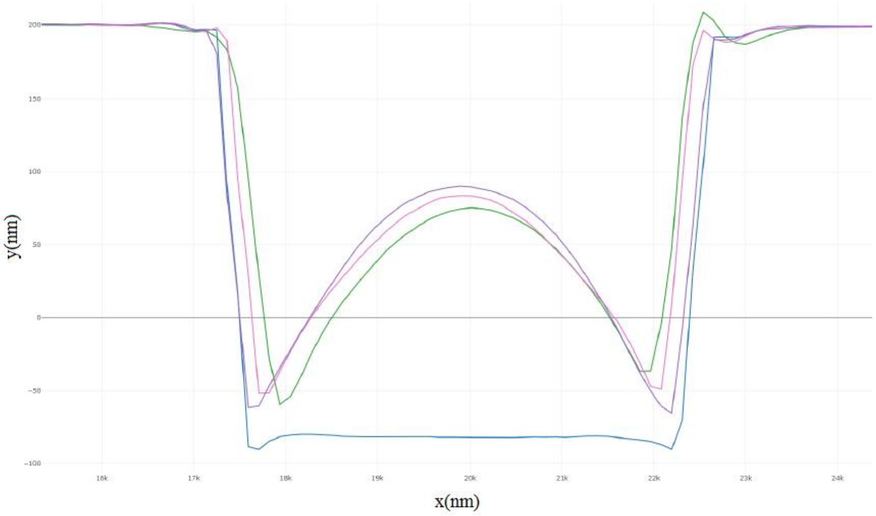


Figure 1. Microbubble inflation in time of 30 nm-thick polystyrene polymer film after blue-0, green-6, pink-68 and violet-133 minutes. Experiment was performed at temperature 65℃ ($T/T_g \approx 0.9$ corresponds to near glass transition region), 50% humidity level and 0.5MPa pressure.

The main goals of thesis are investigation of yielding effect and the influence of different humidity level on the mechanical behaviour of such ultra-films.

References:

[1] P.A. O'Connell, S.A. Hutcheson, G.B.McKenna, J. of Polymer Science, Vol.46, 1952-1965 (2008).
[2] P. Chapuis, P.C. Montgomery, F. Anstotz, A. Leong-Hoï, C.Gauthier, J. Baschnagel, G. Reiter, G.B. McKenna, A. Rubin, Rev. of Sci. Inst., 88, 093901 (2017).

Real-time quantitative elastography with digital holography

PhD student: Agathe MARMIN

Directors: Sylvain GIOUX, Sybille FACCA
Advisor: Amir NAHAS
Laboratory and/or enterprise(s) associated: ICube

Keywords: elastography, digital holography

Summary:

Over the last decades, a large number of methods have been developed to combine quantitative elastography with biomedical imaging modalities [1-3]. Tissue stiffness has been used since the very beginning of medicine to diagnose pathologies through palpation because cells and tissues are characterized by their intrinsic mechanical properties. Indeed, mechanical properties of cells are related to their structures and function, and change of those properties can reflect certain pathology, notably fibrosis or tumors. Adding this contrast to biomedical imaging is a powerful aide to diagnostics.

We present here our latest result combining off-axis digital holography with quantitative shear wave elastography. The experimental setup used in this study is an off-axis digital holography setup illuminated with a solid state laser at 671nm (Figure 1). The resolution is 50µm over a 11x11mm field of view. The typical acquisition frame rate is 500Hz with 1440x1440 pixels and is increased up to 25kHz using a stroboscopic approach. The high sensitivity of digital holography is utilized to image low magnitude (< 1 µm) mechanical waves generated in biological tissue by either natural pulsatility or by external noise.

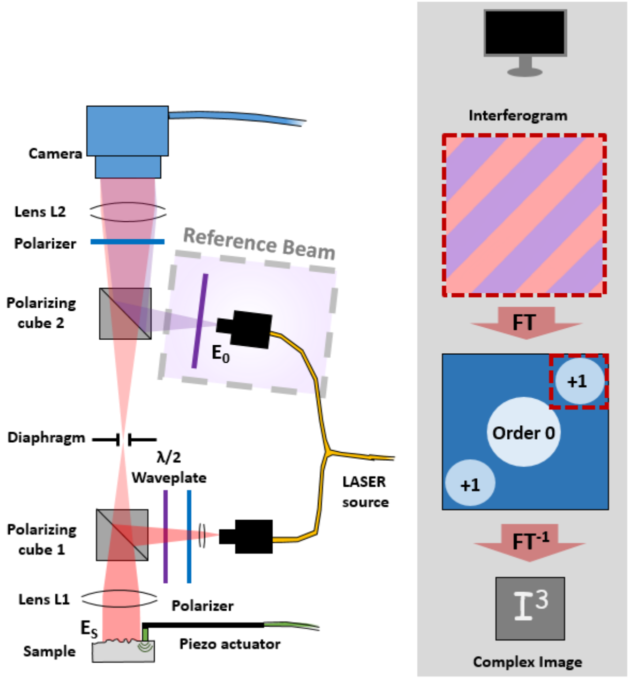


Figure 1: Schematic of the digital holography setup and the image retrieval process.
The object beam (in red) is back-scattered by the sample before interfering with the reference beam (in purple). The resulting interferogram is then numerically processed with two 2D Fourier Transforms (FT) to extract the complex image holding phase and amplitude information (f_{L1} = 100 mm, f_{L2} = 150 mm).

The shear wave elastography method used in this study is based on the direct link, between the local shear wave speed (c) and the local stiffness given by the Young modulus (E). In incompressible medium of mass density ρ, such as biological tissues, it is expressed as:

$$c = \sqrt{\frac{E}{3\rho}}\,. \qquad (1)$$

Two quantitative elastography approaches are presented. The first one is classical shear wave elastography. This method consists in imaging shear wave propagation in the medium to directly assess local shear-wave speed. Classical transient elastography requires a controlled and synchronized source of mechanical waves, which can by limiting for less reachable tissue or during a surgery.

The second method tackles this limitation using noise-correlation-based elastography. This approach allows full-field quantitative elastography using a diffuse shear wave field of mean frequency f_0. The local stiffness is calculated by refocusing the diffuse shear wave field at each pixel using noise correlation algorithms to access the shear wave wavelength [4], At a time $t_0=0$ and location r_0, the wavelength can be indeed calculated from the time-reversed displacement field ψ_z^{TR} and its derivative, the time-reversed strain field ξz^{TR} as followed:

$$\lambda(\vec{r_0}) \approx 2\pi\sqrt{-\frac{\psi_z^{\mathrm{TR}}(\vec{r_0},0)}{\xi_z^{\mathrm{TR}}(\vec{r_0},0)}} \qquad (2)$$

The mean mechanical wavelength is directly related to the shear-wave speed:

$$c(\vec{r_0}) = \lambda(\vec{r_0}) \times f_0 \qquad (3)$$

The local stiffness can then be retrieved using equation 1.

Results are presented on agarose samples with homogeneous optical properties and controlled mechanical heterogeneous properties that mimic biological tissues. Figure 2 and Figure 3 represents respectively the results of classical transient elastography and noise-correlation elastography.

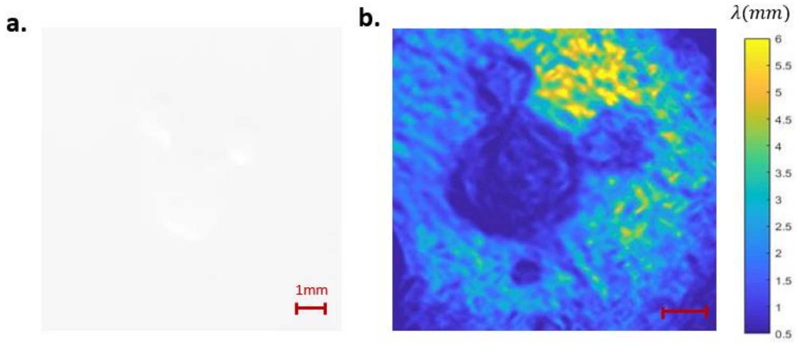


Figure 2a. Image of the surface of a 2% mass concentration agarose sample with a 1% agarose inclusion.
b. Wavelength map retrieved using classical transient elastography.

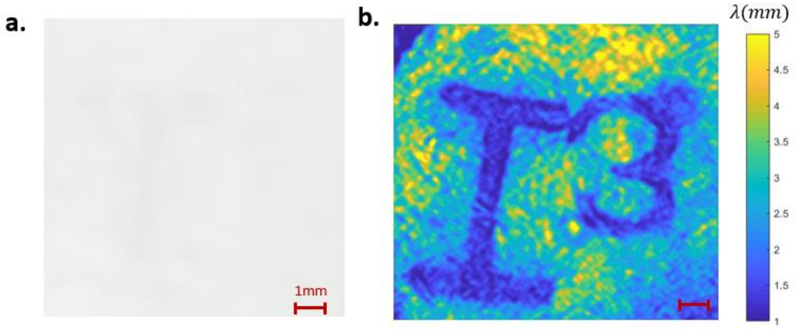


Figure 3a. Image of the surface of a 2% mass concentration agarose sample with a 1% agarose inclusion.
b. Wavelength map retrieved using noise correlation elastography.

Références :

[1] MARIAPPAN, Y. K., GLASER, K. J., et EHMAN, R. L., Magnetic resonance elastography: a review. Clinical anatomy, 2010, vol. 23, no 5, p. 497-511.
[2] TANTER, M., BERCOFF, J., ATHANASIOU, A., et al., Quantitative assessment of breast lesion viscoelasticity: initial clinical results using supersonic shear imaging. Ultrasound in medicine & biology, 2008, vol. 34, no 9, p. 1373-1386.
[3] KENNEDY, B. F., WIJESINGHE, P., et SAMPSON, D. D., The emergence of optical elastography in biomedicine. Nature Photonics, 2017, vol. 11, no 4, p. 215.
[4] CATHELINE, S., SOUCHON, R., RUPIN, M. and al., Tomography from diffuse waves: Passive shear wave imaging using low frame rate scanners. Applied Physics Letters, 2013, vol. 103, no 1, p.014101.

Real time processing and visualization in multispectral quantitative optical imaging: Application to surgical guidance

PhD student: Enagnon Ulysse Fabrice AGUENOUNON

Directors: Sylvain GIOUX,
Co-supervisor : Wilfried UHRING
Advisor: Foudil DADOUCHE
Laboratory and/or enterprise(s) associated: ICube

Keywords: Diffuse optical imaging, Spatial frequency domain imaging, Hyperspectral imaging, Image-guided surgery, Real-time system, GPGPU.

Summary:

Optical imaging methods capable of providing real-time information related to functional and structural conditions of living tissues are becoming increasingly popular. Such parameters can be used by healthcare professionals to assist decision-making during surgery or for patient monitoring. In this work we present a novel GPU processing method, direct programming in C CUDA (Compute Unified Device Architecture), applied to Spatial Frequency Domain Imaging for real-time (SFDI), wide-field, surface profile intensity corrected and quantitative multispectral imaging of tissue properties. Using this novel technology, we are able to obtain functional parameters in living tissue and visualize them at 25 frames per seconds.

The physiological parameters of a biological tissue can be extracted by measuring its optical properties at multiple wavelengths through the exploitation of the Beer-Lambert's law for the absorption maps. In addition, under a power law approximation, the scattering properties can be correlated to the structural information of the tissue. For this purpose, patterns of light are projected onto the tissue (as with any SFDI acquisition system), and the acquired images are processed in the spatial frequency domain to quantify the optical properties of the measured tissue using the Single Snapshot of Optical Properties (SSOP) technique. Multiple wavelengths can be acquired either with a sequential approach or with a spatio-temporal modulation method. As shown in Fig. 1, a typical multispectral system is composed of several modulated laser sources, a projection system and a high-speed camera. Until recently, most of the implementations were not real-time and did not take into account the correction of the diffuse reflectance according to the 3D profile of the sample because of the processing time involved.

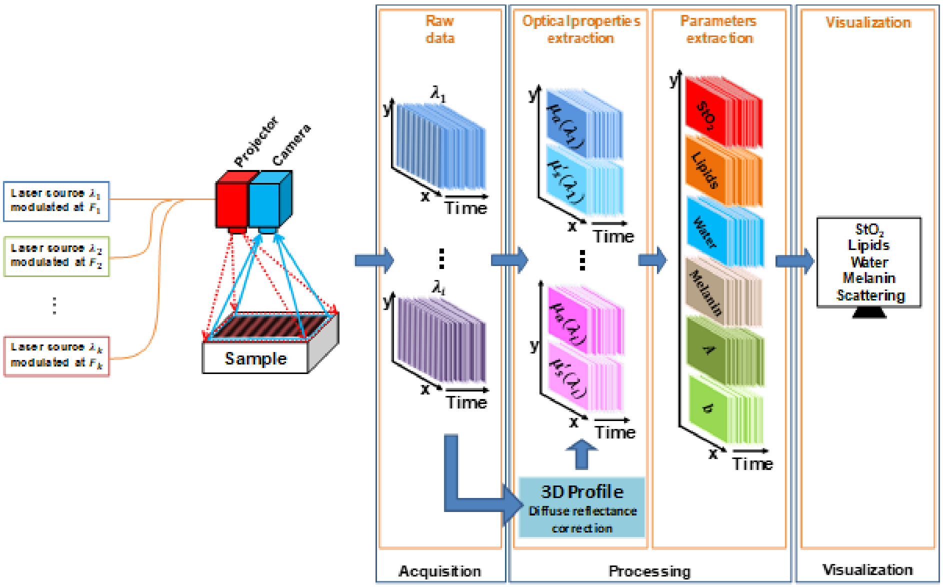


Figure 1: Schematics of the multispectral SSOP imaging system associated with processing workflow and visualization.

With new technologies such as GPUs, we have recently demonstrated that it is possible to extract the optical properties of a tissue in a very short time (1.6 ms) giving the opportunity to add a 3D profile correction to increase measurement accuracy and real-time visualization (25 frames/second).

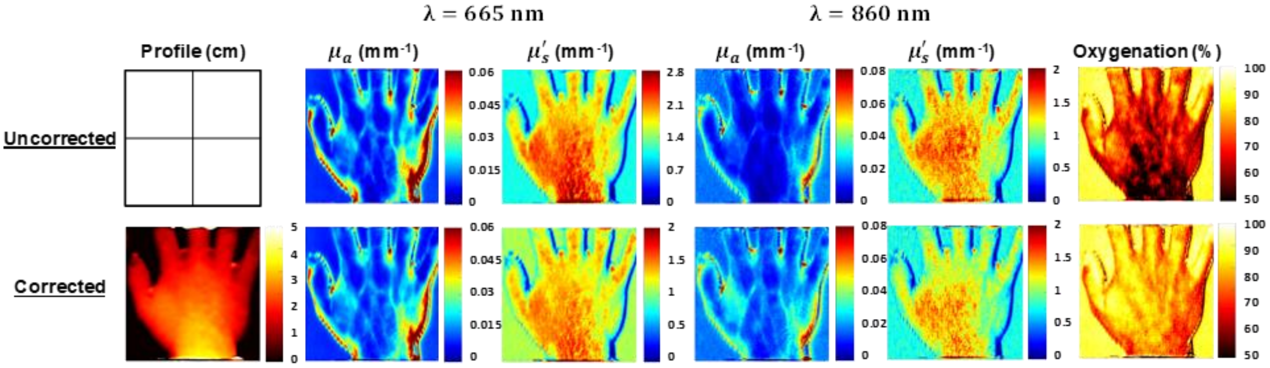


Figure 2: Results obtained with and without surface profile intensity correction. Profile, absorption and reduced scattering maps recovered at 665 nm and 860 nm and saturated oxygenation level.

To evaluate the performance of the implementations, we measured a hand as an in vivo complex sample positioned on a tissue-simulating phantom with known optical properties. Image was acquired at 0.3 mm^{-1} spatial frequency at two wavelengths 665 nm and 860 nm. Processing was performed on the acquired images in their native format (1024 x 1024). We then compared the resulting absorption, reduced scattering and oxygenation images obtained with and without profile intensity correction. The results shown in Figure 2 allow us to visually assess the improvement in homogeneity when the profile is taken into account. The analysis of processing times for the GPU reveals that our implementation to extract the profile takes 0.41 ms. When the profile is used, the whole process takes 2.11 ms against 1.6 ms (i.e. without profile correction). With this processing time we can guarantee a real-time visualization of 25 frames/second.

We demonstrated that we are able to extract optical properties maps of absorption and reduced scattering for two wavelengths 665 nm and 860 nm, as well as saturated oxygenation level with 3D profile correction onto a 1 megapixel image in 2.11 milliseconds processing time with GPU implementation directly written in C CUDA. This work shows the strong potential of using GPUs in cooperation with SSOP to enable multi-spectral, quantitative and wide-field visualization in real-time during surgical procedures. In this sense, our future work will be devoted to the extrapolation of four additional parameters such as lipids, water, melanin and the scattering parameters.

References:

[1] Gioux, Mazhar, Cuccia. Spatial Frequency Domain Imaging in 2019. J Biomed Opt, 2019. 24(7): 07613.
[2] M. Schmidt, E. Aguénounon, A. Nahas, M. Torregrossa, B. J. Tromberg, W. Uhring, and S. Gioux, "Real-time, wide-field, and quantitative oxygenation imaging using spatiotemporal modulation of light," J Biomed Opt 24(2019).
[3] Enagnon Aguénounon, Foudil Dadouche, Wilfried Uhring, and Sylvain Gioux, "Real-time optical properties and oxygenation imaging using custom parallel processing in the spatial frequency domain," Biomed. Opt. Express 10, 3916-3928 (2019)
[4] Gioux, Sylvain et al. “Three-dimensional surface profile intensity correction for spatially modulated imaging.” Journal of biomedical optics vol. 14,3 (2009): 034045. doi:10.1117/1.3156840
[5] M. van de Giessen, J. P. Angelo, and S. Gioux, "Real-time, profile-corrected single snapshot imaging of optical properties," Biomed Opt Express 6, 4051-4062 (2015).

Widefield quantitative multispectral imaging in real-time for image-guided surgery

PhD student: Silvère SÉGAUD

Directors: Sylvain GIOUX
Laboratory and/or enterprise(s) associated: ICube

Keywords: Image-Guided Surgery; Clinical Biophotonics; Spatial Frequency Domain Imaging; Diffuse Optical Spectroscopy

Summary:

As surgical workflows are improved by new technologies, surgeons still have to rely mostly on their perception and experience to distinguish healthy from diseased tissues. In the context of oncologic surgery, this tissue viability assessment is of utmost importance, both for tumor resection or reconstructive surgery. From the lack of objective input to the surgeon, many procedures are still performed subjectively at the cost of increased failure rates and healthcare costs. Using near-infrared (NIR) imaging, tissues can be safely probed in depth and without contact. In particular, fluorescence imaging and oxygenation imaging are well suited to provide respectively structural and functional information.

My work aims at the development of a novel clinically-compatible imaging platform capable of performing widefield quantitative oxygenation and fluorescence imaging as part of the surgical workflow. This 3-channel optical setup provides co-registered images from different spectral bands. Thus, the surgeon is provided with a color channel for anatomical imaging, plus two channels at 700nm and 800nm for fluorescence imaging. Two different dyes can be used to perform structural imaging such as angiography. Long working distance (typically 45cm) and bright filtered white light illumination of the surgical field ensure easy integration into the surgical environment. The platform is equipped with a custom laser diode-based source for selectable illumination wavelengths and matching optical filters sets depending on the fluorophores of interest. The two NIR channels are also used to optically characterize the tissues and perform functional imaging using Spatial Frequency Domain Imaging (SFDI). A fast implementation of SFDI – namely Single Snapshot of Optical Properties (SSOP) – is used to quantitatively measure in real-time the optical properties (absorption and scattering) over a large field of view (>10x10cm²) [1]. For that purpose, the platform includes a custom computer unit for data stream management and high-performance data processing. Concentrations of oxy- and deoxy-hemoglobin are extracted, yielding the tissue oxygen saturation map. Tissue viability assessment is therefore enhanced as oximetry is a standard vital indicator. Moreover, arterial and venous contributions to the oxygen saturation can be separated, as a supplementary input to the surgeon [2].

Examples of fluorescence imaging and oxygenation imaging are shown respectively in Figure 1 and Figure 2. These experiments were performed at the Institut Hospitalo-Universitaire de chirurgie guidée par l'image (IHU) in Strasbourg. *In-vivo* experiments on pigs were perfomed in collaboration with Michele Diana, MD, PhD, from IHU.

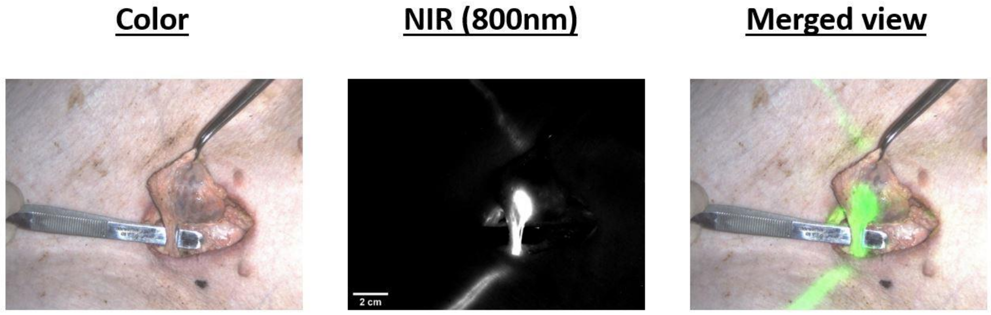

Color
NIR (800nm)
Merged view

Figure 1 – *in-vivo* fluorescence-guided sentinel lymph node resection on pig model. The images from the visible (left) and NIR (middle) channels are merged to produce an augmented reality view the surgeon can use during the procedure.

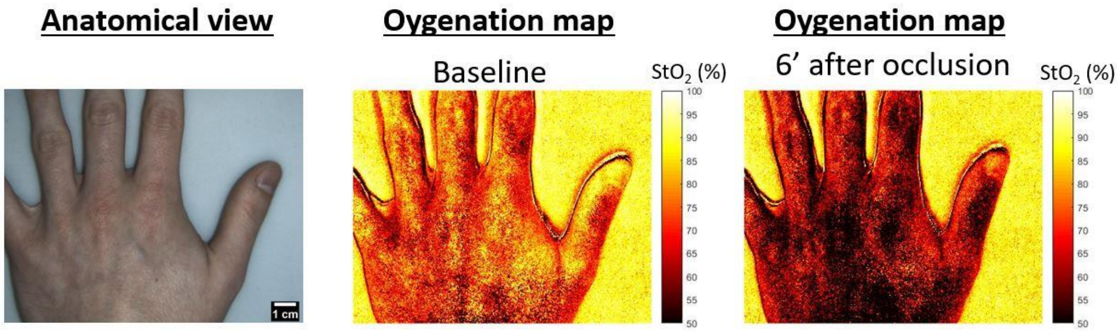


Figure 2 – Oxygenation saturation imaging during armcuff occlusion. Oxygen saturation maps before occlusion (middle) and after six minutes of occlusion (right) are compared. The co-registered color channel (left) can be used for anatomical imaging.

In addition, this setup is capable of performing quantitative fluorescence imaging. As tissues are characterized at the wavelength of excitation and a wavelength close to the maximum of the fluorophore's emission, an algorithm can be applied to the raw fluorescence image to correct in real-time for the distortion effects due to the optical properties of the tissues [3]. Indeed, the direct viewing of fluorescence images can be misleading as the concentration of fluorophore is not the only factor impacting the strength of the measured signal. Using a calibration performed onto tissue mimicking phantoms along with a dedicated SSOP acquisition scheme, the fluorophore concentration map can be extracted in real-time. Currently, my work focuses on the implementation of quantitative fluorescence imaging. Demonstration of the method is planned ex-vivo on mice models during tumor resection procedures, in collaboration with Alexander Vahrmeijer, MD, PhD, from the Leiden University Medical Center (LUMC).

In conclusion, the main goal of my project is to develop a clinically-compatible imaging platform capable of performing widefield quantitative oxygenation and fluorescence imaging and demonstrate its impact on the assessment of tissue viability. The quantitative aspect of the imaging ensures reproducibility across specimens and experimenters, opening the path to consensus-finding about the use of optical imaging to guide surgical procedures. Overall, improved success rates and reduced healthcare costs are expected, for a great benefit for value-based care.

References:

[1] Vervandier J., Gioux S., Single snapshot imaging of optical properties, Biomed. Opt. Exp., 4(12):2938-44, 2013.
[2] Gioux S. et al, First-in-human pilot study of a spatial frequency domain oxygenation imaging system, J. Biomed. Opt., 26: 086015: 1-10, 2011.
[3] Valdes P.A., Angelo J.P. et al, qF-SSOP: real-time optical property corrected fluorescence imaging, Biomed. Opt. Exp., 8(8): 3597-605, 2017.

Design and validation of a diffuse optical characterization platform for tissue mimicking phantoms

PhD student: BARATELLI Luca

Director: GIOUX Sylvain
Co-Supervisor: FLURY Manuel
Laboratory and/or enterprise(s) associated: ICube

Keywords: Diffuse optical imaging ; supercontinuum ; wide field ; multispectral ; spatial frequency domain ; time resolved

Summary:

The performance assessment of diffuse optical imaging systems often requires a benchtop analysis of the instrumentation capabilities. For this purpose, it is common practice to adopt artificial phantoms replicating tissues optical properties (i.e. absorption and reduced scattering coefficients) over a broad spectral range. As a consequence, the first stage in the validation workflow is represented by the optical characterization of such samples.

In this context, we implemented and validated a platform consisting of a benchtop time-resolved diffuse optical spectroscopic system, together with a second set-up based on spatial frequency domain imaging (SFDI) [1]. Both systems share the same source side design, employing a pulsed (< 10 ps) supercontinuum laser source (SuperK Extreme, NKT Photonics®) fiber coupled into a tunable single line filter (SuperK VARIA, NKT Photonics®) necessary for the broadband investigation of the samples over the 550-840 nm spectral range. At the output of this device, a system of ND filters is used to tune the power of the optical signal to be provided to the sample and finally the delivery of the optical pulses is obtained through fiber propagation. At this point, the optical path for the time-resolved system is ended by point-like illumination of the sample, whereas conversely for the SFDI system a Digital Micro-mirror Device (DMD) based projecting system is employed for the generation of wide-field (> 10x10 cm) spatially modulated patterns of light at various spatial frequencies and phases.

The detection chain of the TR system consists of an optical fiber coupled into a SPAD for the point-wise harvesting of the diffused light. In addition, a Time-to-Digital Converter (TDC) is used for the acquisition of the time-resolved reflectance (or transmittance) curves exploiting a standard Time-Correlated Single Photon Counting (TCSPC) technique. In the second case, the SFDI images are collected with a high dynamic range (16 bits) and high frame rate sCMOS camera (pco.edge 5.5); moreover, a pair of polarizers arranged in a crossed configuration are use on the projection and acquisition sides to remove the specular component of the backscattered reflectance signal arising from the sample. Finally, for both systems the computation of the optical properties of the investigated phantom, i.e. the absorption and reduced scattering coefficient, is obtained via a look-up table based algorithm. However, for the TR curves, a least square fitting routine (based on Levenberg-Marquardt algorithm) is also employed to fit the experimental data with Monte Carlo simulated theoretical curves.

To validate the systems capabilities, a collaboration with the Department of Physics of Politecnico di Milano has been carried out. In particular, the MEDPHOT [2] protocol has been exploited together with the nEUROPt [3] protocol, in order to characterize both systems performances. Finally, a future development on the instrumentation will allow us to extend the spectral range up to 1000 nm with respect to the current 840 nm limit, in order to investigate absorption properties of physiological compounds such as water and lipids.

References

[1] D. J. Cuccia et al., "Quantitation and mapping of tissue optical properties using modulated imaging," J. Biomed. Opt. 14(2) 024012 (1 March 2009)

[2] A. Pifferi et al., "Performance assessment of photon migration instruments: the Medphot protocol," in Biomedical Topical Meeting, OSA Technical Digest (Optical Society of America, 2004).

[3] H. Wabnitz et al., "Performance assessment of time-domain optical brain imagers, part 2: nEUROPt protocol," J. Biomed. Opt. 19(8) 086012 (14 August 2014)