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Which wavelength is the best for arterial pulse waveform extraction using laser speckle imaging?

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ABSTRACT

A multi-wavelengths analysis for pulse waveform extraction using laser speckle is conducted. The proposed system consists of three coherent light sources (532 nm, 635 nm, 850 nm). A bench-test composed of a moving skin-like phantom (silicone membrane) is used to compare the results obtained from different wavelengths. The system is able to identify a skin-like phantom vibration frequency, within physiological values, with a minimum error of 0.5 mHz for the 635 nm and 850 nm wavelengths and a minimum error of 1.3 mHz for the 532 nm light wavelength using a FFT-based algorithm. The phantom velocity profile is estimated with an error ranging from 27% to 9% using a bidimensional correlation coefficient-based algorithm. An *in vivo* trial is also conducted, using the 532 nm and 635 nm laser sources. The 850 nm light source has not been able to extract the pulse waveform. The heart rate is identified with a minimum error of 0.48 beats per minute for the 532 nm light source and a minimal error of 1.15 beats per minute for the 635 nm light source. Our work reveals that a laser speckle-based system with a 532 nm wavelength is able to give arterial pulse waveform with better results than those given with a 635 nm laser.

1. Introduction

Laser speckle (LS) is an effect that results from an interference phenomenon and can be characterized as a random pattern of light intensities. Speckle patterns are created when coherent light is reflected by a surface with a rough structure, thus producing random phase variations at different surface locations [1]. The interference between different beams produces a granular pattern of intensities [2]. Historically, this has been considered to be a drawback when using coherent light sources because of the limiting effect on the spatial resolution. To overcome this problem many techniques have been developed [3–5].

Beyond the limitations imposed by speckle, many useful applications of this interferometric effect have been proposed. LS-based techniques are successfully used to estimate two-dimensional blood flow [6,7], to investigate skin vibration [8,9], to measure water flow in plants [10], to assess vibrations modes of remote objects [11], to measure large-object deformations [12] and surfaces movement identification [13]. By using LS pattern analysis, it is also possible to extract information about the target roughness and displacement.

In addition to the possibility of characterizing different materials using LS, the variations of speckle patterns over time (time-varying speckle) can be used to estimate the movement of a specific target [14]. The space-time statistical properties of dynamic speckle patterns depend on the velocity of the target. If the target is static, the speckle pattern does not change in consecutive images [15]. However, if the target is moving, the speckle pattern changes over time and the resulting images can grant information on the original kinetics of the reflecting media [16].

One of the major features of this laser vibrometry technique arises from its truly non-contact nature. This is an unquestionable advantage when compared to other motion assessment techniques that require contact, particularly when the targets are sensitive to mass variations or external pressure [2]. Such is the case of biological systems, like arteries or skin, where the vibration profile can be affected by the forces exerted during the measurement procedure [17].

The aim of the present work is to analyze which wavelength would be the most adequate to extract the arterial pulse waveform using the laser speckle effect. For this purpose, the paper presents

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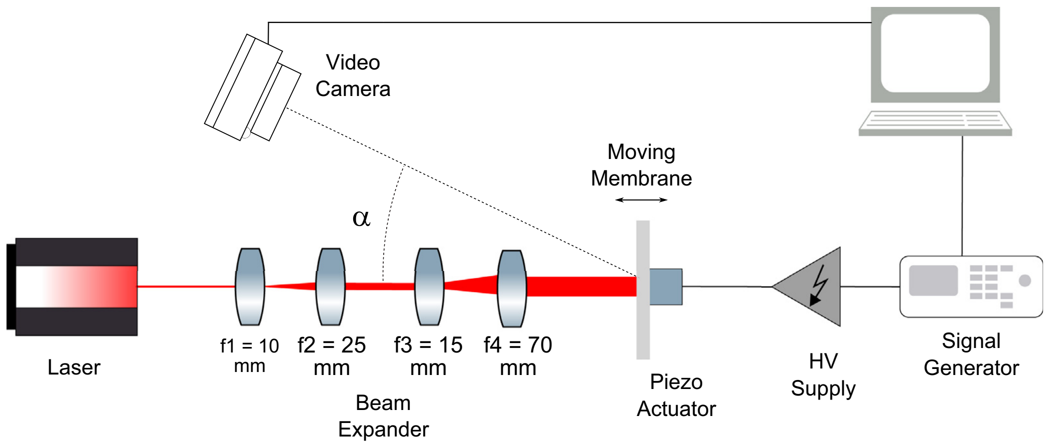

Fig. 1. Optical scheme of the bench-test set up. The angle represented by α is approximately 29°. HV stands for high voltage. Focal distances are expressed in millimeters. Image not to scale.

an apparatus along with a group of methodologies that can be used to evaluate vibration of skin-like phantoms using 3 different optical wavelengths (532 nm, 635 nm, and 850 nm). LS techniques are now widely used to monitor microvascular blood flow [18]. The detection, with a single system, of information from the macro and the microvascular levels would be of great interest.

The methodology used (correlation coefficient) represents a more efficient computational method, compared to the one used by several authors (cross-correlation) [19–21]. The cross-correlation approach involves, in addition to the shifting of two images along all the possible positions, the identification of the maximum correlation peak. The proposed approach applies a one-dimensional correlation coefficient between two consecutive images. This type of approach was used by Nemati et al. [22,23] but using a different measurement site.

2. Methods

2.1. Experimental set-up

Speckle patterns were produced by using three distinct lasers: a green laser diode (L_{532}), CPS532 from Thorlabs, with a wavelength of 532 nm, with an optical power of 4.5 mW, with an output circular beam diameter of 3.5 mm, and with a spectral-width of 0.5 nm; a red laser diode (L_{635}) (VHK Coherent Inc.) with a wavelength of 635 nm, with an optical power of 4.9 mW, with an output circular beam diameter of 1.1 mm, and a spectral-width of 0.5 nm; and a near infra-red laser diode (L_{850}), LDL 175G from Global Lasers, with a wavelength of 850 nm, with an optical power of 3 mW, an output focusable elliptical beam diameter of 4×2 mm, and a spectral-width of 0.5 nm.

Fig. 1 depicts the optical components layout. The laser beam was firstly expanded using a tailored beam expander composed of 4 convergent lenses. The total magnification of the beam expander is equal to 11.67. This magnification produces a laser output beam with the optical characteristics described in Table 1.

Table 1
Laser optical characteristics after beam expansion.

	L_{532}	L_{635}	L_{850}
Expanded diameter (mm)	40.9	12.8	46.6 × 23.3
Illumination (mm^2)	1313.8	128.7	852.8
Optical power (mW)	4.5	4.9	3.0
Irradiance (W/m^2)	3.4	38.1	3.5

The three irradiances are under the maximum permissible exposure (MPE) in skin for large exposure times (10 s to 30 ks) which are 2000 W/m^2 for the L_{635} and L_{532} and 3990 W/m^2 for the L_{850} [24]. All the experiments have been conducted with the respective eye protection for class 3R (L_{635} and L_{532}) and class 3B (L_{850}) lasers.

A layered target composed of several white translucent silicone membranes has been used with the purpose of studying the behavior of speckle patterns when a diffuse surface is moving. The target has been constructed by using 4 overlapped membranes with an approximated total thickness of 2 mm. The target size was 30 mm × 60 mm (W × H). This target was connected to a piezoelectric actuator (PZA) (Physik Instrumente GmbH P-287), driven by a high voltage source (HVS) (Physik Instrumente GmbH, E-580) that is fed with a voltage signal generator (VSG) (Agilent 33220A). The displacement of the actuator and thus the membrane displacement are given by Eq. (1) [13] (Fig. 1):

$$D = \frac{7000}{75} \times V \quad (\mu\text{m}), \tag{1}$$

where D is the displacement in μm and V is the electric potential in Volts applied by the signal generator to the high voltage amplifier. The laser was aligned to the target center to ensure that all the light interacts with the membrane.

A monochrome digital video camera (VC) (PixeLink – B741U) connected to a C-mount lens (Edmund 67715) has been used to record the speckle patterns. This model is widely used in laser speckle applications [25,21]. The maximum camera resolution was used to perform all the bench acquisitions (1280 × 1024 pixels) with an exposure time of 15 ms and a frame rate of 15 frames per second (fps) which was the maximum frame rate admissible by the VC with these parameters. The VC gain was fixed (0 dB) during the experiment in order to maintain a constant level of noise.

The speckle size was controlled by the lens aperture (f-number). Higher f-number corresponds to larger speckles [26] which means that this parameter requires a fine tuning in order to maintain enough light collection and a speckle size greater than or equal to the size of the VC pixels. In our experiment, the minimum speckle size was approximately 4 pixels/speckle. This speckle size ensures a correct spatial sampling because it meets the Nyquist limit for both (x and y) spatial dimensions. Since the spatial resolution is not a key factor in this experiment, the reduction of the spatial resolution that comes from the use of a large speckle size is not an issue.

Data acquisition has been performed using a software interface developed in Python 2.7 (32 bits) with the functions provided by the opencv library, version 2.4.7 [27]. Processing algorithm have