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Uncertainty contribution of the laser-beam orientation for laser Doppler vibrometer measurements at the carotid artery

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Uncertainty contribution of the laser-beam orientation for laser Doppler vibrometer measurements at the carotid artery

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Abstract. Displacement signals acquired at the carotid artery with laser Doppler vibrometry (LDV) present a characteristic waveform that is correlated to the blood pressure inside the vessel. There are different models in literature that relate the displacement amplitude to the pressure. Therefore, a wrong estimation of the displacement amplitude would lead to errors on the extraction of the pressure information. LDV measures the vibration component in the direction of the laser beam. If the laser beam is not parallel to the vibration direction of the target, only a projection of the real vibration amplitude is measured. With a 3D-LDV measurement it is possible to measure the real amplitude of the displacement. For 1D-LDV measurements it is necessary to calculate the contribution of the uncertainty of the laser beam orientation to the displacement. In this paper, we investigate the uncertainty contribution due to the laser beam direction on the displacement amplitude of vibration signals acquired at the carotid artery. We used a multipoint vibrometer for the investigation. Our aim is to quantify this uncertainty for 1D-LDV measurements at the carotid artery. Moreover, we quantify its influence on the detection of the pressure. We derive an uncertainty contribution due to the laser beam direction of 13% for the displacement amplitude.

1. Introduction

The employment of laser Doppler Vibrometers (LDV) for biomedical applications has several advantages due to the contactless nature of the technology itself, the sensitivity and its other beneficial metrological properties. Moreover, vibrational signals acquired on the human body contain information that allows the extraction of medical parameters [1-10]. This technique is named Optical Vibrocardiography (VCG) [1]. In particular, the measurement point on the carotid artery is often chosen for investigations because of its accessibility and its characteristic strong signal (Figure 1). The skin layer at this point is very thin and most of the mechanical energy generated from the blood flow is converted into skin deflections. Deflections of the diameter of the carotid artery relate to the internal blood pressure, which LDV can detect without contact. Usually, continuous pressure waves are monitored in contact or invasively with pressure sensors. To realize noncontact measurements, several studies [5-9] relate the amplitude of the displacement signal acquired with LDV to the internal pressure of the vessel using models that approximate the pressure-radius relationship. In these studies, ideal measuring conditions are assumed for the post-processing [7-9]. However, variations from the ideal situation are always present in practice. These lead to an uncertainty of the velocity and displacement signals and, therefore, of the derived cardiovascular parameters like the pressure wave amplitude. The LDV measures only the vibration component in the direction of the laser beam. If the vibration of the target is not parallel to the laser beam, the projection of the real vibration amplitude in the measuring direction is measured. This leads to a distortion of the characteristic waves of the signal [10]. Pointing the spot at the location of the carotid artery with the right beam orientation is more difficult if the LDV is adopted for tracking applications, like monitoring the health condition of a moving subject. Such conditions can generate severe measurement deviations. 1D measurements with a single point LDV are critical because it is difficult or even impossible to determine the exact angle of incidence. A single

point LDV measurement is not appropriate if the real 3D-vibration amplitude of the signal needs to be detected. A 3D measurement represents an optimal solution to compensate these amplitude deviations. Alternatively, it will be helpful to know the uncertainty related to the laser-beam orientation for 1D measurements.

In this paper, we investigate the uncertainty contribution due to the laser beam direction on the displacement amplitude of vibration signals acquired on the carotid artery. Our aim is to quantify the uncertainty due to the laser beam orientation for 1D-VCG measurements at the carotid artery and evaluate its effects on the detection of cardiovascular parameters. We report our results on the blood pressure evaluation. The measurement point and its position deviation affect also the extraction of parameters from LDV signals, but they are not considered in this work. The real direction of the vibration was investigated with the Multipoint vibrometer (MPV)[11-13]. This allowed to quantify the uncertainty due to the laser beam orientation for 1D-LDV measurement at the carotid artery. With the MPV it is possible to measure from three different direction simultaneously on the same spot and thus, to reconstruct the 3D vector of the vibrations.
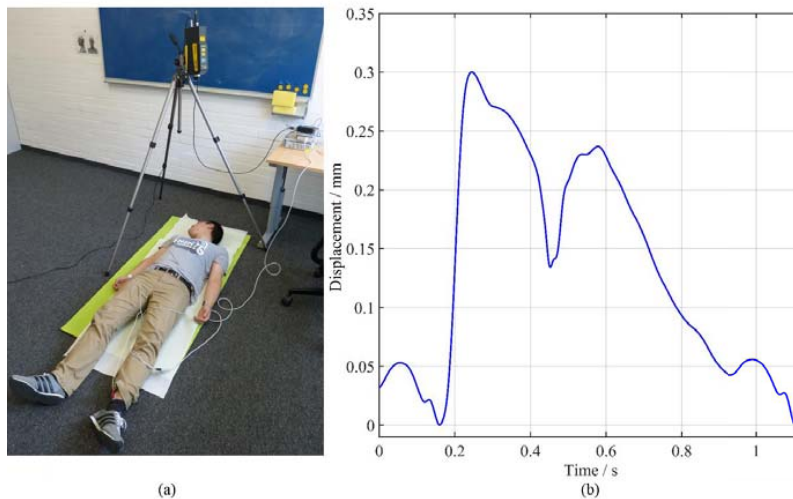
Figure.1 VCG typical set-up (a) and typical VCG signal at the carotid artery acquired with a single point LDV (b).

## 2. Material and Methods

2.1. Measurement set-up

The real direction of the vibration has to be known to quantify the uncertainty due to the laser beam orientation for 1D-LDV measurement at the carotid artery. We measured the time-dependent orientation of the heartbeat vector in the tridimensional space with the multipoint vibrometer MPV-800 (Polytec) in order to investigate the real direction of the vibrations. During the measurements, the subject was laying comfortably with the head turned right. This allowed the measurement on the neck at the left common carotid artery. A simultaneous electrocardiogram (ECG) signal (II lead) was recorded with the ECG BioAmp ® (ADInstrument) to have a time reference signal. Three measuring heads of the MPV-800 were pointed on the same spot from three independent directions $i = i_n(\alpha_n, \beta_n)$ defined by the angles α_n, elevation angle, and β_n, azimuth angle, where $n = 1, 2, 3$ (Figure 2). We selected the following measurement directions for the measurements: i_1, is oriented with $\alpha_1 = 70,5°$ and $\beta_1 = 0°$, i_2, is along the z-axis (defined by $\alpha_2 = 90°$) and i_3, is defined by $\alpha_3 = 72°$ and $\beta_3 = 270°$ (Figure 2). Thus, we obtained three simultaneous velocity vectors from the directions i_1, i_2 and i_3, respectively $v_1 = v_1 i_1$, $v_2 = v_2 i_2$ and $v_3 = v_3 i_3$. The selected measuring directions represent a good compromise between a good in-plane resolution and high light collection. The measurements were performed on nine subjects. The measurement point was chosen with palpation method.

2.2. 3D-vector reconstruction

The acquired velocity signals were integrated in order to reconstruct the 3D displacement vector of the heartbeat on the carotid. Noise and vibration interferences like breathing were removed from the signals.

Thus, only the vibrations generated by the pulse wave are considered. The three simultaneous displacement signals from the directions $\boldsymbol{i_1}, \boldsymbol{i_2}$ and $\boldsymbol{i_3}$, $\boldsymbol{s_1} = s_1 \boldsymbol{i_1}$, $\boldsymbol{s_2} = s_2 \boldsymbol{i_2}$ and $\boldsymbol{s_3} = s_3 \boldsymbol{i_3}$ respectively, were used to reconstruct the 3D-vector of the heart-beat on the carotid artery in the defined Cartesian coordinate system $\boldsymbol{s} = (s_x, s_y, s_z)$ by the following coordinate transformation [10]

$$\boldsymbol{s_{meas}} = \begin{Bmatrix} s_1 \\ s_2 \\ s_3 \end{Bmatrix} = \begin{bmatrix} \cos\alpha_1 \cos\beta_1 & \cos\alpha_1 \sin\beta_1 & \sin\alpha_1 \\ \cos\alpha_2 \cos\beta_2 & \cos\alpha_2 \sin\beta_2 & \sin\alpha_2 \\ \cos\alpha_3 \cos\beta_3 & \cos\alpha_3 \sin\beta_3 & \sin\alpha_3 \end{bmatrix} \cdot \begin{Bmatrix} s_x \\ s_y \\ s_z \end{Bmatrix} = \mathbf{E} \cdot \boldsymbol{s} \Leftrightarrow \boldsymbol{s} = \mathbf{E}^{-1} \cdot \begin{Bmatrix} s_1 \\ s_2 \\ s_3 \end{Bmatrix}. \tag{1}$$
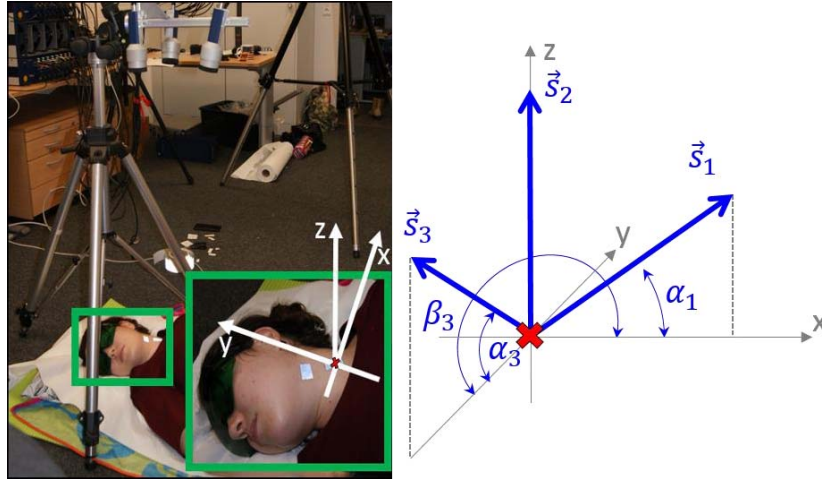
Figure 2. Set-up and defined Cartesian coordinate system

The typical LDV displacement signals acquired on the carotid present several characteristic points [5]. In our work we investigate only the maximum of the flow point (i.e. maximum of the signal in figure 1b), which is related to the maximal pressure value of the pulse wave obtained with the calibration models [7-9].

The 3D displacement vector is reconstructed in the Cartesian coordinate system for every beat. The time instant, where the selected beats present its maximum amplitude, has been chosen. The displacement vector with maximal length s_M is the displacement vector at maximum amplitude. Its length results from

$$s_M = |\boldsymbol{s_M}| = \left(s_{Mx}^2 + s_{My}^2 + s_{Mz}^2 \right)^{\frac{1}{2}}, \tag{2}$$

where s_{Mx}, s_{My} and s_{Mz} are the amplitude components in the Cartesian coordinate system.

The direction of s_M is defined by the angles α_M (elevation) and β_M (azimuth)

$$\alpha_M = \arcsin\left(\frac{s_{Mz}}{s_M} \right), \tag{3}$$

$$\beta_M = \text{atan2}\left(\frac{s_{My}}{s_M} \right). \tag{4}$$

This analysis is performed for twenty beats of all the nine subjects.

The estimation of the uncertainty has been performed as described in the following paragraph only for the maximal amplitude point and for the case of a 1D measurement in the direction perpendicular to the skin, which is the most used set-up for this application. In the defined coordinate system, the direction perpendicular to the skin corresponds to the z-axis (Figure 2).

2.3. Uncertainty determination for 1D LDV-measurement at the carotid artery
To calculate the combined uncertainty for the displacement amplitude, we made the assumption of a simple displacement model

$$s = s_0 + \Delta s_A + \Delta s_B, \tag{5}$$

where s is the measured displacement amplitude, s_0 is the real value of the displacement, Δs_A is the type A uncertainty deviation and Δs_B is the type B uncertainty deviation according with the guide to the expression of uncertainty in measurement GUM [14]. Thus, the combined uncertainty for the displacement $u_{C,1D}$ is

$$u_{C,1D} = \left(u_{A,1D}^2 + u_{B,1D}^2 \right)^{1/2}, \tag{6}$$

where $u_{A,1D}$ for a subject is calculated by multiplying the student-t factor for 20 values for 68% confidence bound, $t_{0.68}(20)$, by the empirical standard deviation of s_{Mz}, $\mathrm{std}(s_{Mz})$ for the selected 20 beats. For the calculation of the uncertainty of 1D-LDV displacement measurements at the carotid artery we have to consider the uncertainty due to the laser beam orientation as type B uncertainty according with GUM [14]. In particular if we are measuring from the direction i_p (Figure 3a), at the maximum of the flow point we measure the amplitude $s = s_p$

$$s_p = |s_p| = |s_M| \cos \gamma, \tag{7}$$

where γ is the angle between the direction of the vibration and the measuring direction. In order to calculate the uncertainty for any displacement it is helpful to define the relative amplitude error $E(\gamma)$

$$E(\gamma) = \frac{|s_M| - |s_p|}{|s_M|} = 1 - \cos \gamma. \tag{8}$$

We evaluated the γ for the case of a 1D measurement on the z-axis (Figure 3b), thus $s_p = s_M$ and

$$\gamma = 90° - \alpha_M. \tag{9}$$

We calculated γ for 20 beats of 9 subjects to find γ_{max}. The uncertainty contribution $u_{B,1D}$ calculated for the maximal value of γ_{max} with the assumption of a rectangular distribution of γ, results in

$$u_{B,1D} = \frac{E(\gamma_{max}) \cdot s_{Mz}}{\sqrt{3}}. \tag{10}$$

2.3.1. Uncertainty contribution of the displacement measurement to the blood pressure. The displacement amplitude acquired with LDV is related to the blood pressure inside the vessel as explained in the introduction. The displacement uncertainty has a contribution to the combined uncertainty of the pressure P. The pressure waveform $P(t)$ can be expressed with one of the calibration models described in [7-9]. The most accurate one is the exponential model [9]

$$P(t) = p_d \exp\left[q\left(\frac{A(t)}{A_d} - 1 \right) \right], \tag{11}$$

where p_d is the diastolic pressure, A_d the diastolic arterial cross-section and q is the wall rigidity coefficient which depends on the systolic and diastolic pressure and cross-section area. The variable $A(t)$ is the section at the time instant t. For our analysis we take into consideration only the time instant t of the upstroke, $t(s_{Mz})$. According with [7-9]

$$A\left(t\left(s_{Mz} \right) \right) = \pi \frac{\left(d_0 + 2 \cdot s_{Mz} \right)^2}{4} \tag{12}$$

where d_0 is the diameter of the vessel at rest. Thus, the contribution of s_{Mz} to the combined uncertainty of the pressure P is $u_{C,P,s_{Mz}}^2$

$$u_{C,P,s_{Mz}}^2 = \left(\frac{\partial P}{\partial s_{Mz}} \cdot u_{C,1D} \right)^2 = \left\{ p_d \exp\left[q\left(\frac{A\left(t\left(s_{Mz} \right) \right)}{A_d} - 1 \right) \right] \cdot \pi q \frac{\left(d_0 + 2 \cdot s_{Mz} \right)^2}{A_d} u_{C,1D} \right\}^2. \tag{13}$$

For the calculation, we took the typical values of the systolic and diastolic pressure and cross-section area from references [15].

*2.4. Uncertainty determination for 3D LDV-measurement at the carotid artery*

In a 3D-LDV measurement, the amplitude of the vibrations is measured along its direction. Thus, we neglected the uncertainties of type B.

By applying the same approach of the uncertainty of 1D case to the 3D case, we have that the combined uncertainty for the displacement u_{3D} presents only the contribution of the type A uncertainty

$$u_{3D} = u_{A,3D}, \tag{14}$$

where $u_{A,3D}$ for a subject is calculated by multiplying $t_{0.68}(20)$ by the empirical standard deviation of s_M, $\text{std}(s_M)$ for the selected 20 beats. The contribution of s_M to the combined uncertainty of the pressure P is u_{C,P,s_M}^2

$$u_{C,P,s_M}^2 = \left(\frac{\partial P}{\partial s_M} \cdot u_{C,1D} \right)^2 = \left\{ p_d \exp\left[q\left(\frac{A(t(s_M))}{A_d} - 1 \right) \right] \cdot \pi q \frac{(d_0 + 2 \cdot s_M)^2}{A_d} u_{C,1D} \right\}^2. \tag{15}$$
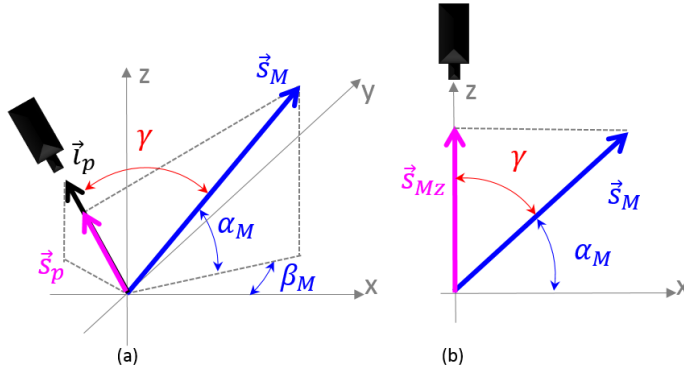
Figure 3. 1D-LDV measurement from an arbitrary direction (a), from the z-axis of the defined Cartesian coordinate system (b)

3. Results

Figure 4 shows the reconstruction of the 3D displacement vector. The amplitude of 3D-displacement vector over the time is presented in the upper part of the figure. The displacement vector in the 3D space is presented in the bottom of figure 4. The paths of the 3D-vector from the beginning till three different time instants are showed in the defined Cartesian coordinate system. The three selected time instants are: the maximum of the flow point t_{max} (right), the end of the heart beat $t_{end,beat1}$ (middle) and the end of the following beat $t_{end,beat2}$ (left). From the beginning of the beat till t_{max}, i.e. during the upstroke, the vibrations are almost along the same direction. After the upstroke (Figure 4 middle) the vector deviates and changes its direction. This behavior could depend on the expansion and contraction of the vessel due to the blood flow passing through the vessel. The pattern delivered by the second beat (Figure 4 right) seems to follow the same path of the previous beat. Thus, the pattern delivered by a beat is very reproducible for each subject.

Figure 5 shows the amplitude of the 3D vector and its projection on the z-axis. It is possible to notice that the amplitude of the projection in z-axis is smaller than the real 3D amplitude. The amplitude difference is not constant during the beat. This can be explained since the direction of the 3D vector changes (Figure 4), and therefore also its projection in the z-axis.

The calculation of α_M, and thus γ, performed for 20 beats of each subject leaded to a $\gamma_{max} = 39.97°$. The obtained value of γ_{max} is used to calculate the type B uncertainty for 1D measurement with LDV. In particular from equation (8), the relative error is $E(\gamma_{max}) = 0.23$ and thus, the uncertainty contribution $u_{B,1D}$ from equation (10) becomes

$$u_{B,1D} = 0.13 \cdot s_{Mz}. \tag{16}$$

The contribution of the laser beam orientation at the maximum point is 13% of the measured amplitude with the measuring conditions described in the paragraph 2.1.

For the calculation of the combined uncertainty, the example of one subject is reported.

In particular for a selected subject the type A uncertainty is

$$u_{A,1D} = t_{0.68}(20) \cdot \text{std}(s_{Mz}) = 0.011 \text{ mm}. \tag{17}$$

For the same subject is for example $s_{Mz} = 0.301$ mm, thus the type A uncertainty in this case is about 3.7%. Therefore the uncertainty due to the laser beam orientation is not negligible respect to the statistical determined uncertainty.

The contribution of the displacement uncertainty to the uncertainty of the pressure P can be calculate as described in equation (13)

$$u_{C,P,s_{Mz}} = 3.43 \text{ mmHg}. \tag{18}$$

$u_{C,P,s_{Mz}}$ results in 2.9% of the pressure at the maximal point $P(s_{Mz}) = 118.28$ mmHg calculated according with equation (11).

In the case of a 3D measurement $u_{A,3D} = 0.012$ mm and the contribution of the displacement uncertainty to the uncertainty of the pressure is described in equation (15). It results in

$$u_{C,P,s_M} = 1.04 \text{ mmHg} \tag{19}$$

and it represents the 0.9% of $P(s_M) = 121.61$ mmHg, calculated according with equation (11).
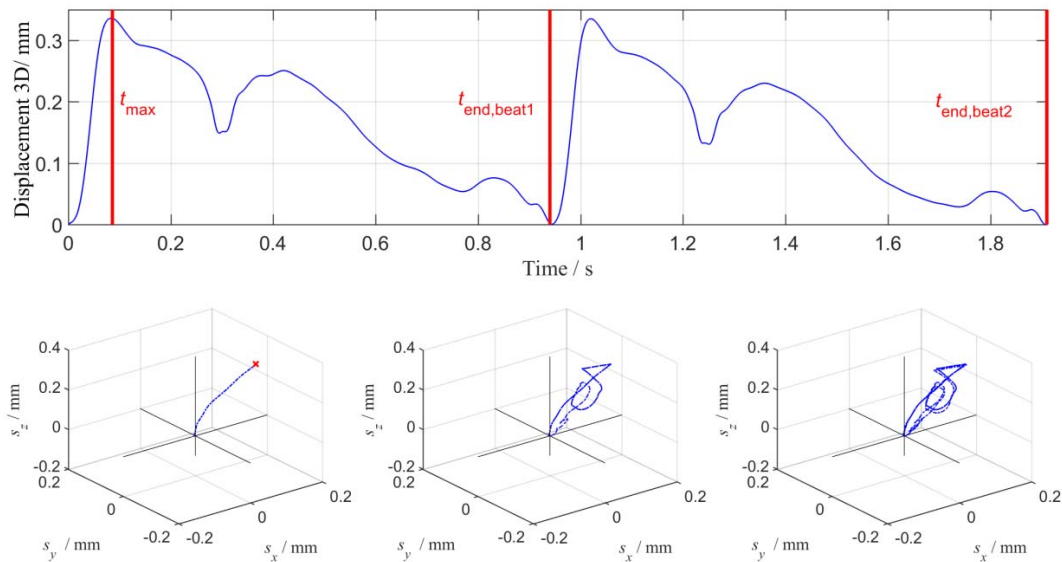
Figure 4. 3D displacement amplitude over the time of two consecutive beats (above). 3D representation of the vector at three different time instant: t_{max} is the maximum flow point (left), which is identified by the red cross, $t_{end,beat1}$ is the end of the first beat (middle) and $t_{end,beat2}$ is the end of the second beat (right). s_x, s_y and s_z indicate the displacement in x, y and z axis respectively.
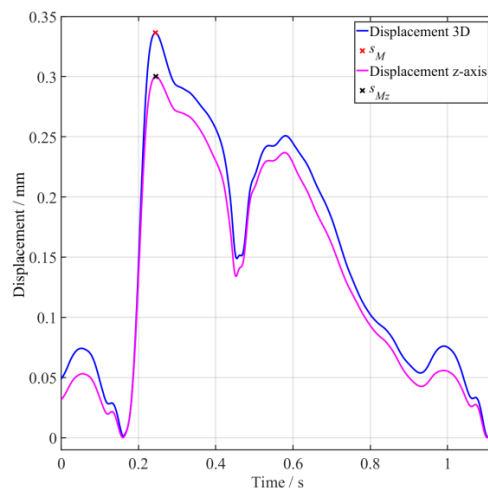
Figure 5. 3D displacement amplitude (blue) and its projection in z-axis (magenta). Their maxima s_M and s_{Mz} are marked with a red and a black cross respectively.

The uncertainty in the determination of the peak of the pressure are lower in the case of a 3D measurement. However, a normal individual that breaths spontaneously shows changes of the maximal pressure of about 5 mmHg [16], thus $u_{C,P,s_{Mz}}$ is still acceptable. If the type A uncertainty of a subject is comparable to the type B uncertainty then also the contribution to the uncertainty of the pressure increases. However, in the exponential model of the pressure P, the displacement appears on the exponent; therefore to a great variation of the displacement amplitude corresponds a small variation of the pressure P. Thus, even a large measurement error of the displacement-amplitude measurements results in a rather small error of the determined pressure amplitude.

4. Conclusion

In this work, we investigated the uncertainty contribution due to the laser beam direction on the displacement amplitude of vibration signals acquired on the carotid artery. We quantified the uncertainty due to the laser beam orientation for 1D-LDV measurements at the carotid artery and its effect on the detection of the blood pressure by measurement performed with the multipoint vibrometer. From our investigation the uncertainty contribution due to the laser beam direction is 13% of the displacement amplitude. A 3D-LDV measurement leads to a lower uncertainty in the determination of the displacement amplitude, and thus of the blood pressure. However, if the exponential model of the pressure is used, the repercussion of the uncertainty of the displacement to the value of the pressure, is not critical.

In our analysis we did not consider the influence of the set-up for the calculation of the uncertainty in the case of a 3D measurement. This analysis is addressed to future works. A further interesting analysis is the quantification of the uncertainty of the laser beam orientation for the extraction of other cardiovascular parameters.

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