PPG motion artifact handling
using a self-mixing interferometric sensor

Ralph W.C.G.R. Wijshoff\textsuperscript{a,b}, Jeroen Veen\textsuperscript{b}, Alexander M. van der Lee\textsuperscript{b}, Lars Mulder\textsuperscript{c}, Marco Stijnen\textsuperscript{c}, Sjoerd van Tuijl\textsuperscript{c}, Ronald M. Aarts\textsuperscript{a,b}

\textsuperscript{a}Eindhoven University of Technology, Den Dolech 2, 5612 AZ Eindhoven, The Netherlands;
\textsuperscript{b}Philips Research, High Tech Campus 34, 5656 AE Eindhoven, The Netherlands;
\textsuperscript{c}HemoLab BV, Den Dolech 2, 5612 AZ Eindhoven, The Netherlands

ABSTRACT
Pulse oximeters measure a patient’s heart rate and blood oxygenation by illuminating the skin and measuring the intensity of the light that has propagated through it. The measured intensities, called photoplethysmograms (PPGs), are highly susceptible to motion, which can distort the PPG derived data. Part of the motion artifacts are considered to result from sensor deformation, leading to a change in emitter-detector distance. It is hypothesized that these motion artifacts correlate to movement of the emitter with respect to the skin. This has been investigated in a laboratory setup in which motion artifacts can be reproducibly generated by translating the emitter with respect to a flowcell that models skin perfusion. The top of the flowcell is a diffuse scattering Delrin skin phantom under which a cardiac induced blood pulse is modeled by a changing milk volume. By illuminating the flowcell, a PPG can be measured. The emitter’s translation has been accurately measured using self-mixing interferometry (SMI). The motion artifacts in the PPG as a result of emitter motion are shown to correlate with the emitter’s displacement. Moreover, it is shown that these artifacts are significantly reduced by a least-mean-square algorithm that uses the emitter’s displacement measured via SMI as artifact reference.

Keywords: in vitro modeling, motion artifacts, normalized least-mean-square, photoplethysmography, pulse oximetry, self-mixing interferometry

1. INTRODUCTION
Nowadays, pulse oximeters are widely applied in clinical practice to measure a patient’s heart rate and blood oxygenation.\textsuperscript{1} Pulse oximeters obtain this data by illuminating the skin and measuring the intensity of the light that has propagated through the skin in a transmissive or planar setup (Figs. 1a, 1b). The measured light intensities, called photoplethysmograms (PPGs), show periodic decreases as a result of the cardiac induced increases in arterial blood volume (first 10 s and last 12 s in Fig. 1c). Heart rate therefore can be obtained directly from a PPG.\textsuperscript{2} Blood oxygenation can be determined by measuring PPGs at two wavelengths (e.g. red and infrared). Since blood oxygenation determines the blood’s colour, oxygenation can be determined by comparing the amplitudes of the cardiac induced pulses in both PPGs.\textsuperscript{2}

It is foreseen that pulse oximetry is one of the monitoring modalities that will be applied in ambulatory settings (e.g. the patient’s home) in the near future. It is believed that long-term home monitoring can lead to an improved diagnosis and treatment of chronic cardiovascular and respiratory diseases. Long-term home monitoring allows for capturing sporadic events and for the early detection of exacerbations. In addition it can...
be used to more objectively assess the effect of therapy and medication, which can facilitate precise titration of therapy and medication.\textsuperscript{3, 4}

PPGs are highly susceptible to motion which can distort PPG derived data.\textsuperscript{1, 5} This hampers application of pulse oximetry in ambulatory settings.\textsuperscript{5} Figure 1c illustrates PPGs obtained with a transmissive finger clip in which the cardiac component is clearly distorted by motion artifacts when the finger is bent slightly. The motion artifacts are presumably caused by hemodynamic effects, changing tissue compression and sensor movement and deformation. This paper focuses on the motion artifacts caused by deformation of the flexible sensors (Fig. 1b), which alters the emitter-detector distance. It is hypothesized that these optical motion artifacts correlate to movement of the emitter with respect to the detector. In this case, these optical motion artifacts can be corrected using a measure of the emitter’s displacement, which is believed to outperform (non-linear) PPG post-processing methods not employing a measured motion reference.\textsuperscript{6}

In this paper it is studied whether it is fundamentally possible to correct optical motion artifacts using a measure of the emitter’s displacement. Section 2 explains how displacement of the emitter is determined using self-mixing interferometry (SMI), as measured by the laser diode’s internal photodiode. Using SMI is advantageous, since this self-aligning, compact and cheap method measures relative displacement of the light source itself, rather than displacement at a different sensor site or global sensor movement, as additional optical sensors or accelerometers do.\textsuperscript{3, 6} The influence of an altering emitter-detector distance on PPGs is investigated in a controlled laboratory setup, as explained in Section 3. This setup contains a flow cell that mimics changes in blood volume underneath a diffuse scattering Delrin skin phantom. A laser diode illuminates the pulsatile flow through the cell to obtain a PPG, and a shaker translates the laser with respect to the detector to generate the motion artifacts. Section 4 then presents a normalized least-mean-square (NLMS) algorithm that uses the SMI displacement measurement as a reference for the optical motion artifacts in order to retrieve the cardiac component from the distorted PPGs. Finally, the experimental results are presented and discussed in Sections 5 and 6, and the conclusions are stated in Section 7.

2. SELF-MIXING INTERFEROMETRY

SMI is observed when a laser diode illuminates an external object such that part of the light backscattered by the object enters the laser diode’s cavity again. The backscattered light interferes with the standing wave inside the laser cavity, thus changing the emitted optical lasing frequency and power.\textsuperscript{7} Moreover, when part of the light backscattered by a moving object enters the cavity again, a beat frequency equal to the Doppler shift $f_d$ [Hz] will be observed in the optical power:

$$f_d(t) = \frac{v_o(t) \cos(\theta)}{\lambda(t)/2},$$

where $v_o(t)$ is the velocity of the object and $\lambda(t)$ is the wavelength of the laser at time $t$. This equation shows how the Doppler shift is related to the velocity of the object and the wavelength of the laser.
with time \( t \) [s], object velocity \( v_o(t) \) [m/s], angle \( \theta \) [rad] between the object’s velocity vector and the laser beam, and lasing frequency \( \lambda(t) \) [m]. The component of the target’s displacement in the direction of the laser beam then follows by equating each full cycle in the optical power to half of the emitted wavelength.

However, only counting the number of cycles in the optical power does not reveal the direction of motion. Without directional information the displacement measurement may have a frequency twice as high as the displacement itself, complicating its use to correct motion artifacts in PPGs. Using SMI, the direction of motion can be obtained from the shape of the interference pattern in the optical power or by emitting multiple wavelengths. At high levels of optical feedback the interference pattern is sawtooth shaped, of which the direction of the fast edge depends on the direction of motion. Such high levels of optical feedback may not be obtained because of the diffuse optical scattering of skin though. Therefore an amplitude modulation of the laser current is applied which induces a continuous wavelength modulation. In this case the direction of motion can be recovered by using the phase relationship between the different wavelengths emitted.

### 2.1 Measuring displacement using SMI

The Doppler frequency in the optical power can be measured by the laser diode’s internal monitor diode. The monitor signal \( v_{MD}(t) \) [V] obtained by a transimpedance amplifier with gain \( Z \) [V/A], can be expressed as:

\[
v_{MD}(t) = Z \cdot i_{MD}(t) = Z R (P_{DC} + \Delta P_m(t) + \Delta P_{fb}(t)),
\]

in which \( i_{MD}(t) \) [A] is the monitor diode’s current, \( R \) [A/W] the diode’s responsivity, \( P_{DC} \) [W] the DC optical power in the laser cavity, and \( \Delta P_m(t) \) [W] and \( \Delta P_{fb}(t) \) [W] the fluctuations in optical power caused by modulation and optical feedback respectively. The object’s displacement information is contained in the latter term, for which it holds in approximation: \(^8,9\)

\[
\Delta P_{fb}(t) \approx [J_0(\phi_0(t)) + 2 J_2(\phi_0(t)) \cos(2(\omega_m t + \phi_m))] \cos(\phi_d(t)) + 2 J_1(\phi_0(t)) \sin(\omega_m t + \phi_m) \sin(\phi_d(t)),
\]

in which \( \phi_{ext}(t) \) is the phase change of the external cavity, which equals the phase change as a result of the distance \( L_o \) [m] traveled between laser diode and object plus the phase change as a result of object motion. This relationship shows that the optical power in the cavity increases maximally when the backscattered light is in phase and decreases maximally when the backscattered light is in antiphase.

The influence of modulation and optical feedback on Eq. (3) are determined next. Therefore, the continuous wavelength variation as a result of amplitude modulation of the laser current at \( \omega_m \) [rad/s] with initial phase \( \phi_m \) [rad] is expressed as \( \Delta \lambda_m(t) = \lambda_0 + \Delta \lambda_m \sin(\omega_m t + \phi_m) \) [m], and the feedback induced wavelength change is indicated by \( \Delta \lambda_{fb}(t) \) [m]. The phase difference between the backscattered light with the longest and shortest wavelengths is approximated by \( \phi_0 \) [rad]:

\[
\frac{4 \pi L_o}{\lambda_0 - \Delta \lambda_m} = \frac{4 \pi L_o}{\lambda_0 + \Delta \lambda_m} + \phi_0 \rightarrow \phi_0 \approx 8 \pi L_o \frac{\Delta \lambda_m}{\lambda_0^2}.
\]

As \( \Delta \lambda_m / \lambda_0 \ll 1 \) and \( \Delta \lambda_{fb}(t)/\lambda_0 \ll 1 \), Eq. (3) can be approximated by:

\[
\Delta P_{fb}(t) \approx \cos\left(4 \pi L_o + \cos(\theta) \int_0^t v_o(\xi) d\xi \right) \approx \cos\left(4 \pi \frac{L_o + \Delta L_d(t)}{\lambda_0 + \Delta \lambda_m \sin(\omega_m t + \phi_m) + \Delta \lambda_{fb}(t)} \right)
\]

\[
\approx \cos\left[4 \pi \frac{L_o}{\lambda_0} \left(1 + \frac{\Delta L_d(t)}{L_o} - \frac{\Delta \lambda_{fb}(t)}{L_o}\right) - \phi_0 \right] \left(1 + \frac{\Delta L_d(t)}{L_o}\right) \sin(\omega_m t + \phi_m),
\]

\[
\Delta L_d(t) = \cos(\theta) L_o = \cos(\theta) \int_0^t v_o(\xi) d\xi \approx \frac{\lambda_0}{2} \int_0^t f_d(\xi) d\xi,
\]

with \( \Delta \lambda_{fb} \) [m] the object’s displacement and \( \Delta L_d(t) \) [m] the object’s displacement as observed by the laser diode. Via the Jacobi-Anger expansion Eq. (6) can be expanded into signals in baseband, around the modulation frequency and around the second harmonic of the modulation frequency:

\[
\Delta P_{fb}(t) \approx [J_0(\phi_0(t)) + 2 J_2(\phi_0(t)) \cos(2(\omega_m t + \phi_m))] \cos(\phi_d(t)) + 2 J_1(\phi_0(t)) \sin(\omega_m t + \phi_m) \sin(\phi_d(t)).
\]
in which $J_n$ is the $n^{th}$ Bessel function of the first kind, and:

\[
\phi_0(t) = \frac{\phi_0}{2} \left(1 + \frac{\Delta L_d(t)}{L_o}\right), \quad (9)
\]

\[
\phi_d(t) = \frac{4\pi}{\lambda_0} (L_o + \Delta L_d(t)) - \frac{4\pi L_o}{\lambda_0^2} \Delta \lambda_{fb}(t). \quad (10)
\]

The expansion in Eq. (8) shows that light backscattered into the laser cavity by the moving object yields Doppler signals with a phase $\phi_d(t)$ as in Eq. (10). The object’s displacement $\Delta L_d(t)$ appears both in $\phi_0(t)$ and $\phi_d(t)$. Displacement $\Delta L_d(t)$ is reconstructed using $\phi_d(t)$, because the influence of speckle on the amplitude of $v_{MD}(t)$ and phase ambiguities complicate recovering $\phi_0(t)$. As modulation causes $\phi_d(t)$ to appear both in a sine and a cosine, it can be recovered conveniently by tracking the phase of the rotating vector of which the sine and cosine terms are the Cartesian coordinates. Moreover, Eq. (8) shows that $\cos(\phi_d(t))$ appears both in the baseband and around the second harmonic. The $\cos(\phi_d(t))$ term around the second harmonic is used for the displacement measurements, because it has a better SNR given the $1/f$ noise characteristic and mains interference.

To obtain the vertical coordinate of the rotating vector, the monitor signal is first multiplied by the modulation frequency, and passed through a low-pass filter (LPF) with a cut-off at the maximum Doppler frequency $\omega_{d,\text{max}} < \omega_m$:

\[
v_y(t) = 2 \cdot \text{LPF} \left\{ v_{MD}(t) \cdot \sin(\omega_m t + \phi_m) \right\} \sim A_{1,\text{st}} + 2J_1(\phi_0(t)) \sin(\phi_d(t)), \quad (11)
\]

in which $A_{1,\text{st}} [-]$ results from the amplitude modulation of the laser current. Similarly, to obtain the horizontal coordinate of the rotating vector, the monitor signal is first multiplied by double the modulation frequency, and passed through the same low-pass filter:

\[
v_x(t) = 2 \cdot \text{LPF} \left\{ v_{MD}(t) \cdot \cos(2(\omega_m t + \phi_m)) \right\} \sim A_{2,\text{nd}} + 2J_2(\phi_0(t)) \cos(\phi_d(t)), \quad (12)
\]

in which $A_{2,\text{nd}} [-]$ is proportional to the second harmonic of the modulation frequency in the monitor signal. Finally, the vector coordinates $(x_n(t), y_n(t))$ are the normalized, zero mean version of $(v_x(t), v_y(t))$:

\[
(x_n(t), y_n(t)) = \left( A_x(t) \cos(\phi_d(t)), A_y(t) \sin(\phi_d(t)) \right), \quad (13)
\]

such that $A_x(t) \approx A_y(t)$. Object displacement now can be reconstructed by tracking the phase of the rotating vector $(x_n(t), y_n(t))$ and equating each full rotation of $2\pi$ rad to a displacement of half a wavelength.

The vector coordinates in Eqs. (11) and (12) have amplitudes proportional to the Bessel functions $J_1(\phi_0(t))$ and $J_2(\phi_0(t))$ respectively. A proper choice of $\phi_0$ thus assures these signals to be large, which can be realized via the modulation depth $\Delta \lambda_m/\lambda_0$ (Eq. (4)). For $\pi/2 < \phi_0 < \pi$, Bessel functions $J_1$ and $J_2$ are close to their maximum. In practice, this situation can be conveniently recognized by the disappearing baseband signal, because $J_1$ and $J_2$ are close to their maximum when $J_0$ is close to 0. Maximizing $J_1$ and $J_2$ in this way has the additional advantage of reducing the artifacts in the PPG as a result of the Doppler frequencies in baseband, since these are scaled by $J_0$. Finally, by using $\pi/2 < \phi_0 < \pi$, $L_o \sim 10^{-2}$ m and $\lambda_0 \sim 10^{-7}$ m in Eq. (4), it follows that $\Delta \lambda_m/\lambda_0 \sim 10^{-6}$, which shows that the assumption $\Delta \lambda_m/\lambda_0 \ll 1$ holds true.

2.2 Accuracy analysis

In practice, $v_x(t)$ and $v_y(t)$ (Eqs. (12) and (11)) are perturbed by additive noise terms $n_x(t)$ and $n_y(t)$ respectively, caused by shot noise, thermal noise and quantization noise. These noise terms influence the accuracy of the method. Taking into account these noise sources, the displacement reconstruction method can be expressed as:

\[
\Delta L_{\text{sim}}(t) = \frac{\lambda_0}{4\pi \cos(\theta)} \text{unwrap} \left[ \arctan \left( \frac{y_n(t) + n_{yn}(t)}{x_n(t) + n_{xn}(t)} \right) \right] \quad (14)
\]

\[
\approx \frac{L_o}{\cos(\theta)} + \Delta L_o - \frac{L_o}{\lambda_0} \frac{\Delta \lambda_{fb}(t)}{\cos(\theta)} \tan(\phi_d(t)) + \frac{\lambda_0}{4\pi \cos(\theta)} \tan(\phi_d(t)) (1 + \tan^2(\phi_d(t))) \left[ \frac{A_y(t)}{A_x(t)} - 1 \right] + \frac{n_{yn}(t)}{A_x(t)} \right) \quad (15)
\]

\[
\leq \frac{L_o}{\cos(\theta)} + \Delta L_o + \frac{\lambda_0}{8\pi \cos(\theta)} C + \max t \left[ \frac{A_y(t)}{A_x(t)} - 1 \right] + \frac{n_{xn}(t) + n_{yn}(t)}{A_x(t)/2} \quad (16)
\]

Proc. of SPIE Vol. 7894  78940F-4
in which $n_{n}(t)$ and $n_{y}(t)$ are the normalized noise terms, and the change in wavelength as a result of optical feedback has been upper bounded using the lasing condition and optical feedback parameter $C$. Equation (16) shows the upper bound of three additive noise sources which distort the displacement reconstruction. The first noise source is caused by the change in emitted optical wavelength as a result of optical feedback and has been upper bounded by $\left(\lambda_{0}C\right)/(4\pi\cos(\theta))$. Since only weak feedback regimes are expected in this application, it holds that feedback parameter $C < 1$. Therefore this error term will have a magnitude in the order of $\left(\lambda_{0}C\right)/(4\pi\cos(\theta)) \sim 10^{-8} - 10^{-7}$ m. The second noise source is caused by imperfect normalization as a result of which $A_{x}(t) \approx A_{y}(t)$. Assuming that normalization is effective such that $\max(A_{y}(t)/A_{x}(t)) \approx 1$, this error will have a magnitude in the order of $10^{-8} - 10^{-7}$ m as well. Normalization may cause the third noise term $2\max((n_{x}(t) + n_{y}(t))/A_{x}(t))$ to become relatively large, since speckle effects may cause the amplitudes of the signals $v_{x}(t)$ and $v_{y}(t)$ to become very small. Since sensor displacement is expected to be in the order of $10^{-4} - 10^{-3}$ m, the first two error sources introduce an error of roughly 0.1% - 1%.

Inaccuracies also result from not exactly knowing the average emission wavelength $\lambda_{0}$ and angle $\theta$. The effect of modulation on the wavelength can be neglected, since that yields a wavelength change in the order of $10^{-13}$ m. A laser diode’s emission wavelength can be specified with an accuracy of 10 nm, which thus may result in a displacement error of approximately 1%. The inaccuracy $\delta \theta$ in the angle results in a displacement error of $(\tan(\theta)/\cos(\theta))\delta \theta \approx 0.67 \cdot \delta \theta$ for $\theta = \pi/6$ rad, which equals approximately 1% for $\delta \theta = \pi/180$ rad. However, in the context of PPG motion artifact handling, it is most important to accurately measure the frequency of motion of the sensor. Constant scaling inaccuracies affecting the amplitude are not relevant.

### 3. EXPERIMENTAL SETUP

An experimental setup has been built to simulate pulsatile blood volume and optical motion artifacts in a controllable and reproducible manner. This setup has been used to study whether it is fundamentally possible to remove optical motion artifacts from a PPG caused by an altering emitter-detector distance, when a measure of the emitter’s motion is available.

### 3.1 Flowcell

The flowcell in Fig. 2 has been made to model pulsatile blood volume. The insert goes into the base of the flowcell, on top of which a 1 mm thick window can be mounted using the stainless steel ring. The insert of the flowcell defines a rectangular flow channel, with a width of 20 mm and a height of 1 mm. Because the topmost layers of the skin contain a dense network of capillaries and microvessels, blood flow has been modeled by a thin layer of flow. A diffuse scattering Delrin window is used as a skin phantom, because the optical properties of Delrin are similar to skin. This window also models the optical shunt of non-perfused tissue. A transparent window is used to determine the influence of the skin phantom on the PPGs measured.

The flowcell can be configured to have a rigid or a pulsatile flow channel to determine the origin of the pulse in the modeled PPG. A rigid flow channel is obtained by fixating the insert in the base via the rubber ring at
its bottom (Fig. 2b), by omitting the flexible membrane underneath the base (Figs. 2a, 2c) and by mounting
the cell on a flat ground plate. A pulsatile flow channel is obtained by omitting the rubber ring at the insert’s
bottom so it can move in the base (Fig. 2b), by adding the flexible membrane underneath the base (Figs. 2a,
2c) and by mounting the cell on a ground plate with a cut-away underneath the insert (Fig. 2a). In the latter
case, the insert moves up and down when a pulsatile flow is applied, thus modeling a change in blood volume.

Finally, milk has been used to mimic blood, because both milk and blood contain light scattering particles. In
blood, erythrocytes having a typical diameter of 8 μm scatter light. In milk, fat globules scatter light, which
have a diameter between 1 μm and 10 μm with an average of 4 μm.

3.2 Measuring PPGs and generating motion artifacts

To measure PPGs and generate optical motion artifacts in a controllable and reproducible manner, the setup in
Fig. 3 has been built. Here a roller pump with three rollers generates a pulsatile flow of milk, which results in
a pulsating volume of milk in the flow cell. The photodiode on top of the flowcell’s window can measure a PPG
when the laser diode illuminates the flowcell. The distance between the laser spot on the flowcell’s window and
the photodiode is approximately 1 cm. The laser pen that contains the laser diode is attached to a linear stage,
which is driven by a shaker. In this way the shaker can translate the laser diode to generate motion artifacts in
the PPG as a result of a dynamically changing emitter-detector distance.

Sufficiently strong optical feedback is required to measure displacement of the laser diode using SMI. This is
achieved by focussing the laser beam on the flowcell’s window using the ball lens in the laser pen. The distance
between the laser diode and the window is \( L_o \approx 1 \) cm. The angle between the laser pen and the flow cell’s
surface normal is 30°. To verify the SMI displacement measurement, a reference displacement measurement is
obtained by a commercially available Laser Distance Triangulation Sensor (LDTS). The LDTS directly measures
the translation of the linear stage (Fig. 3b) and has a resolution of 45 μm.

A laser driver steers the current through an 855 nm VCSEL (Vertical-Cavity Surface-Emitting Laser Diode),
which has an internal monitor diode. An optical output power of 0.45 mW is obtained by a 1.5 mA DC current.
A 40 kHz AC current with an amplitude of 48 μA is superimposed to obtain the desired \( \phi_0 \) (Section 2.1).
The PPG photodiode and monitor diode currents are amplified by transimpedance amplifiers to obtain the voltages $v_{PD}(t)$ and $v_{MD}(t)$ respectively. The PPG photodiode and monitor diode voltages, and the LDTS signal are band limited at 100 kHz and recorded by a 16 bit digital data acquisition card (DAQ) at 200 kHz. A LabVIEW interface controls the DAQ. The LabVIEW interface also generates the signal that is sent out by the DAQ and amplified in order to control the shaker. PPGs are obtained by band limiting $v_{PD}(t)$ at 15 Hz.

## 4. PPG MOTION ARTIFACT REDUCTION

An NLMS algorithm reduces the optical motion artifacts in the motion distorted PPG by using the laser’s displacement measured via SMI as a reference for the artifacts. To determine to which extent NLMS can remove motion artifacts using the displacement measurement, the distorted PPG is first modeled using the Beer-Lambert law to see how it is affected by changes in channel volume and emitter-detector distance.

### 4.1 Modeling the PPG

Laser light that reaches the PPG photodetector has either propagated through the window directly or has propagated through the milk in the channel and the insert. In the latter case, the light also passes the window twice. This can be modeled as follows using the Beer-Lambert law:\textsuperscript{2,6}

$$P_d(t) \approx P_0 \left\{ \exp \left[ -\varepsilon_w c_w (l_{ed} + \Delta l_{ed}(t)) \right] + \exp \left[ -2\varepsilon_w c_w l_{ed} - \varepsilon_m (c_m + \Delta c_m(t)) (l_{mi} + \Delta l_{mi}(t)) \right] \right\}$$

$$\approx \alpha_0 - \alpha_1 \left( 1 + \Delta l_{mi}(t) \right) \Delta c_m(t) - \alpha_2 \Delta l_{ed}(t) - \alpha_3 \Delta l_{mi}(t),$$

in which $P_0$ [W] and $P_d$ [W] are the emitted and detected light power respectively, subscripts $w, ed, wt, m$ and $mi$ stand for window, emitter-detector, window thickness, milk and milk plus insert respectively, $\varepsilon$ [M\(^{-1}\)m\(^{-1}\)] is the total optical molar extinction coefficient (both scattering and absorption), $c$ [M] is the substance’s concentration in the light path, $l$ [m] is the optical pathlength and the $\alpha$’s are proportionality constants obtained by a first order Taylor approximation. The first exponent in Eq. (17) describes the optical shunt through the window. The second exponent in Eq. (17) describes the propagation of light through the milk in the channel and the insert. The laser’s motion causes the change over time in optical pathlengths $\Delta l_{ed}(t)$ and $\Delta l_{mi}(t)$. The pulsating milk volume causes the change over time in milk concentration $\Delta c_m(t)$ in the light path through the insert. The first order Taylor approximation in Eq. (18) shows that the laser’s motion mainly causes the PPG $\alpha_1 \Delta c_m(t)$ to be distorted by a multiplicative artifact $\alpha_1 (\Delta l_{mi}(t)/l_{mi}) \Delta c_m(t)$ and by two additive artifacts $\alpha_2 \Delta l_{ed}(t)$ and $\alpha_3 \Delta l_{mi}(t)$.

### 4.2 The NLMS algorithm

Based on the first order Taylor approximation in Eq. (18) that describes the influence of laser motion on the PPG, an NLMS algorithm\textsuperscript{15} is used in a first attempt to reduce the motion artifacts in the PPG. If the NLMS algorithm succeeds in reducing the motion artifacts using the SMI displacement measurement as a reference for the motion artifacts, it also proves correlation between the displacement measurement and the artifacts.

The NLMS algorithm implemented (Fig. 4) subtracts the reconstructed motion artifact $h_0 \cdot \Delta l_{ma}[k]$ from the zero-mean photodiode signal $\tilde{v}_{PD}[k]$ in order to recover the PPG $ppg[k]$. Here $\Delta l_{ma}[k]$ is the zero-mean version...
Figure 5. The spectrogram of monitor signal \( v_{MD}(t) \) in subfig. 5a shows the Doppler components as a result of laser motion in baseband and around the modulation frequency at 40 kHz and its second harmonic. Demodulation and normalization of the monitor signal yields vector coordinates \((x_n(t), y_n(t))\) in subfig. 5b. Subfigure 5c shows the displacement \( \Delta L_{smi}(t) \) measured using this vector in solid blue, the LDTS reference \( \Delta L_{ref}(t) \) in baseband and around the modulation frequency at 40 kHz and its second harmonic. Demodulation and normalization yields the Cartesian coordinates \((x_m(t), y_m(t))\) in subfig. 5b. The fragment in Fig. 5b shows a change in the laser’s direction of motion: at first the Doppler frequency decreases, and when it starts increasing again, the order of the coordinates’ local extremes has changed which indicates the change in direction. The carriers required for demodulation are ideally, only the Doppler signals as a result of laser motion can be observed in baseband and around the modulation frequency at 40 kHz. Normalization is achieved by dividing \( v_x(t) \) and \( v_y(t) \) by the square root of their 10 Hz low-pass filtered power. The Doppler signals in baseband are weaker than the Doppler signals around 40 kHz and 80 kHz because of the modulation depth used (Section 2.1). Figure 5a also illustrates a higher noise level in baseband compared to the frequency bands around 40 kHz and 80 kHz.

Demodulation of the monitor signal as described by Eqs. (12) and (11) and subsequent removal of the mean and normalization yields the Cartesian coordinates \((x_n(t), y_n(t))\) of the rotating vector, which are illustrated in solid blue and dashed red in Fig. 5b. The fragment in Fig. 5b shows a change in the laser’s direction of motion: at first the Doppler frequency decreases, and when it starts increasing again, the order of the coordinates’ local extremes has changed which indicates the change in direction. The carriers required for demodulation are conveniently obtained by band-pass filtering the monitor signal at 40 kHz and the monitor signal squared at 80 kHz. Normalization is achieved by dividing \( v_x(t) \) and \( v_y(t) \) by the square root of their 10 Hz low-pass filtered square multiplied by two. A cut-off of 10 Hz is used to prevent creating a square wave at low velocities and to prevent extreme amplification of signal parts that have a very small amplitude as a result of destructive speckle interference. Normalization is reasonably effective, because \( A_y(t)/A_x(t) = 1.01 \pm 0.261 \text{ [-]} \) for the 11 s

\[
\min_{h_0} \xi[l] = \min_{h_0} \frac{1}{N} \sum_{k=1}^{N} e_0^2[k] = \min_{h_0} \frac{1}{N} \sum_{k=1}^{N} (\bar{v}_{PD}[k] - h_0[l] \Delta l_{ma}[k])^2,
\]

\[
h_0[l + 1] = h_0[l] - \mu \nabla_{h_0} \xi[l] = h_0[l] + \frac{2 \mu}{N} \sum_{k=1}^{N} e_0[k] \Delta l_{ma}[k],
\]

with step size \( \mu \). The minimum of output power \( \xi[l] \) is determined by successively taking steps in the opposite direction of its gradient \( \nabla_{h_0} \xi[l] \) with step size \( \mu \). When \( h_0[l] \) has converged, the minimum output power has been found and \( e_0[k] \) does not contain any information anymore that correlates with \( \Delta l_{ma}[k] \). Ideally, only the PPG remains when \( h_0 \) has converged, which would imply that \( \Delta l_{ma}[k] \) correlates with the motion artifacts very well and not at all with the PPG as a result of the modeled cardiac activity.

5. EXPERIMENTAL RESULTS

5.1 Measuring laser displacement

By focussing the laser beam on the Delrin window, the laser’s displacement can be measured using SMI (Fig. 5). The spectrogram of the monitor signal \( v_{MD}(t) \) in Fig. 5a is obtained when the shaker is driven by a 1 Hz sinusoid. Doppler signals as a result of laser motion can be observed in baseband and around the modulation frequency at 40 kHz and its second harmonic. The Doppler signals in baseband are weaker than the Doppler signals around 40 kHz and 80 kHz because of the modulation depth used (Section 2.1). Figure 5a also illustrates a higher noise level in baseband compared to the frequency bands around 40 kHz and 80 kHz.
measurement of which Fig. 5 shows a fragment. Imperfections in normalization therefore result in an error in the order of $10^{-8} - 10^{-7}$ m, assuming a maximum of five times the RMS value (Eq. (16)). A 13 s background measurement obtained by illuminating a stationary black object has shown that the normalized noise terms $n_{xn}(t)$ and $n_{yn}(t)$ respectively equal $-2.04 \cdot 10^{-3} \pm 69.6 \cdot 10^{-3}$ [μm] and $8.47 \cdot 10^{-3} \pm 51.7 \cdot 10^{-3}$ [μm], and that $2(n_{xn}(t) + n_{yn}(t))/A(t) = 23.5 \cdot 10^{-3} \pm 0.457$ [μm]. Assuming a maximum of five times the RMS value, it follows that shot noise, thermal noise and quantization noise result in a displacement error in the order of $10^{-8} - 10^{-7}$ m (Eq. (16)). Measurements therefore show that the inaccuracies in displacement taken into account by Eq. (16) are in the order of $10^{-8} - 10^{-7}$ m.

Figure 5c shows the displacement $\Delta L_{\text{smi}}(t)$ obtained via Eq. (14) in solid blue, the LDTS reference $\Delta L_{\text{ref}}(t)$ in dashed red, their difference $\Delta L(t) = \Delta L_{\text{smi}}(t) - \Delta L_{\text{ref}}(t)$ in dotted purple and the scaled shaker control voltage $V_{\text{skr}}(t)$ in dash-dotted green. A positive displacement corresponds to a decrease in laser-detector distance (Eq. (14)). The mean value of the displacement measurements has been removed in Fig. 5c, because it is not relevant in the context of PPG motion artifact handling. The mean value of $\Delta L_{\text{smi}}(t)$ depends on the time instant at which the measurement was started during the periodic motion of the shaker. By first using $\theta = 0^\circ$ in Eq. (14), the ratio of the peak-to-peak displacements obtained by SMI and the LDTS has shown that $\theta = 61.0^\circ \pm 0.255^\circ$. The deviation of $1^\circ$ can result from the fixation of the laser diode in the laser pen. By using $\theta = 61^\circ$ the peak-to-peak displacement measured via SMI equals 2002 ± 3.25 μm. The reference yields a peak-to-peak displacement of 2003 ± 4.93 μm. The difference between both displacement measurements equals $\Delta L(t) = -1.19 \cdot 10^{-12} \pm 9.08 \mu m$. Both displacement measurements show a lag with respect to the control voltage as is to be expected because of inertial effects.

Comparing the displacement measured via SMI to the reference measurement obtained by the triangulation sensor shows that both displacement measurements are equal in shape (Fig. 5c). The mean difference of 1 μm in peak-to-peak displacement is well within the 45 μm resolution of the triangulation sensor. A difference $\Delta L(t)$ can be observed between the SMI and LDTS displacement measurements when speckle interference leads to a very low SNR of the coordinates, to distortions in the 90° phase relationship between the coordinates or to jumps of π rad in the coordinates’ phase. Speckle interference therefore occasionally prevents the vector to rotate properly. Consequently reconstruction of the displacement by tracking the vector’s phase leads to errors. The local minima in the amplitude of the vector coordinates in Fig. 5b (e.g. at 0.045 s and 0.125 s) illustrate the impact of destructive speckle interference on the coordinates’ amplitude. Not being able to track tens of cycles as a result of speckle leads to an error of $10^{-6}$ m. The precision of the SMI displacement measurement is mostly the result of speckle interference. The noise sources in Eq. (16) cause errors which are smaller by a factor of at least 10. A precision of $10^{-6}$ m is sufficient, since sensor motion is expected to be in the order of 10⁻⁴ – 10⁻³ m. Therefore, this measurement shows that translation of the laser above a Delrin window can be reconstructed with sufficient accuracy using SMI by applying the theory outlined in Section 2.

### 5.2 Measuring PPGs

PPGs have been measured when a pulsating flow of milk goes through the rigid and the pulsatile channel of the flowcell, to verify that the change in milk volume in the pulsatile channel indeed is the cause of the PPG. Results are shown in Fig. 6, obtained when the roller pump rotates at 20 RPM, thus simulating a heart rate of 60 BPM.

For the rigid channel with the transparent and the Delrin window, the PPGs have magnitudes of approximately 2 mV and 3 mV respectively (Figs. 6a, 6b). For the pulsatile channel, the respective PPGs have magnitudes of approximately 50 mV and 20 mV (Figs. 6d, 6e). For the rigid channel, the transparent and Delrin windows respectively deflect by approximately 10 μm and 8 μm as measured by the SMI algorithm with $\theta = 29^\circ$ (Fig. 6c). For the pulsatile channel, respective deflections of 10-15 μm and 12 μm have been obtained (Fig. 6f). Similar window deflections have been measured using the TESATRONIC TTA 20 analog length measuring instrument with a scale interval of 0.1 μm, which verifies the SMI displacement measurements.

The rigid channel PPGs have comparable and very small magnitudes. If the PPGs would have been a result of light traveling through the flow channel, the scattering behaviour of Delrin would have caused the resulting PPG to be significantly smaller compared to the PPG obtained with a transparent window. Moreover, the window deflections are similar in both cases. Therefore it is assumed that the rigid channel PPGs result from changes in ambient light intensity reaching the photodiode, caused by the deflection of the windows. The pulsatile channel
Figure 6. PPGs measured by the photodiode on the flowcell’s window for a rigid and a pulsatile channel, with a transparent and a Delrin window are shown in subfigs. 6a, 6b, 6d and 6e. Deflection of the transparent and Delrin windows measured using SMI is shown in subfigs. 6c and 6f, for a rigid and a pulsatile channel respectively.

PPGs are approximately 25 and 7 times larger than the rigid channel PPGs. Moreover, motion of the windows is comparable to the rigid case. This indicates that the pulsations in the pulsatile channel PPGs are a result of the change in milk volume in the channel. It can also be observed that the magnitude of the pulsatile channel PPG is approximately 2.5 times smaller when the transparent window is replaced by a Delrin window, which is a result of the light scattering by Delrin (Eq. (17)). The light scattering by the Delrin window also results in a stronger optical shunt compared to the transparent window, as can be observed from the increase in DC level when comparing Figs. 6a and 6b and Figs. 6d and 6e. Finally, one can observe that the SMI displacement measurements obtained for transparent windows are more noisy compared to those obtained for Delrin windows. This is because Doppler shifted light backscattered by the milk flow also interferes in the laser cavity when applying a transparent window.

5.3 Reducing optical motion artifacts

Reduction of optical motion artifacts using NLMS with the SMI displacement measurement as artifact reference is illustrated in Fig. 7. Here, the laser is moved by steering the shaker with a 0.5 Hz - 10 Hz band-pass filtered white noise sequence. All PPGs have been measured from the flowcell with a Delrin window. The NLMS algorithm has been trained using a step size of $\mu = 0.001$ for 2500 iterations. Zero mean inputs to the NLMS algorithm have been obtained using a 0.3 Hz high-pass filter (Fig. 4).

First the reduction of a pure optical motion artifact is considered (blue in Fig. 7a). The pure artifact is measured by illuminating a stationary milk volume and by moving the laser as shown in Fig. 7c (SMI result in blue and LDTS result in dashed red). By using $\Delta L_{smt}(t)$ as artifact reference, NLMS reduces the motion artifact significantly (red in Fig. 7a). The performance of the NLMS algorithm is quantized by the difference between the artifact (blue/red) and the “DC” reference (green), which is obtained by illuminating the stationary milk volume with a stationary laser. NLMS reduces the artifacts by a factor of 7.4 from $-0.329 \pm 5.38$ mV to $-0.0715 \pm 0.730$ mV using $h_0 = -0.0053$. Second, the reduction of a motion artifact perturbing a PPG is considered (blue in Fig. 7b). The motion distorted PPG is obtained by illuminating the pulsatile milk volume and by moving the laser as shown in Fig. 7d (SMI result in blue and LDTS result in dashed red). The pure reference PPG (green in...
Figure 7. Subfigures 7a and 7b respectively show a pure motion artifact and a motion distorted PPG (blue) measured in the laboratory setup. Laser displacement causing the artifacts in these subfigures is respectively shown in subfigs. 7c and 7d, as measured by SMI (blue) and the LDTS (dashed red). Reduction of motion artifacts achieved via NLMS using these SMI displacement measurements is shown in red in subfigs. 7a and 7b. The references (green) in subfigs. 7a and 7b are respectively the “DC” voltage measured when illuminating stationary milk and a pure PPG.

Fig. 7b) is obtained by illuminating the pulsatile milk volume with a stationary laser. The reference and motion distorted PPG have been synchronized by visual inspection. Also in this case NLMS significantly reduces the motion artifacts (red in Fig. 7b), even though they are in the frequency band of the PPG. NLMS reduces the artifacts by a factor of 4.3 from $-0.398 \pm 6.59 \text{ mV}$ to $-0.319 \pm 1.55 \text{ mV}$ using $h_0 = -0.0067$. Finally, the periodic component in the difference $\Delta L(t)$ between the SMI and LDTS measurements in Fig. 7d is most likely caused by deflection of the Delrin window (Fig. 6f).

The results in Fig. 7 prove that correlation exists between optical motion artifacts as a result of laser motion and the laser’s displacement. They also show that these motion artifacts can be reduced significantly using an NLMS algorithm with just a single coefficient. The motion artifacts are not completely removed though, which can be understood using Eq. (18). In case of a pure optical motion artifact, the artifact will mainly result from $\Delta l_{ed}(t)$ and $\Delta l_{mi}(t)$. Since $\Delta l_{ed}(t)$ is directly measured, the change in optical shunt is probably reduced largely. The change in optical pathlength $\Delta l_{mi}(t)$ through the milk in the channel and the insert may not be a linear function of $\Delta l_{ed}(t)$ though. The remaining optical artifact is therefore considered to result from the change in pathlength $\Delta l_{mi}(t)$ not linearly related to $\Delta l_{ed}(t)$. In case of a motion distorted PPG, the multiplicative term $\Delta l_{mi}(t)/l_{mi}$ is thought not to be fully removed either, as indicated by the reduced suppression of the artifacts. It may be removed partly, as $h_0$ is larger in magnitude in this case compared to the pure artifact.

6. DISCUSSION AND OUTLOOK

From the experimental results it can be concluded that laser displacement can be measured sufficiently accurate using SMI, that a PPG can be modeled by a pulsating milk volume in the flowcell, and that an NLMS algorithm
with a single coefficient can already significantly reduce optical motion artifacts in the PPG using the SMI displacement measurement. However, in the laboratory setup only a one dimensional motion has been considered resulting from sensor deformation. To determine the full potential of the SMI displacement measurement, changes in height and the angle of the laser have to be considered, as well as motions of the laser-photodetector combination. In case of a three dimensional motion it is further to be determined whether a single SMI measurement can still suffice or whether multiple SMI measurements on orthogonal axes would be required to reduce the motion artifacts. Moreover, a very simple algorithm has been used to remove the optical motion artifacts. More complex algorithms are to be considered which may exploit the fact that the PPG is distorted by additive and multiplicative terms. Finally, the whole sensor is to be miniaturized, starting by reducing the dimensions of the laser pen configuration, in part to relax the requirement of focussing the laser to observe SMI.

Although a PPG can be modeled using a pulsatile milk volume in the flowcell, the PPG does not have a realistic shape. Therefore the flowcell’s channel is to be improved, so a more realistic PPG can be measured in the laboratory setup. To start, the moving insert is to be replaced by a flexible membrane, to improve reproducibility of the pulse shape and amplitude. Optical shunt resulting from non-perfused tissue has been modeled by a Delrin skin phantom. It is not known however, whether the relative contribution of this shunt to the whole PPG is realistic. In addition, the rigid skin phantom is to be replaced by a flexible one. This allows modeling of pulsations in the PPG caused by non-perfused tissue and investigating the effect of changing sensor pressure on the measured PPG.

7. CONCLUSIONS

It has been hypothesized that optical motion artifacts in a PPG as a result of a changing emitter-detector distance correlate with movement of the emitter with respect to the skin. This hypothesis has been proven true in a laboratory setup that can reproducibly induce optical motion artifacts in a PPG by translating a laser with respect to a flowcell that models skin perfusion. Moreover, it has been shown that significant reduction of the optical motion artifacts can be achieved using an NLMS algorithm with only a single coefficient, that uses the laser’s displacement as measured by SMI as a reference for the motion artifacts.

ACKNOWLEDGMENTS

This work was supported by AgentschapNL, IOP Photonic Devices, IPD083359 HIP - Hemodynamics by Interferometric Photonics. The authors are very grateful to Mr. Ben Wassink of VDL ETG Research, for his great efforts in designing and constructing the experimental setup. The authors are also grateful to dr. Cristian Presura of Philips Applied Technologies for his contribution to the SMI displacement measurement.

REFERENCES


