Three-Dimensional Measurements of Bodies in Motion Based on Multiple-Laser-Plane Triangulation

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Abstract This paper presents laser-based, three-dimensional (3D) measuring applications involving three different bodies in motion: a knee joint during leg motion (1), thoraco-abdominal and back deformation during breathing (2) and the shape of a foot during walking (3). The first (1) setup is based on a commercial sensor Kinect, whereas the second (2) and the third (3) are based on custom-developed, multiple-line, triangulation measuring systems. Special attention was given to the color-modulation principle and the selection of the proper optical components. Based on the calibration, the accuracy of the system is 1.4 mm (1), 0.7 mm (2) and 0.5 mm (3), while the measuring range is 900×700×600 mm (1), 400×600×500 mm (2) and 400×160×180 mm (3). The camera frame rate for each setup is 30 Hz (1), 25 Hz (2) and 30 Hz (3). All the systems were evaluated in vivo on adult volunteers. The presented measuring systems are capable of real-time measurements, while enabling a precise and nonintrusive analysis of shape deformation, which has a lot of potential in clinical diagnosis, patient assistance or the development of new shoe models.

Keywords: Laser triangulation, 3D measurement, bodies in motion, color-modulation, shape deformation

1. INTRODUCTION

Over the past two decades, various optical, three-dimensional (3D) imaging methods for measuring the motionless shapes of objects have been established (Pavlovič et al., 2013; Poredoš et al., 2015; Hackenberg et al., 2003; Legaye, 2012). Particularly in the field of medicine, advanced therapies have spurred the need for non-contact and non-invasive 3D measuring systems that can provide high-accuracy measurements while maintaining robustness and mobility (Pavlovič et al., 2013; Seoul et al., 2010).

Similar trends are observed in the footwear industry, where the ability to acquire a 3D shape of the foot is important for measuring its specific geometrical characteristics (Novak et al., 2014). Over time, the need for 3D measurements of the shape of a deformable object in motion has arisen (Jezeršek and Možina, 2009; Timo et al., 2010; II Novak et al., 2014).

Measurements of a foot in motion under different load conditions, in the case of a bare or shod foot, allow us to analyze the various shape characteristics of the foot (II Novak et al., 2014). This can lead to an even more precise shoe-size determination for population groups of different gender and age. Another example is in the field of orthopedic surgery, where an analysis of knee-joint motion is important for determining the pathological condition of the patient. It has been proven that only a certain type of leg motion induces forces so that the knee joint shows a deviation from that of a healthy knee (Miranda et al., 2013; Gao et al., 2012). Another example is in the field of pulmonology, where the deformation analysis of a thoraco-abdominal surface during breathing can be used to obtain the volume of inhaled and exhaled air. This can be useful during volumetric measurements or effective breathing training (Povšič et al., 2012).

(Su et al., 2010) made a thorough review of high-speed, 3D-shape measurement methods. Stereophotogrammetry, which is a typical representative of the passive 3D measurement methods, is capable of measuring objects in motion (Hackenberg et al., 2003; Legaye, 2012). However, their surfaces must have dense texture information. Time-of-flight (TOF) cameras capture the entire 3D scene based on the known speed of light (Oggi et al., 2004). They are used in automotive, human-machine interfaces and gaming applications, but a major drawback is their limited resolution, which is currently around 7 mm. The third category is triangulation-based methods, where structured light-pattern projection is used to demodulate the measured shape of the object. Furthermore, triangulation-based techniques are subdivided by their projected pattern shapes into single-spot projection, single-line projection and 2D fringe projection. Only methods that are based on 2D fringe projection are appropriate for measuring the whole 3D shape of the object in motion since a single image is needed to recover the shape information (Poredoš et al., 2015; Seoul et al., 2010; Povšič et al., 2012; II Novak et al., 2014; Amann et al., 2001). All those methods are primarily used for measuring from a single viewpoint, since light patterns interfere when using multiple measuring modules.

This interference can be avoided by using time multiplexing, where individual camera images capture consecutively and only the corresponding projector illuminates the surface at a particular time. Such a technique was used, for example, by (Timo et al., 2010) for 3D measurements of a whole foot in motion. Simultaneous
illuminating and capturing is possible using the color-modulation principle, where multiple-laser-plane projectors use a unique wavelength (Jezeršek and Možina, 2009; II Novak et al., 2014). In this way, any unwanted overlapping between adjacent light patterns is solved and the measurement speed is increased up to the limits of the selected cameras.

In this paper we present the principles of a 3D measuring method that is capable of full-field, real-time measurements of deformable bodies in motion. Special attention is given to the color-modulation principle and the selection of the appropriate optical components, i.e., laser projectors, cameras and narrowband filters. The usefulness of the method is demonstrated for three measuring applications: knee-joint motion, breathing-related body deformations and foot-shape measurements during walking.

2. MEASURING PRINCIPLE
The 3D shape measurement is based on the principle of triangulation (Amann et al., 2001) where a laser projector illuminates the measured surface with multiple laser planes, while a camera acquires the illuminated surface from a different viewing angle (see Figure 1a). As a result, the light pattern on the acquired images is distorted by the shape of the surface. An example of the digitized image of the measured human foot is shown in Figure 2. Since the laser projector illuminates the entire surface simultaneously, the acquisition time and therefore the time resolution is equal to the shutter time of the camera, which is typically 5 ms.

Figure 1. Multiple-laser-plane triangulation principles: a) single measuring module with one camera; b) single measuring module with two cameras; c) multiple measuring modules.

Figure 2. Example image of measured foot, illuminated by multiple laser planes.
According to Figure 3, where the basic triangulation scheme with a single laser line is shown, the light-pattern translation on the camera’s sensor (Δν) is expressed as (Pears et al, 2012):

$$\Delta v = \Delta z \cdot m \cdot \sin \alpha$$  \hspace{1cm} (1)

where Δz denotes the vertical movement of the surface, m denotes the optical magnification of the camera lens and α denotes the mutual angle between the light plane and the camera’s optical axis, which is also known as the triangulation angle. Based on equation 1 it is clear that both m and α increase the vertical resolution. However, limitations related to the measuring range and the shadowing effects often lead us to choose a relatively small magnification (m< 0.1) and triangulation angle (α< 30°).

The second way to minimize the shadowing effect is the inclusion of a second camera, which is symmetrically positioned relative to the laser projector (see Figure 1b). Such a setup can efficiently measure the object from a single viewpoint, but multiple measuring modules (camera-projector or camera1-projector-camera2) are needed when an all-around 3D object shape has to be measured (see Figure 1c). In the case of an object in motion, all the cameras must acquire images simultaneously. To overcome the interference between neighboring light patterns, each measuring module uses a unique wavelength of laser light and the corresponding cameras use narrowband optical filters that pass only the laser light of a certain wavelength, particular to each module. The transmission spectra of the lasers’ emissions and filters in the case of three measuring modules are schematically presented in Figure 4, where the following conditions must be fulfilled: (1) the lasers’ spectral line width (measured as the full width at half maximum intensity – FWHM) are smaller than or equal to the corresponding filters’ FWHM and (2) the difference between the central wavelengths (λ₁, λ₂ and λ₃) must be greater than the sum of the corresponding FWHM filters. By using this technique, which is called color modulation, the measuring speed is limited only by the cameras’ frame rate and the camera-to-computer communication bus.
The image-processing algorithm and the 3D shape reconstruction are independent of the configuration (see Figure 1). After the image acquisition the light pattern is detected using a sub-pixel algorithm (Jezeršek and Možina, 2003). Afterwards, the detected contours are sorted and indexed. The transformation from two- to three-dimensional space is performed using the mathematical equations described in (Jezeršek and Možina, 2009).

3. APPLICATION EXAMPLES
The above-described principles are demonstrated in several applications where the primary aim is to measure human body parts in motion.

3.1. Knee-joint motion measurements
The first example shows a solution for a robust 3D knee-joint motion measurement that is used for determining the pathological condition of a patient’s knee. The measuring system is based on the commercially available Microsoft Kinect device. It comprises a near-infra-red laser projector with a wavelength of 830 nm, which projects a structured pseudo-random dot pattern onto a measured surface. Besides the 3D shape it also measures the surface color using a RGB camera. The measuring range is 900×700×600 mm (width×height×depth) and the resolution is 1.4 mm at a distance of 1 m (Raposo et al., 2013; Khoshelham and Elberink, 2012).

The experimental setup is shown in Figure 5. The distance between the Kinect and the knee is approximately 1 m. The subject is seated on a table so that both feet can move freely and with the upper leg (thigh) in contact with the table across the whole length of the thigh. During the tests the subjects are asked to perform a periodic movement of raising and lowering the shank.
The 3D shape of the thigh and the shank from the depth image as well as the image coordinates of four markers from the RGB image are acquired with a frequency of 30 Hz. An example of raising the shank is shown in Figure 6a. The extraction of the leg contours and the marker positions (M1-M4) is shown in Figure 6b. These markers are used for the thigh-movement compensation during the raising/lowering of the shank. The result of the compensation is shown in an example in Figure 6b. It is clear that the black curves, which show the tendency for raising the thigh during the measurement, are successfully compensated (blue profiles).

After the extraction and compensation of the leg’s profiles from the 3D data a linear approximation of the shank’s profile between the markers M3 and M4 is then calculated during the flexion/extension movements. Two envelopes are then constructed from a group of lines: a flexion and an extension (see Figure 7). An area between both envelopes, the so-called hysteresis, is the final result of the analysis, which is shown with an orange color in Figure 7b. Our hypothesis is that a healthy knee joint exhibits lower values of hysteresis compared to a knee joint with an anterior cruciate ligament (ACL) rupture.

Preliminary results show a clear trend of kinematic differences between healthy and injured knees. Therefore, this method could provide a quick, simple and non-invasive way of detecting knee instability after an ACL injury as well as an evaluation of the outcome of ACL reconstruction surgery.

### 3.2 Visual feedback during breathing training

The next example shows a method for breathing-training assistance, where the main goal is to offer patients a simple and intuitive feedback during exercise on a bicycle or a treadmill. Since the body is subjected to motion, only the displacements related to breathing need to be extracted. In traditional setups the subject is leaned against a wall in the standing posture and close contact is required to limit the body’s movement. In such setups, the wall is used as a reference surface on which the thoraco-abdominal displacement calculations are based.

To avoid this limitation, a double-sided measuring setup was developed (see Figure 8). The breathing-related deformations are calculated by subtracting the front surface from the back surface. This allows the subject to move freely and only the displacements related to the breathing remain. Furthermore, the system does not...
interfere with the human respiratory mechanics, therefore providing more objective results, while maintaining the patient's stress levels at a minimum.

**Figure 8.** Experimental setup for thoraco-abdominal surface measurements during breathing, based on a multiple-line laser triangulation system with two modules (front and back).

Figure 9 shows a typical measuring sequence of the front and back surfaces for a subject with abdomen-dominant breathing, where the surface displacements are displayed with a color palette. The colors are used as a visual feedback method, where the blue color represents inward (negative) displacements and the red color represents outward (positive) displacements.

**Figure 9.** A typical sequence for a 3D reconstructed shape with the color of the front and back during abdomen-dominant breathing.

The results show that the 3D measuring system offers a simple, intuitive and effective method of communication with the patient with respect to his/her breathing patterns.

### 3.3 Foot measurements during walking

The following example shows a system for 3D measurements of foot shape during walking. A foot in motion is constantly subjected to deformation, which puts further requirements on the internal strength and shape of the footwear. It must be able to allow and withstand hose deformations. Otherwise, damage to the footwear and, more importantly, injuries to the feet may occur.

The design of the system is shown in Figure 10. With the use of four measurement modules, which are arranged around the measured foot, the whole surface of the foot is covered. To measure the underside of the foot, an elevated walking platform with a glass plate is used. Its dimensions are 0.78 × 4.68m (width × length). For this type of measurement the principle of color modulation is used. All the measuring modules are identical to those that are shown in Figure 1b. The laser projectors (Lasiris SNF 533L, Coherent Inc.) have wavelengths of 635, 685, 785 and 830nm. The number of light planes is 33, the fan angle is 45°, and the inter beam angle is 0.38°. The cameras (FFMV-03M2M-CS, Point Grey) have a resolution of 640 × 480 pixels. The speed of the video acquisition
is 30 Hz. Between each camera sensor and objective a narrow band filter is installed (Coherent Inc.), with the light-transmittance spectral bands being at 635, 685, 780, and 830 nm and with a spectral line width of 20 nm.

To capture the video signals from eight cameras a PC with an Intel® Core™2 Quad Processor Q9400, 2.00 GB of RAM and Windows XP was used. A connection between the PC and the cameras was established using two PCI 1394a FireWire adapter cards.

**Figure 10.** Schematic representation of the 3D foot-measurement system during walking.

The described system is used to perform measurements on a bare and a shod foot, which allows us to analyze the effect of different models of footwear on the deformation of the foot while walking. An example of 3D measurements of the foot at 80% of the stance phase is shown in Figure 11. It is clear that the system measures the whole surface of the foot. The dimensions of the selected cross-section, such as the circumference, width, height and its orientation, can be extracted from the 3D measurements. The relative measurement repeatability across the entire stance phase is 0.5% for the bare foot and 1% for the shod foot (II Novak et al., 2014).

**Figure 11.** A sequence of 3D measurements of a shod-foot shape during the stance phase.

The presented measuring system for the 3D foot-shape determination during walking enables a much more precise evaluation of fitting the foot in the desired shoe as well as a more optimized development of the footwear. The algorithm for the calculation of fitting the footwear to the foot is based on the following equation:

\[
Fit = Fit_L + \sum_{i=1}^{N} Fit_{section,i}
\]  

(2)

where \(Fit_L\) denotes fitting the lengths of the foot and the shoe, and \(Fit_{section,i}\) denotes the fitting of the dimensions in the i-th section. Larger values represent a poor fit and vice versa.

The proposed algorithm was verified on one particular shoe (Alpina Binom, model Panda, product 8F84. Alpina, 2014). The inside dimensions of the shoe were determined using the last of this shoe. The shoe size was 37 (French measure), because the tested shoe was found to be the most appropriate for the test subject. First, the
static shape of the foot was measured using the measuring system introduced in (I Novak et al., 2014). Second, based on a physical test of the shoe’s comfort the test subject chose the most appropriate shoe width label from the four available versions (A, B, C, D) of the presented shoe. The final step was a measurement of the dimensions of the foot for the previously chosen sections based on 3D measurements of the bare foot during walking.

![Figure 12](image.png)

Figure 12. The result of the fitting calculation, depending on the width of the shoe.

The calculated fit, depending on the width of shoe, is shown in Figure 12. Based on the results, we can conclude that the test subject would be most comfortable when wearing shoes with width C or B. The least comfortable would be model A (width A), which is, according to the calculation, much too tight. The result of the calculation based on measuring the shape of the feet during walking is completely equal to choice, based on a physical trial of the shoe for the test subject.

4. DISCUSSION AND CONCLUSION

The presented examples show great potential for 3D measurements of the human body in motion. They can provide quick, precise and nonintrusive information about shape deformation, which is useful for clinical diagnosis, patient assistance or the development of new shoe models.

The main characteristics of the presented measuring systems are shown in Table 1. The system’s complexity is mostly related to the number of measuring modules integrated into the system. If a single module is used, only an internal calibration has to be made, otherwise the relative positions between the modules have to be determined using an external calibration procedure (Jezersk¡ and Možina, 2009).

<table>
<thead>
<tr>
<th>Application example</th>
<th>Knee joint motion</th>
<th>Measurement of breathing</th>
<th>Foot measurement</th>
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<tr>
<td>Measurement system</td>
<td>Kinect</td>
<td>Multiple line triangulation</td>
<td>Multiple line triangulation</td>
</tr>
<tr>
<td>Number of measuring modules</td>
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<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Laser projector pattern</td>
<td>Pseudo-random dot pattern</td>
<td>33 equally inclined light planes</td>
<td>33 equally inclined light planes</td>
</tr>
<tr>
<td>Camera frame rate [Hz]</td>
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<td>25</td>
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</tr>
<tr>
<td>Measuring range [mm]</td>
<td>900×700×600</td>
<td>400×600×500</td>
<td>400×160×180</td>
</tr>
<tr>
<td>Precision [mm]</td>
<td>1.4 mm</td>
<td>0.7 mm</td>
<td>0.5 mm</td>
</tr>
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</table>

The measurement speed is normally equal to the camera’s frame rate, since the measurement principle in all systems is based on single image acquisition.

In all cases the limiting factor for the speed of the measurement is therefore the transfer rate of the video signal from the camera to the computer and the data processing. The latest industrial cameras are able to acquire a video signal with a frequency of up to 200frames/s, but in the case of simultaneous recording with multiple cameras a reduction in the video-acquisition frequency is necessary in proportion to the number of cameras.

Such a case was presented with the measuring system for foot measurements during walking, which uses eight cameras. In our opinion, increasing the speed of the measuring systems is possible by parallel processing the video signal, for which a specially developed platform, based on a FPGA platform or a DSP unit, which is
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REFERENCES


