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ORIGINAL ARTICLE

Holographic topometry for a dense visualization of soft tissue for facial reconstruction

Frank Prieels · Sven Hirsch · Peter Hering

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Abstract Facial reconstruction can be used as a forensic technique to identify a person, when no other identification method is applicable. The facial soft tissue thickness applied to the skull is crucial when performing an accurate facial reconstruction. Historically, scientists developed several techniques to measure the soft tissue of the face. It was their aim, to build a database of a unique point-set, differentiated by gender, age, ethnic origin, BMI. All used a limited number of landmarks and an inaccurate measuring technique. We developed a contact-free and precise measuring technique, using low-dose CT and holographic data. Due to the extremely short exposure time, the holographic measurement is very precise. We lay out our first experiences to create a facial soft tissue layer map of the face.

Keywords Holographic imaging · Topometry · Soft tissue · Computer tomography · Facial reconstruction · Forensic

F. Prieels · P. Hering
Institute for Laser Medicine, University of Duesseldorf, Universitaetsstrasse 1, Building 22.03, 40225 Duesseldorf, Germany

F. Prieels
e-mail: frank.prieels@uni-duesseldorf.de

P. Hering
e-mail: hering@uni-duesseldorf.de

S. Hirsch (✉)
Computer Vision Laboratory, ETH Zurich, Sternwartstrasse 7, 8092 Zurich, Switzerland
e-mail: hirsch@vision.ee.ethz.ch

The objectives of soft tissue reconstruction

Facial reconstruction, the scientific art of visualizing faces on skulls, for the purpose of identification, has been exercised for over a century. It is used when all other alternatives remain unsuccessful. The technique is indicated when dealing with burnt, severely mutilated, skeletalized, or decomposed bodies or remains. It is generally recognized that there are three different techniques for facial reconstruction:

– two-dimensional facial reconstruction (2D)
– video superimposition
– three-dimensional facial reconstruction (3D)

In the 2D facial reconstruction, an artistic drawing is made over the photograph of the skull. Later, computer-assisted approaches of 2D facial reconstruction became more popular [9, 16, 27, 45, 44]. The technique of video superimposition is used to compare the skull with a pre-mortem photograph. The purpose is to establish a close enough relationship between the two images, to state that these belong to the same individual, with a high degree of confidence. The validity of superimposition has always been a point of discussion [8, 10, 20, 25, 33, 39]. In 3D facial reconstruction, different methods exist which utilize soft tissue depth markers, fixed to the skull or a cast. The soft tissue of the face is then built up with clay, plasticine, or wax. The method is dependent on the knowledge of certain features of the skull, as well as the use of tables of mean values of soft tissue thickness, measured at some specific landmarks [15, 17, 34, 41]. The first research on facial soft tissue depth was done in the 19th century by the early practitioners of facial reconstruction. Scalpel blades, needles, and probes were used at that time [23, 26, 47–49]. Later, new techniques were introduced, e.g., radiographs and ultrasound. These datasets had limitations in accuracy.

As well there is only a small number of subjects in the soft tissue depth studies, and there are little data available of different age, gender, and race groups [3, 5, 11, 19, 28, 32, 35, 37, 46].

Soft tissue measurement with analog holographic topometry

The Holographic topometry method [7, 12, 18, 21, 42] was developed to visualize deforming or moving objects. It is especially suited for tissue profiling of living persons, but is applicable as well to industrial tasks. The first experiences in soft tissue reconstruction we gained from a comparative project between plastic, drawing, and video reconstruction [40] where we learned about the potential of the different facial reconstruction approaches. The holographic recording technique is especially suited for precisely measuring the skin surface. The main advantage is the avoidance of motion artifacts, which usually degrade the measurement. As well we used our technology to archive and analyze archeological findings [1, 13, 24]. In this study we capture the holographic recording from a single perspective, which means that the view is limited to the directly visible field. The field of view may be further extended by the introduction of mirrors [14]. There we recorded three perspectives simultaneously in one holographic recording. By combining these mirror views afterward we can accomplish a surround view of the object. We did not use this technique for this particular study as it is connected with significant additional effort. Holographic topometry is a two-step process. First a hologram of a scene is recorded with a pulsed laser, which virtually freezes all motion. The second step is the optical reconstruction of the recorded light field with the subsequent extraction of the profile. The result from the holographic measurement is a dense object surface and a perfectly fitting texture of the surface. The texture data are especially useful to measure the distance map between two surfaces [6].

Holographic recording

In holography both, amplitude and phase, of a wave field are recorded, which yields the possibility to capture and reconstruct the light field three dimensionally [31]. The basic idea of holography is to create an interference of the object wave field with a reference wave. A coherent light beam, usually a laser, is split into two equal copies. One illuminates the object and the reflection forms the so-called object beam; the second part travels directly to the recording medium as the reference. The interference of both beams constitute a static light field, this is called a hologram. Reference and object beams include a large angle (off-axis) to separate the different diffraction orders [29, 30], revealing a finely structured interference grating. The hologram is recorded with a highly resolving photographic emulsion ($\approx$3000 lines/mm). Generally, electronic sensors (CCD, CMOS) are possible recording devices [22], whereas for off-axis arrangements these lack sufficient resolution [38]. In cooperation with GEOLA (Vilnius, Lithuania) we custom designed a mobile holographic camera [4] with a maximum laser energy output of 1.4 J at 532 nm wavelength (green) . The camera is used for field recordings and may be assembled within 15 min. The illumination beam is widened and guided over two ports, situated at both sides in front of the patient (see Fig. 1). Eyes' safe recording is guaranteed by placing a diffuser screen at each illumination port. The reference beam is expanded into a divergent wave with two concave lenses and guided to the hologram plate via two overhead mirrors. A shutter system allows for hologram recording under daylight conditions. Green light is perfectly suited for skin imaging owing to its minimal tissue penetration depth of 1mm and the high reflectivity of 60% [36].

Optical reconstruction

The second step in analog hologram topometry is the optical reconstruction of the hologram. The reconstruction beam perfectly resembles the time-reversed (conjugate)

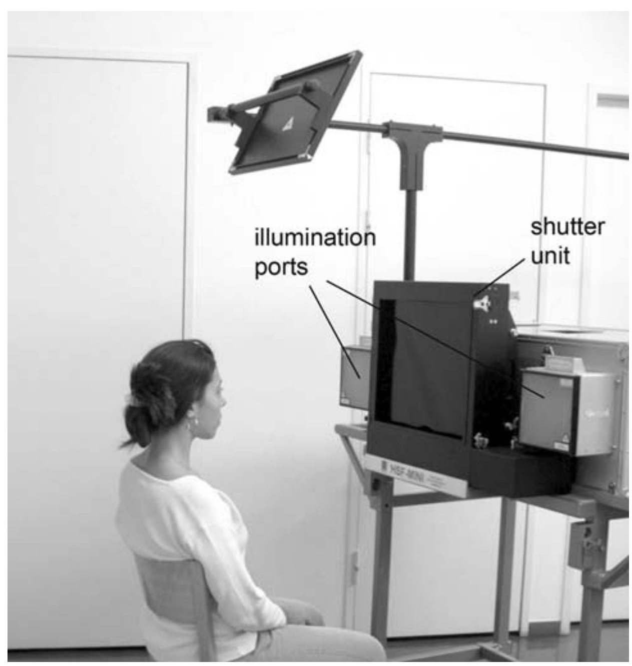

Fig. 1 The proband sits in front of the holographic camera. The hologram plate resides behind the black shutter curtain. The illumination ports are on both sides of the patient. The diverging reference beam exits the camera at the top and is guided to the hologram plate over two mirrors

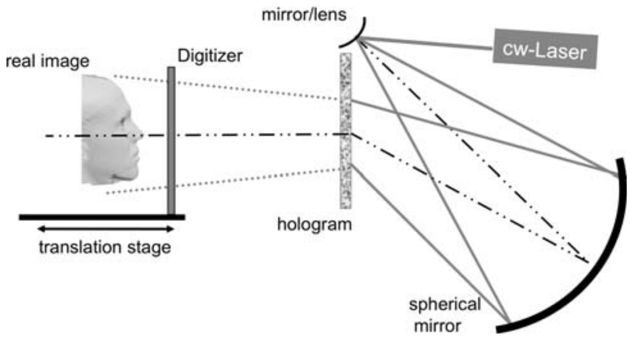

Fig. 2 In the optical reconstruction step the information is extracted from the hologram. A cw-laser illuminates the hologram over a spherical mirror, with the time-reversed reference beam. The real image constitutes, exactly positioned where the patient was during recording. A digitizer is guided through the image and captures the whole 3d volume slice-by-slice

reference beam thus forming the real image (see Fig. 2). Here a continuous wave Nd:YAG diode pumped solid state laser (Coherent, Verdi V-2, 532 nm) is used, forming a static light field at the former object position. The real image has exactly the same dimensions as the real objects, as there is no frequency shift between the recording laser and the reconstruction laser. The real image is then digitized axially in 2d-projections of equal distance by travelling a recording device (Varian PaxScan 2520) over a translation stage (hologram tomography) with a lateral resolution of 127 μm. The inter-slice distance is chosen between 100 μm and 0.5 mm, a typical image stack contains 300 slices representing the full volume of the face.

Surface extraction

In the volumetric image stack, each slice contains information of the focused regions and blurred information of all neighboring regions. We face the task of discriminating between focused and unfocused regions (see Fig. 3). A focus measure operator F_{xy} evaluates the local contrast by determining the variance in a small x,y-region, usually 5 × 5 pixels. Finding the maximal focus measure along the z-axis leads to the desired axial surface coordinate [2]. Using this shape-from-focus approach, a depth value is generated for each point (x,y), resulting in a height map of the complete face [43]. The focus measure $F_{xy}(z)$ is determined through the image stack. The maximum of contrast coincides with the surface of the object. At the surface, the brightness $I(x,y)$ is extracted from the image stack. In combination one obtains a height map and a perfectly fitting texture image.

At the identified surface point, the brightness information is extracted [14]. Such, one obtains a 2d monochromic representation $I(x,y)$ of the surface texture beside the surface point. The combination of the surface and texture

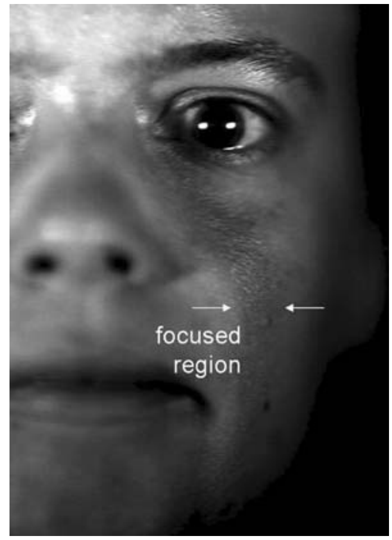

Fig. 3 Each slice of the image stack contains only a confined region of in-focus information

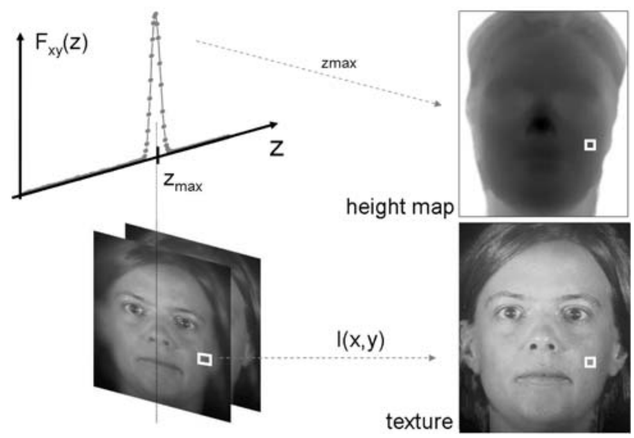

Fig. 4 The focus measure $F_{xy}(z)$ is determined through the image stack. The maximum of contrast coincides with the surface of the object. At the surface, the brightness $I(x,y)$ is extracted from the image stack. In combination one obtains a height map and a perfectly fitting texture image

yields a textured 3d model with fine details (see Fig. 4). The surface points are connected to a polygon mesh, the alignment of the texture is ideal since no further mapping is involved. The accuracy of the surface gained by the holographic topometry is about 0.4 mm. The lateral resolution is limited by the physical resolution of the digitization. The actual resolution limit of the real image itself is well below 10 μm.

Soft tissue measurements

In forensic facial soft tissue depth measurement, there is a strong need for a contact-free, optical measurement system.

We introduced a new method for measuring soft tissue thickness, using low-dose CT and hologram tomography, in order to create a *facial soft tissue database*. We will demonstrate the principles of using a holographic and CT dataset for soft tissue thickness estimation with the software RapidForm (INUS Technologies).

The study

For the study, we collected low-dose CT data and holographic data from 14 probands. We performed two hologram recordings per proband, one in reclined and one in upright position. For the present aspect we only used the recordings probands in upright position (see Fig. 1).

We used a 4-slices Siemens Somatom Plus (80kV, 50 mA, 1 mm slice cut). Compared to the conventional CT the radiation is reduced by a factor 10, the radiation dose of 2 mSv was ethically approved. As a consequence of the low intensity the images are of a lower signal-to-noise ratio, which is nonetheless sufficient for bone and outer skin segmentation.

A critical step is to register the holographic dataset to the skull, since they have no common regions. To fulfill this task, the facial surface was also extracted from the CT data. CT scans are recorded in a reclined position, whereas holograms are taken in an upright position. This is why only regions with little soft tissue displacement (due to gravity) are considered for the registration between the holographic and the CT facial surface model. These regions are mainly the back of the nose and the lower forehead. RapidForm is a powerful full featured software for processing 3D scan data. RapidForm converts data from any 3D scanning device (laser, white light, CT/MRI) into high quality polygon meshes or geometrically solid models. Initially, the DICOM files are loaded to RapidForm and are segmented to mark the bone outline. The built-in RapidForm algorithm can provide a satisfying segmentation; for the bone threshold we used the typical Hounsfield value of 1250 HU. Although this choice is fairly standard, the segmentation of low-dose CT data is still a point of discussion. From the volume data we created a polygonal isosurface. After eliminating stray points (scattering, ear fixation) we obtained a nice 3D working model of the skull. If necessary we can derive a shell out of the polygonal isosurface; this allows us to significantly reduce the number of data and retain only the surface of interest. To mark the CT soft tissue outline it is necessary to perform another segmentation on the volume data. The second polygonal shell provides all the soft tissue information from the low-dose CT image. This polygonal shell will be the reference shell for positioning the holographic image. Via locking the grid and both an initial and regional registration, we can adjust both soft tissue outlines. The initial registration allows us to roughly adjust the images by picking reference points on both images. This first step is necessary to initialize the ICP algorithm (iterative closed point) based regional registration with a reasonable first guess. Using regional registration, we can make a precise superimposition of both the soft tissue polygonal shell and the holographic surface (see Fig. 5). After marking the area where we do not expect a soft tissue shift, superimposition of both shells will allow us to obtain a good positioning of the hologram to the polygonal shell of the skull (see Fig. 6).

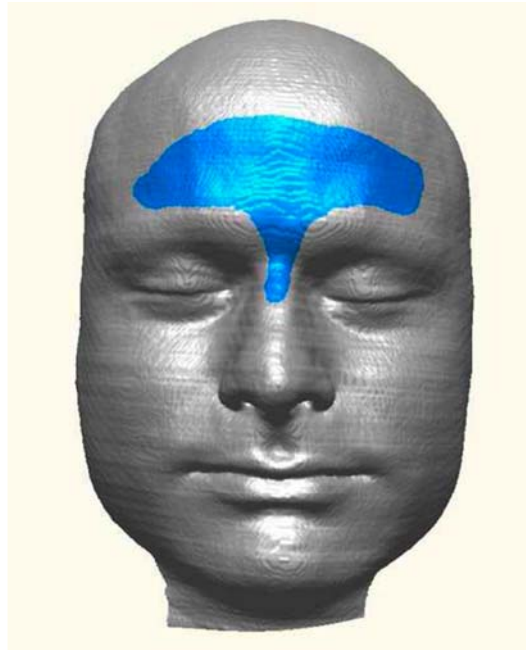

Fig. 5 Regional registration of holographic surface and low-dose CT facial surface

Establishment of the facial soft tissue map

Classical soft tissue databases have average soft tissue thickness at specific anatomical landmarks. In contrast to former work, where cadavers were used to estimate soft tissue thickness, Helmer was the first one to measure on living persons using ultrasonic device; a sensor with a contact gel was positioned at specific anatomical landmarks [19]. The sensor is in direct contact with the skin, which might lead to deformations. The holographic method for soft tissue thickness measurement provides contact-free information of living persons' face in upright position. Additionally, the soft tissue information is not restricted to anatomical landmarks, but is accessible for the whole face. Figure 7 shows the soft tissue thickness map perpedicular to the bone. Thus we can create a whole soft tissue layer,

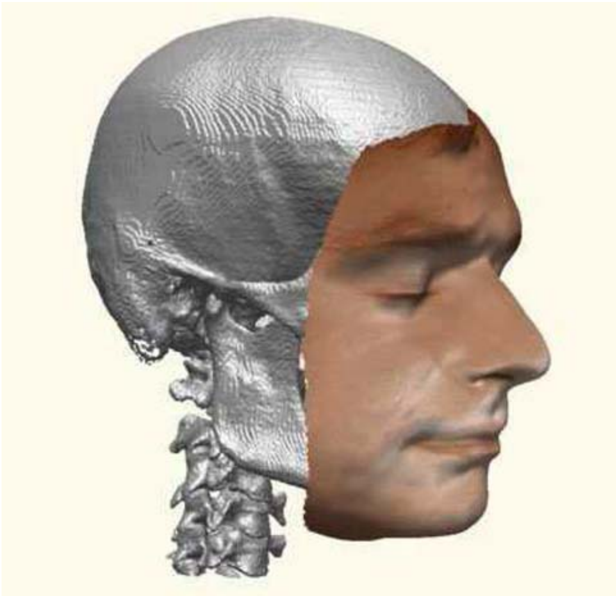

Fig. 6 Positioning of the holographic surface to the skull. The texture from hologram is included

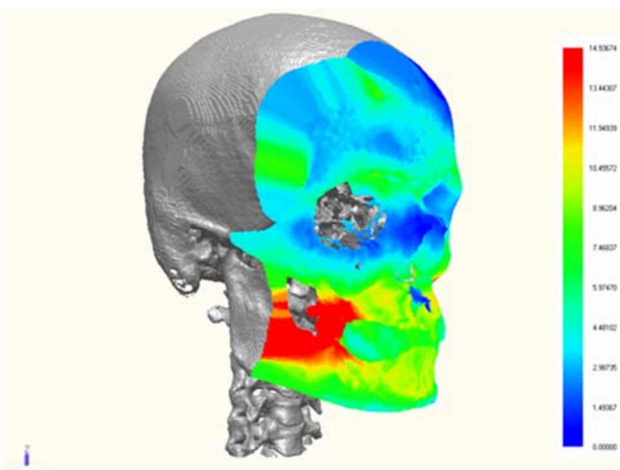

Fig. 7 Visualization of soft tissue thickness

where anatomical landmarks may be selected deliberately at any point of the bone (see Fig. 8).

Conclusion

We presented a new approach to facial soft tissue thickness measurement. Compared to other measurement techniques, our method is very precise due to the contact-free capturing and a very short exposure time. This method creates opportunities to develop a facial soft tissue database, important to reconstruct a face from an unknown skull. The

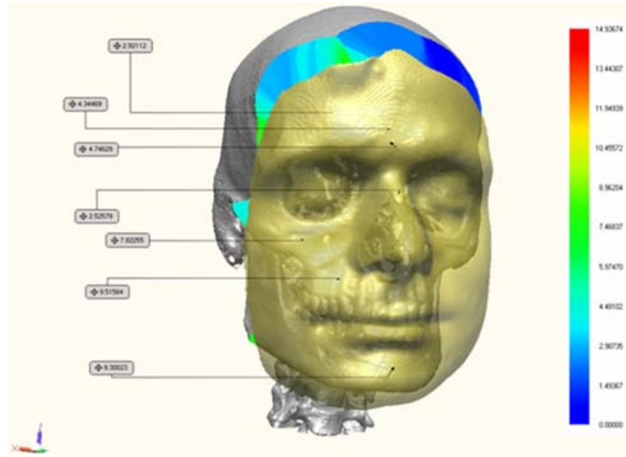

Fig. 8 Positioning of the holographic surface to the skull, with soft tissue thickness indication for selected landmarks

evaluation of the complete study is subject of our current investigations and will be presented in a forthcoming publication.

We set the foundations for further investigations in the soft tissue modeling. This technique provides two major opportunities: due to the fact that we can record holograms of probands in upright and reclined position, we can visualize the soft tissue shift due to gravity [21]. Considering influences from age, gender, race, body mass index, a large database of facial measurements may be used to analyze an extended existing CT database, all taken in reclined position. Secondly, every skull in the corresponding category of the database could be transformed into the skull of the unknown person, using an elastic transformation. Applying the same transformation to the face, one can get the average face corresponding to the skull of the unknown person. Finally, this can be transformed in an automated process without directly measuring any soft tissue thickness.

Educational message

1. Pulsed holographic topometry allows us to get a very precise, contact-free facial outline without movement artifacts.
2. A dense field of landmarks is ideal to represent a precise soft tissue thickness pattern of the face.
3. A critical step is the registration of the holographic surface to the CT soft tissue surface.

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