

# THE PHOTOGRAMMETRIC DETERMINATION OF HEAD SURFACE SHAPE AND ALIGNMENT FOR THE OPTICAL TOMOGRAPHY OF NEWBORN INFANTS

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## ABSTRACT:

The development of optical tomography at University College London (UCL) has been motivated by the urgent need for tools to monitor the brains of newborn infants who are vulnerable to brain injury during the first few hours and days following birth. Injury associated with a lack of sufficient blood and/or oxygen, which can occur deep within the brain, is a major cause of permanent disability in infants who survive after neonatal intensive care (particularly those who are born very prematurely). Results obtained using a 32-channel time-resolved system have already shown that optical tomography can provide 3D images which reveal spatial and temporal variation in intrinsic optical properties, and of absolute physiological parameters such as tissue oxygenation and blood volume.

The technique requires that source fibers and detector bundles (optodes) are coupled to the head using a plastic helmet. Images are generated using a sophisticated non-linear image reconstruction package, TOAST, developed by Prof. Simon Arridge and his team at UCL. TOAST generates images by determining the parameters which describe an appropriate model of photon transport within the infant head by comparing its predictions with measured data. The model is then adjusted iteratively until acceptable correspondence is achieved, and convergence towards the correct solution is assisted by the use of regularisation methods. The model requires a finite-element mesh of the infant head with a realistic geometry.

The plastic helmet in which the optodes are mounted is necessarily mechanically deformable, the optodes inevitably move after the infant is removed, and the measured positions have a degree of uncertainty which restricts the accuracy of the reconstructed images. Measuring the positions during tomographic scanning is impractical since the infant's head prevents access to the rear section of the helmet. Accordingly knowledge of the location of the optodes with respect to the infant head surface is required.

This paper describes the application of close range photogrammetry to map each individual infant head surface in the clinic, and to provide more accurate measurements of the optode positions during tomography scans. Whilst such tools have been used for facial mapping and for engineering metrology, the specific challenge is to create tools which can be employed on newborn, and often severely ill, infants in an intensive care environment.

## 1. INTRODUCTION

### 1.1 Background

Premature infants are liable to suffer lack of oxygen to the brain which can lead to permanent brain damage [1]. Certain interventions are being developed, but an imaging method is urgently needed to determine when treatments are necessary, and how effective they are. At UCL, optical tomography has been developed as a means of generating 3D images of blood volume and oxygenation of the infant brain at the bedside. The imaging instrument [2] and the TOAST reconstruction software [3] have already been used successfully to image the brains of infants in the UCL neonatal intensive care unit [4-6]. However, progress on this work has been limited by the lack of knowledge of the true external geometry of the infant head and its precise alignment during optical tomography image capture. In order to fill this gap and to more fully exploit the capabilities of optical tomography it is necessary to extend the technique by including digital photogrammetry which can provide 3D coordination and surface measurement. This paper presents new 3D surfaces and alignment of the infant's head, using photogrammetric tools, which will eventually be used routinely in optical tomography to map each individual infant head at the bedside in the clinic.

### 1.2 Current methods

The UCL imaging instrument measures the times of flight of individual photons diffusely transmitted across the infant head at two wavelengths (780 nm and 815 nm) [2]. The light is delivered and collected through optical fibre bundles (optodes) which are coupled to the infant head using a plastic helmet. In order to convert the time-resolved data into 3D images of the internal optical properties, an accurate 3D finite-element mesh (FEM) of the infant head with a realistic geometry is required. Images of absorption and scatter can then be produced by matching the predictions of the model to the experimental data [7]. The challenge is to determine an accurate surface mesh that is correctly registered to the 3D locations of the optodes at the time of the tomographic study so that an accurate 3D FEM model may be produced.

For experiments conducted so far, the only information available are the approximate positions of the optodes, which are measured on the helmet using a 3D digitizing arm after the study. A generic phantom surface mesh is warped to fit these points, and the surface mesh is then used to make a volume mesh, which is used for image reconstruction. The reliability of this approach in producing the true surface of the infant head is in doubt and it is likely that considerable errors are present. A

key reason for this is that because the helmet structure is necessarily mechanically deformable, the position of each optode inevitably changes after the infant is removed from the helmet. Measuring the positions during tomographic scanning is impractical since the infant's head prevents access to the rear section of the helmet.

### 1.3 Development of a photogrammetric measurement system for surface mesh generation

Photogrammetry is an established technique whereby multiple 2D images of a 3D object are measured and analyzed to produce accurate spatial information. The method involves using overlapping converging photos recorded with either a single mobile camera and fixed reference points in the field of view, or two (or more) cameras fixed relative to a common axis a known distance apart. Common features on the surface of the object are identified in each image, enabling the surface to be coordinated in three dimensions. For the purpose of this research appropriate features might be identified from the hair and skin on the head surface of the infant head, or might be artificial markers fixed to, or projected onto the head. 3D surface data in the form of surface patches from each image pair are then registered together to produce a complete 3D surface of the head. Registration may be performed either by identification of common points in overlapping areas of the data or through the use of surface point matching techniques such as iterative closest point (ICP) [8].

Critically ill infants in intensive care represent a novel and challenging subject and the acquisition of photogrammetric data obviously cannot interfere with their normal handling and treatment. The infants lie in cots, in close proximity to items of monitoring equipment which restrict both visual and physical access. In practice, a nurse, physician, or parent is able to readjust the position of the infant to enable imaging of as much of the surface of the head as practicable. A low cost reconfigurable high resolution photogrammetric system for acquiring accurate surface meshes from the heads of newborn infants has been built and is undergoing testing. Whilst there are commercial systems available from several manufacturers which employ photogrammetry for acquiring measurements without a skilled operator [9], these systems do not offer the flexibility necessary for determination of accurate optode alignment and are generally unsuitable for operation in a busy and crowded neonatal unit. The purpose-built system being tested consists of a pair of synchronized high resolution digital cameras (6.1 mega-pixel Nikon D70) mounted on a fixed support. The cameras have been modified to employ fixed focus lenses and provide a stable geometrically calibrated imaging configuration which is robust enough for routine clinical use.

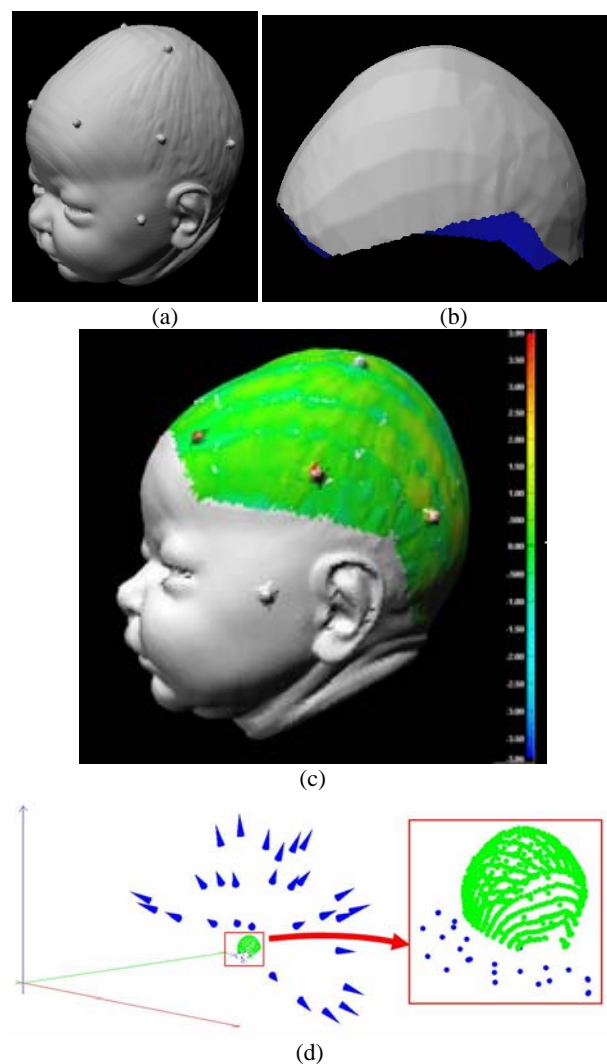
To provide a consistent measurement surface that circumvents measurement constraints imposed by varying amounts of head hair and skin colour, a short length of tubular net bandage (FRA Surgifix, Italy) is stretched around the infant head during image capture. The net is made from a soft, expandable fabric, the weave of which provides consistent features for photogrammetric image measurement. Photogrammetric software, VMS (Vision Measurement System) [10], is used to generate partial surface meshes from each stereoscopic view, and Innometric's Polyworks software [11] is used to register the individual sets of mesh data to produce a complete head model.

## 2. EXPERIMENTAL METHOD AND RESULTS

In order to validate the measurement system for routine use, a series of experimental tests are being undertaken. The following constitutes an analysis of the tests carried out to date.

### 2.1 Validation

The photogrammetric method was initially validated using plastic head models in order to establish its accuracy and repeatability. For this purpose meshes generated using photogrammetry were compared with gold standard surfaces, which were provided by Laser Scan and CT data. Prior to routine use, the photogrammetric system has to be calibrated to determine the geometrical optical properties of the cameras and their alignment to each other. A photogrammetric process, known as a self calibrating bundle adjustment allows both the geometric properties of each camera to be established as well as their alignment to each other [12].



**Figure 1.** (a) CT Scan surface, (b) Photogrammetric surface, (c) Comparison between surfaces, (d) Multi-photo imaging geometry.

Figure 1(a) shows the surface of a plastic doll's head acquired from x-ray CT, and figure 1(b) shows the corresponding (partial) surface generated by photogrammetry. The comparison between these two surfaces is represented in figure 1(c) and the

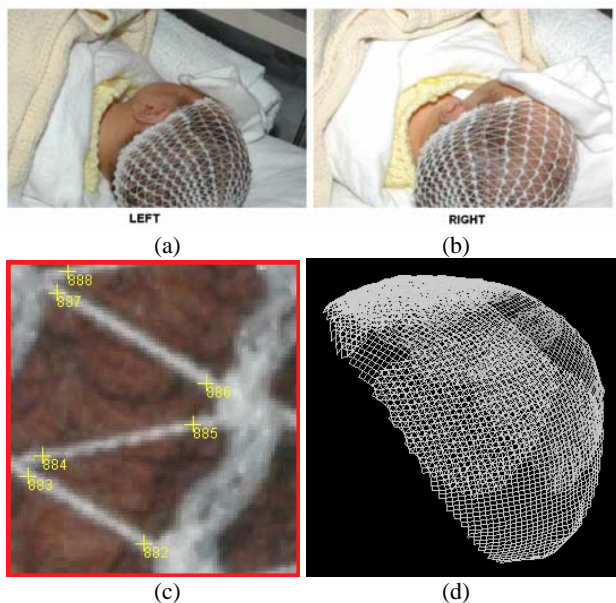
bar at the side shows the discrepancy in millimeters, which in most regions is within 0.5 mm and in the worse case is about 1.5 mm. 3D measurement precision estimates and other statistical quantities provide an estimate of the photogrammetric data quality obtained through photogrammetric bundle adjustment for both the camera calibration and plastic head measurement processes. The relative degradation, approximately an order of magnitude, between the 3D coordinate determination of the calibration object and the doll's head are attributable to the difference in measurement precision between signalized retro-reflective targets and natural features extracted from the mesh. Figure 1 (d) demonstrates the photogrammetric network of images taken to measure the surface of the dolls head in which the blue cones illustrate the camera positions and the central set of green points are those measured on the surface of the doll.

	Calibration	Doll
Number of 3D points in the network	64	861
Number of target image observations	842	4084
Number of images in the network	44	23
RMS image residual ( $\mu\text{m}$ )	1.60	6.65
Mean precision of targets coordinates ( $\mu\text{m}$ )	X: 3.7, Y: 3.9, Z: 6.8	X: 34.3, Y: 34.5, Z: 36.8
Relative precision for the network	1 : 86,000	1:6,000

**Table 1.** Some pertinent statistics from the photogrammetric bundle adjustments.

## 2.2 Clinical evaluation

Following a satisfactory initial validation process, the photogrammetric technique was applied to a healthy premature infant in the clinic. A series of stereoscopic views around the infant's head were taken, and then several partial image pairs (patches) were generated using photogrammetric intersection techniques. These surface patches were then registered together



**Figure 2.** (a) left and (b) right images of a stereo pair (c) detail showing image content, (d) partial 3D surface.

in order to generate the head mesh.

Figure 2 shows one of the stereo image pairs used to generate a partial surface mesh (illustrated in figure 2 (c)). Table 2 shows some pertinent data quality parameters, which were output following the processing of a typical stereo pair.

Mean standard deviation of individual surface data points ( $\mu\text{m}$ )	X: 43, Y: 42, Z: 194
Mean image residuals ( $\mu\text{m}$ )	7.1

**Table 2.** Some pertinent statistics from the photogrammetric data processing of a single stereo pair.

There are two key limitations to the technique at this stage. First, the structure and density of the weave of the medically approved bandage used to provide a photogrammetrically measurable surface that is consistent for all types of babies in the clinic and does not produce any detrimental effect to the infant. Second, the extent of the surface that is measurable within each stereo pair limits registration due to the ball and socket geometric nature of the adjoining surfaces.

## 2.3 Optode alignment

Work is in progress to define the location and alignment of the optodes at the time of tomographic data collection. Again photogrammetric methods are being used to image retro reflective targets located on the optodes, the helmet, and its supporting structure. These targets can be coordinated using standard photogrammetric metrology techniques and can provide a coordinate framework within which the locations of all of the optodes can be located. (see figure 3)

	Helmet
Number of 3D points in the network	133
Number of target image observations	2611
Number of images in the network	42
RMS image residual ( $\mu\text{m}$ )	3.6
Mean precision of targets coordinates ( $\mu\text{m}$ )	X: 76, Y: 106, Z: 85
Relative precision for the network	1: 6,000

**Table 3.** Some pertinent bundle adjustment output statistics from the combined retro target and optode coordination solution.

Comparison between the manually identified points on the net placed over the infant head demonstrate close agreement in terms of image measurement precision with the network geometry (23 images in a convergent network geometry vs. a single stereo pair) giving an expected degradation in measurement precision from  $\sim 35\mu\text{m}$  in all three axis using the network to  $\sim 40\mu\text{m}$  in plan and  $200\mu\text{m}$  in depth for the stereo pair. With a two camera system, the practical constraint within this process was that both the baby and the net could move between the acquisition of each stereo image pair, hence no common registration points could be reliably assumed necessitating that the registration of the extracted surface patches had to be achieved by surface fitting based on starting values from common features on the net bandage.

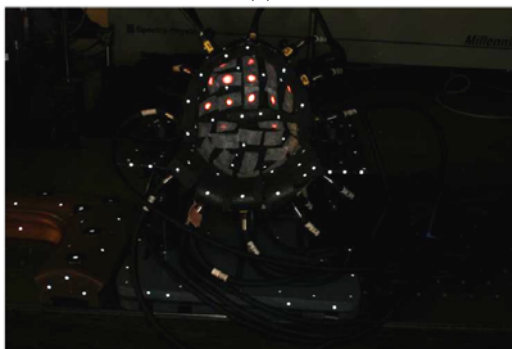
Analysis of the data from retro target imaging of the head and combined retro-target and optode illumination imaging of the helmet demonstrate a much bigger variation  $\sim 4\text{mm}$  in plan and  $7\text{mm}$  in depth for the retro targets which are consistent from viewpoint to viewpoint to  $\sim 100\text{mm}$  on plan and  $85\text{mm}$  in depth for the combined system. This large discrepancy is



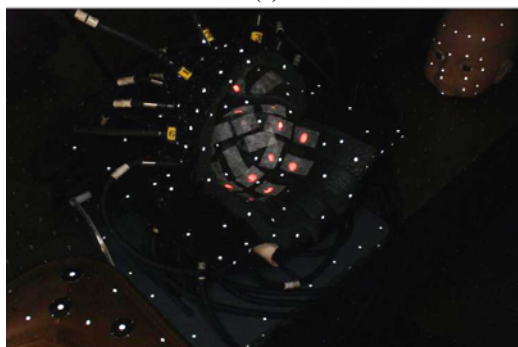
(a)



(b)



(c)



(d)

**Figure 3.** (a) the optode equipped helmet (b) the helmet positioned on a baby during a clinical trial (c & d) example images from a photogrammetric network containing both retro target images and optode illumination.

attributable to the fact that the optodes are located within cavities in the foam structure of the helmet and do not provide

consistently circular images from each viewing direction deployed in the network. The results are however at least an order of magnitude better than anything previously available and will allow comprehensive evaluation of the complete tomographic imaging and reconstruction process.

### 3. SUMMARY

After careful selection of both image content and geometry, the photogrammetric technique has been proven to be able to extract 3D surface information that is expected to yield superior models of the infant head for optical tomography of the newborn infant brain. The photogrammetric technique is now proven and work is on-going to produce an efficient clinical imaging process that can be used routinely on all infants in the neonatal intensive care unit on whom optical tomography studies are performed.

Further work is in progress to expand the use of photogrammetry to routinely determine the position and orientation of the optodes and ascertain their location relative to the surface of the infant's head whilst the helmet is being worn. A series of experimental work is also being undertaken to explore the influence of uncertainty in optode location and surface model fidelity on the output from the tomographic process.

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