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Technical note

A visual patient feedback device using optical surface measurement for the cooperative management of setup and body dynamics during radiotherapy

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ABSTRACT

In this technical note we describe a real-time visual feedback device for use during radiotherapy treatment. The device displays a patient's live pose and position, relative to a reference, to them, helping them to control and maintain their motion. The device uses an optical sensor system developed at The Christie NHS Foundation Trust that is capable of real-time performance of up to 24 unique wide-area body surface measurements per second. The feedback device has integrated audio and three intuitive visualisation modes designed to show different levels of detail with varying degrees of complexity: a '2D traffic-light display', '3D flexing lamina display' and '3D colour-mapped surface display'. The performance characteristics of the system were measured, with the frame rate, throughput and latency of the feedback device being 22.4 fps, 47.0 Mbps, 109.8 ms, and 13.7 fps, 86.4 Mbps, 119.1 ms for single and three-channel modes respectively. We additionally present a novel fast method for calculating the vertical displacement map of two 3D surfaces suitable for live, real time display and evaluate its precision with respect to other methodologies.

1. Introduction

Patient positioning is vital to successful modern radiotherapy treatment. The three-dimensional pose and location captured in their pre-therapy CT scan, upon which their individually tailored treatment plan is developed, must be precisely replicated if accurate disease targeting is to be maintained. Furthermore, this positioning must be sustained over each daily 15–30 min treatment 'fraction', with the whole course potentially lasting for several weeks. Failure to deliver the prescribed radiation dose to the tumour can result in treatment failure, whilst needlessly irradiating healthy tissues may lead to severe complications.

At present, the patient setup process remains generally manual, with the body surface manipulated by expert radiographers. They are commonly guided by a handful of skin marks, added by colleagues during an earlier treatment simulation procedure, with the result often verified via planar or volumetric X-ray imaging. The patient is passive, playing little or no part in the proceedings, save for being responsible for 'keeping still' once setup is considered to have been achieved. True immobilisation devices, or restraints, are less common than simple patient supports, exemplified by inclined lung and breast boards with arm rests. Apart from the (in)tolerability of restraints, this is largely for practical workflow reasons.

It is self-evidently impossible for even a healthy patient to remain motionless over the required time scales [1,2], and thus both quasi-periodic (e.g. respiratory) and irregular transitory (e.g. swallowing, coughing) motion must be monitored and accounted for. Current image guidance technology such as broad-field X-ray transmission imaging is not suitable for continuous monitoring – it cannot provide live body surface measurements and is unethical for radiation dose reasons. Consequently, there is an unmet need for assistive technology to both measure changes in patient pose and position live, and to provide the human interfaces to enable such information to be meaningfully employed. Feeding data back to the patient in an intuitive manner, we hypothesise, will engage them with their treatment and enable them to better control their motion.

There are in fact clear precedents for patients to become actively involved in their radiotherapy treatment. When presented with a respiratory waveform on an external device they are reportedly able to alter their breathing to match it, increasing the stability of their breathing pattern [3]. Conversely, in breath-hold techniques feedback devices have been used to show patients a line

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Table 1
Client and server computer hardware specifications.

	Client	Server
CPU	Intel[a] Core i7-975 EX 3.33 Ghz	Intel Xeon X5680 3.33 GHz × 2
RAM	4 Gb	8 Gb
GPU	ATI[b] Radeon HD4850 × 2	NVIDIA[c] GeForce GTX480
Networking	Intel Pro/1000 PT NIC (dual port)	Intel Pro/1000 PT NIC (quad port)

[a] Intel Corporation, Santa Clara, CA, USA.
[b] AMD Inc., Sunnyvale, CA, USA.
[c] NVIDIA Corporation, Santa Clara, CA, USA.

trace of their interrupted respiration measured using an added marker [4–6] or small area sensing of the body itself [7]. However, to address pose, position, and motion requires accurate live information from the extensive body surface, at least equivalent to that used for treatment planning.

In this technical note, we describe a true real-time, intuitive visual feedback device developed primarily to permit patients to cooperatively engage with the setup and delivery of their own radiation therapy. The device operates on optical skin surface measurements and additionally provides enhanced visual analyses of the motion extent to clinical staff. We present detailed technical descriptions of the system implementation, explain the design decisions, and report the device performance specifications. We give simple case study exemplars to provide operational context.

2. Materials and methods

The device we report here operates on surface measurements from an in house developed real-time optical sensor system. We describe this in detail elsewhere [8] and thus limit our discussion here to a brief review of the system and discussion of new features developed explicitly to support the presented apparatus. It is important to note at this point that the device is independent and can easily be adapted to operate with any suitably specified measurement system.

Our optical surface sensor system operates via the principle of Fourier Profilometry: a regular sinusoidal pattern is projected onto a patient, permitting the recovery of their surface topology through the analysis of the fringe pattern modulation as viewed by a video camera. In Price et al. [8] we discuss the use of multiple projector-camera sensors to further increase the optical measurement device's field of view and to provide detail in regions that would be occluded in single view systems (see Fig. 1). This is a persuasive argument and we thus incorporated this functionality into the assistive device we present here.

One high performance server provides enough concurrency to perform capture and processing simultaneously for the clustered sensors and personal feedback device. Note that the co-alignment of the surfaces from the different sensor heads is ensured through careful cross-calibration (detailed and validated in [8]) and as such attracts no image fusion processing overheads. One client machine operates the sensor projectors (see Table 1).

Processing itself is split to make use of the server's 12 CPU cores (Fig. 1). Master threads separately control image capture and processing. Within the video capture and image processing blocks, each sensor channel is given its own thread that performs the data capture or processing for that particular projector-camera pair. The master threads synchronise their worker threads and trigger execution when new data becomes available. By allowing new data to be captured whilst the current data is being processed and then rendered, the throughput of the system can be increased. Image rendering and user interface interaction are governed by additional threads. The processing necessary for the feedback device, described below, is additional to that necessary for surface calculation and is performed in the same threads. Table 2 details the resultant performance implications.

The selection of specific display technology and user interface design was guided by formal engagement with national patient and consumer representatives. They confirmed (a) an overwhelming desire to use personal technology to end the feeling of isolation during radiotherapy delivery, and (b) that this could best be achieved by giving patients the means to confirm the integrity of their own daily set-up. It was agreed that either a simple abstract graphical representation or an intuitive freeform rendering of the patient's body surface would be selectable according to preference. An audio signal is provided to help focus attention on the significance of visualised changes.

Images are currently displayed via a tripod mounted data projector providing VGA image quality wall/ceiling projection (DLP, Optoma Technology Inc., Fremont, CA, USA), or lightweight personal video glasses (Wrap 920, Vuzix Corp, Rochester, NY, USA). Of course, any display hardware may be accommodated.

2.1. Device requirements

To discern anatomical motion, the measurement rate must be such that it allows users to unambiguously distinguish between intermediate states. A common benchmark is respiration: quasi-regular motion with a period typically ranging from a 'rapid' 2 s to a 'slow' 5 s. For a significant 10 mm displacement in chest wall, breaking this motion into 10 phases (5 inhalation, 5 exhalation) equates to views at approximately 2 mm intervals from a sensor frame rate between 5 Hz and 2 Hz. However, this would not allow the capture of sudden shifts or transients, which dictate much higher measurement speeds. Additionally the human visual system perceives motion displayed at less than around 10 Hz as discontinuous. Historically, to avoid such effects standard video systems started operating at a de-facto 24 frames per second (fps). This has to be the target frame-rate for patient personal display devices, especially where extended use is envisaged. Necessarily, all associated devices must operate at a comparable rate, i.e. from data measurement through to processed graphical output.

The field of view also needs to be considered. In order to provide information on patient pose and position, greater coverage than the treatment field alone is required. To achieve this whilst maintaining reasonable spatial resolution, data densities approaching 512 × 512 surface points are necessary. Without this resolution (approximately millimetre over a ∼50 cm field of view) it becomes difficult to contemplate the tracking of surface features such as patient set-up 'tattoos'.

Throughout this paper therefore, we define the term 'real-time' as meaning the measurement of high density data (∼512 × 512 direct surface measurements) at speeds close to 24 fps.

2.2. The visual interface: preserving information in dynamic surface representations

The potential changes in a patient's pose and position may be very varied thus making visual interpretation over different scales difficult. Through discussion with patient representatives, we developed a simple and intuitive data representation model in which the live patient surface is compared to a reference position. Calculating the exact differences between two deformable surfaces is very difficult and in practice requires dense landmarks that correspondences may be calculated from. Human skin textures rarely contain such features at high densities and so instead we must calculate approximate correspondences as surrogates for quantitative motion analyses. In the context of a live feedback device, accuracy