BRAINLAB

POTENTIAL AND CHALLENGES OF SURFACE GUIDANCE IN RADIATION THERAPY

White Paper

SURFACE GUIDANCE IN RADIOTHERAPY

The introduction of image-guided radiation therapy (IGRT) in the early 2000s offered major accuracy improvements. Linac based X-Ray imaging drastically reduced patient setup uncertainties and inter-fraction motion. However, the intra-fraction imaging capabilities of linac based IGRT systems are limited, giving rise to a complementary technique for intra-fraction patient monitoring: Surface-guided radiotherapy (SGRT). The constant monitoring of the patient's surface movement and the comparison to a pre-recorded reference surface offer the possibility to detect and reduce intra-fraction patient motion. This paper will explain the basic technical concepts and limitations of SGRT and its core technology, structured light scanning (SLS). The second part of the paper will show how ExacTrac Dynamic® introduces technological advancements to overcome the limitations of SLS for patient positioning and monitoring.

PRINCIPLES OF STRUCTURED LIGHT SCANNING

The general goal for all surface imaging techniques is to measure the (x, y, z) coordinates of points on a surface. The result of the measurement is presented as a map of depth z as a function of the position (x, y). To acquire the surface data, the system projects a pattern, also known as structured light, onto the patient.

Patterns can vary in color and can range from one dimensional line structures to 2D grids to multiple pseudo-random patterns. Pseudo-random patterns are designed to avoid ambiguity during surface reconstruction, as they are unique at every point. Fast moving patterns allow for better statistical sampling of surface point information leading to higher surface reconstruction accuracy, while still being tolerable to the eyes for the majority of patients undergoing treatment.

An imaging sensor, typically a video camera, records the 2D image of the pattern on the patient's surface. If the surface is flat without any variations in depth, the recorded pattern is similar to the original projection. If the surface is not flat, however, the projected structured light pattern appears distorted[1]. If the spatial relation between projector and camera is defined, the depth information z can be recalculated using the following formula[1].

$$R = B\frac{\sin(\theta)}{\sin(\alpha + \theta)}$$

To enhance system accuracy, current clinical SGRT systems use up to three camera pods mounted in different positions in the treatment room in conjunction with one or multiple structured light projectors.

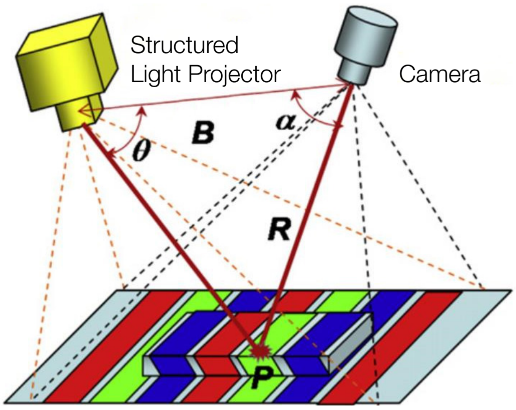

Figure 1:
Schematic presentation of a structured light scanner setup[1]

PROBLEMS AND LIMITATIONS FOR SURFACE TRACKING SYSTEMS

Surface tracking technology provides new intra-fraction motion monitoring capabilities and possibilities for additional applications such as respiratory motion control and gating, however several limitations and challenges of SLS in radiotherapy (RT) still remain.

Availability of Internal Information

All surface tracking systems are based on the assumption that there is a perfect correlation between surface and internal organ or tumor motion, since precise, real-time information about internal anatomy is generally not available during treatment. Correlations between surface and internal structures were investigated in several studies and found to be highly dependent on treatment site[2].

In particular for some regions of interest used for respiratory gating, this correlation can be inadequate for further margin reduction and normal tissue sparing. Alderliesten et al. investigated the heart position variability in deep inspiration breath hold (DIBH) radiation therapy[3]. Only a modest correlation between surface and heart position was found, demonstrating that surface guidance isn't a suitable technique to confidently monitor the dose to the heart.

During DIBH treatments for pancreatic cancer, internal organs move about 5 mm on average and in some cases movement even exceeds 1 cm[4]. Poor correlation of surface to internal motion may be a limiting factor if the treatment beam is planned to be gated by the surface system, as it could trigger inaccurate beam starts or stops.

This may require IGRT verification and cause subsequent delays in treatment or potential inaccurate delivery. Furthermore, the calculation of couch shifts can be compromised by a lack of internal information. Comparison between surface and volumetric registration of patients showed a mean translational discrepancy of 2.7 mm[5]. Error prone regions, such as facial soft tissues, are generally easily deformed. The option to use surface registration in conjunction with internal imaging is therefore crucial to verify the accuracy of the surface system for a particular patient and fraction.

Today, images of internal anatomy are most commonly acquired using devices mounted to the linac. However, the use of these devices throughout treatment is very limited[6]. Cone beam computed tomography (CBCT) or electronic portal imaging devices (EPID) at non-coplanar couch positions are either confined to inconvenient gantry angles or not possible at all due to the risk of linac collisions. Gantry rotations or extended imagers can occlude the view of lateral surface cameras, compromising the accuracy achieved by the surface tracking system. Simultaneous and flexible image acquisition of patient surface and internal anatomy is therefore the gold-standard for meaningful patient monitoring.

Sensitivity to External Factors

Like all optical systems, the effectiveness of structured light systems is dependent on ambient light and reflectivity. As displayed in Figure 2, the intensity of ambient illumination of an object can compromise scan quality and uneven illumination may cause errors in image reconstruction. Over illumination and uneven illumination can occur in the treatment room due to standard room lighting systems.

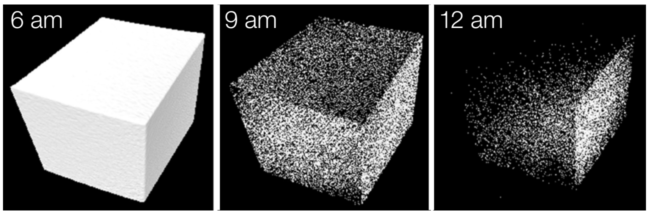

Figure 2:
Effect of ambient illumination on structured light 3D scanning. A white cube was placed outdoors on a clear day and scanned with a conventional structured light scanner at differing times and ambient light intensities (2000 lux, 24,000 lux and 90,000 lux, respectively)[7].

Light attenuating surfaces such as darker skin tones or body hair can compromise image registration due to limited visibility of the projected pattern[8].

Correct Matching of Live and Reference Surface

At the core of any SGRT system is the ability to compare and register a live patient surface to a reference surface in order to detect spatial positioning deviations. This also represents the most complex process.

Matching two 3D point clouds is a common problem in computer vision; the state-of-the-art matching algorithm is the iterative closest point (ICP) algorithm. ICP matching describes an alternation between finding correspondence and optimizing an objective function to minimize the distance between corresponding points[9]. The ICP algorithm, however, shows significant instabilities in the registration of objects with translational or rotational symmetries as shown in Figure 3.

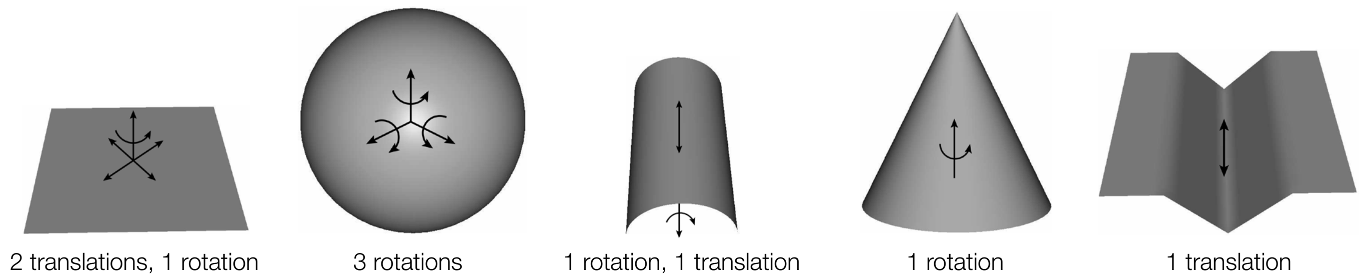

Figure 3:
Examples of simple shapes that are unstable for ICP registration. Each shape has at least one translational or rotational symmetry that corresponds with the direction of instability. Below each figure the number and type of instability is noted[10].

Image registration of objects like these can cause registration sliding effects, which for SGRT risk misalignment of the live patient surface with the reference setup surface. These errors in registration are described by Krell et al.[11] who investigated a commercially available surface tracking system. Uniform surfaces with minimal topographic information (e.g. breast, chest, flat abdominal area) caused problems during surface registration, forcing the clinician to choose larger than desired regions of interest to provide enough topographical information for sufficient surface registration, instead of smaller, more precise regions which may more closely represent the treatment location. This is a key limiting factor to the usefulness of surface tracking applications in RT.

In applications outside of RT, different approaches were tested to improve image registration and avoid sliding effects. The most common technique is to perform the alignment in a higher-dimensional space, characterized by 3D position in addition to other available information. It is much easier to establish sufficient correspondence in a four- or six-dimensional space than just in the physical three dimensions. Several studies showed that registration quality could be improved significantly by adding color information to the dataset as an additional dimension[9,12,13].

System Latency

A crucial requirement for the use of SLS systems in RT is to monitor possible patient shifts during treatment in real-time. System latency may cause problems in usability for patient pre-positioning and, more significantly, gating the treatment beam to prevent irradiation of normal tissue or insufficient target coverage.

For technologies used today, overall system latency is not limited by the frame rate of the SLS system, but rather the reconstruction time required to match the live and reference surfaces. This limitation is therefore not dependent on scanning hardware but rather on image post-processing software as well as the size of the tracked surface.

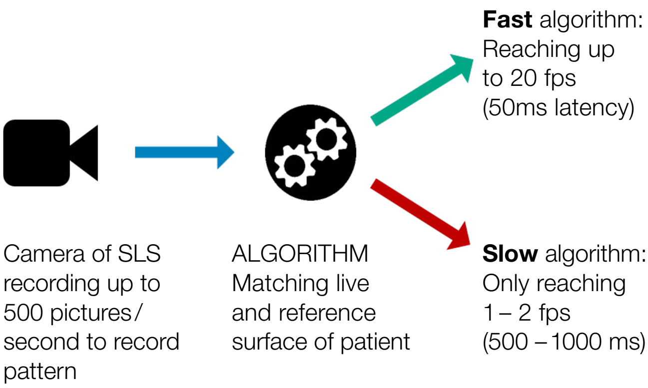

Figure 4:
The system latency does not only depend on the camera hardware but rather on the speed of the processing algorithm.

EXACTRAC DYNAMIC – CONSOLIDATED SGRT AND IGRT

ExacTrac Dynamic* from Brainlab provides an alternative approach to RT patient positioning and monitoring. The system consists of two kV X-Ray tubes mounted on the floor next to the linac, two ceiling mounted flat panel detectors and a single ceiling mounted 4D Thermal Camera* that contains a SL projector, two high resolution cameras, and an integrated thermal camera.

ExacTrac Dynamic Surface Tracking System

The 4D Thermal Camera is positioned centrally above the treatment couch. This position enables a clear field of view during treatment without risk of occlusions caused by gantry or gantry based imagers. The system can be operated in two different modes. The first is used to roughly pre-position the patient before treatment by matching the live 3D surface (Figure 5A) with the reference contour extracted from the treatment planning CT. This technique is used by other commercially available systems as well[14], but ExacTrac Dynamic performs final positioning based on stereoscopic X-Ray images of internal anatomy using the integrated IGRT system and updates surface tracking accordingly.

The second mode, unique to ExacTrac Dynamic, is used to track intra-fraction patient motion. 3D information is projected over the thermal image plane making it possible to combine the 3D and 2D thermal data using the Perspective-n-Point algorithm (Figure 5B) to calculate a hybrid 3D/thermal matrix. This is a common technique in computer vision to correlate 3D points with 2D information (thermal) to enrich every 3D point (x, y, z) with thermal information T.

$$P_i = (x_i, y_i, z_i) \rightarrow P_{\alpha i} = (x_i, y_i, z_i, \alpha T_i)$$

The weighting factor α ensures the comparability between geometric and thermal data and allows it to be utilized while matching the reference data P_i and the live surface P_j (Figure 5C).

$$\|P_{\alpha i} - P_{\alpha j}\| = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2 + \alpha^2(T_i - T_j)^2}$$

The thermal information creates an additional dimension, or virtual topography, allowing for higher tracking accuracy compared to algorithms using 3D data alone.

With every stereoscopic X-Ray acquisition, ExacTrac Dynamic records a new reference surface including updated thermal information. The simultaneous tracking of 3D position and thermal signature reduces sliding effects and provides higher accuracy compared to algorithms using 3D data alone. Furthermore, unlike color information, thermal imaging is unaffected by ambient lighting conditions. With this additional dimension of thermal information, ExacTrac Dynamic algorithms achieve much faster matching of live and reference surfaces. The system is able to track the patient's position at up to 20 frames per second with system latency as low as 50 ms. This enables ExacTrac to trigger a beam hold within milliseconds if the patient moves out of tolerance.

* commercial availability pending

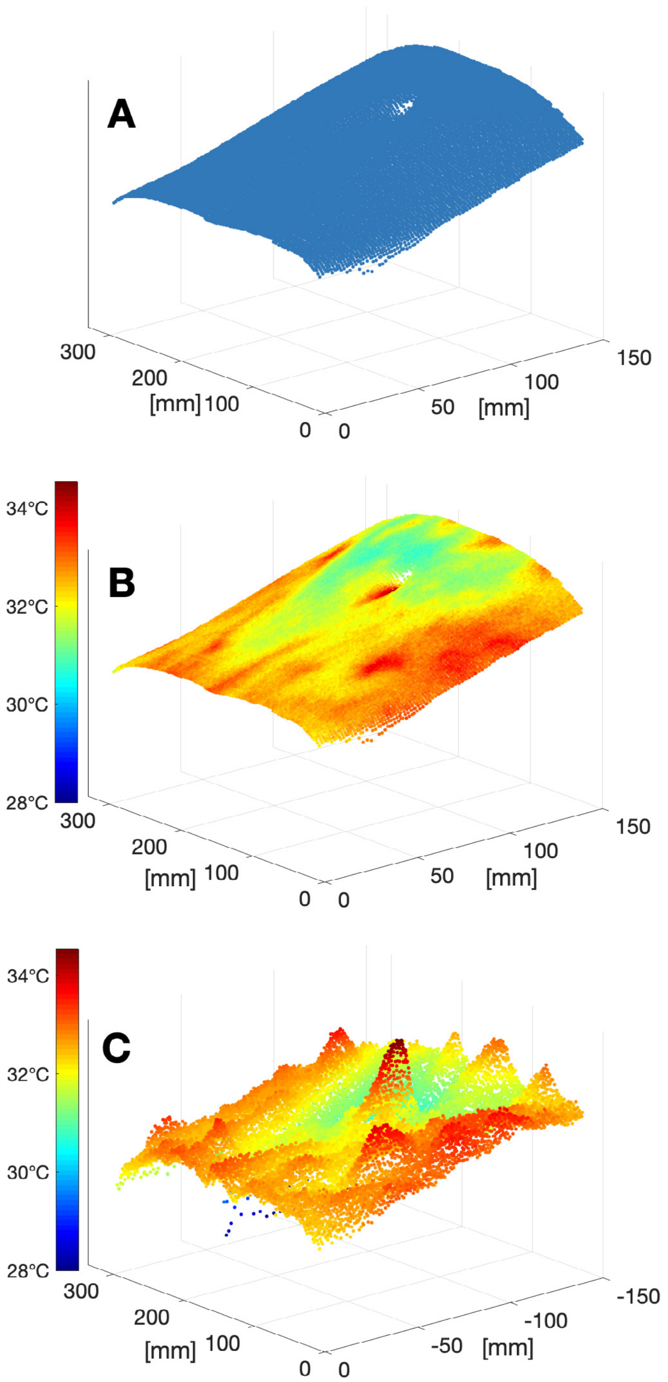

Figure 5:
All three graphs show an image of a male patient's stomach.
***A** shows the area as surface only.*
***B** displays the same area color coded with the patient's surface temperature.*
***C** shows the hybrid-thermal surface as calculated and used by ExacTrac Dynamic and how thermal information can be used to create an additional dimension of information.*

To ensure thermal imaging is a sufficient data source, internal tests confirmed that patient surface temperature shows a heterogeneous, but temporally stable pattern for typical durations of RT treatments.

ExacTrac Dynamic X-Ray Imaging System
Unlike other SLS systems, ExacTrac Dynamic is able to provide internal anatomical information. The floor mounted X-Ray tubes offer the possibility to acquire live images showing bony structures, fiducials and soft tissue. Due to their position and independence from the linac, intra-fraction X-Ray imaging is possible at any time and with low imaging dose. As shown by Alderliesten et al.[3] this imaging modality is essential to avoiding unnecessary organ dose. Furthermore, the ability to quickly acquire stereoscopic X-Ray images without rotating the table and immediately correct for patient motion in the final treatment position can decrease patient setup time[15].

Together SGRT and IGRT Provide Greater Accuracy Before and During Treatment
The combination of room based X-Ray tubes, live surface tracking, and thermal camera in a single system enables ExacTrac Dynamic to reduce or even overcome SGRT challenges and limitations. The system provides a fully integrated patient positioning system that can monitor patients before and during the treatment with higher accuracy and shorter treatment times compared to currently available workflows.

References
[1] Geng J. Adv. Opt. Photon. 2011; 3: 128
[2] Fayad H, et al. Medical physics. 2011; 38: 3157–3164
[3] Alderliesten T, et al. Radiotherapy and Oncology: Journal of the European Society for Therapeutic Radiology and Oncology. 2013; 109: 442-447
[4] Zeng C, et al. Journal of applied clinical medical physics. 2019; 20: 37–43
[5] Kim Y, et al. Medical physics. 2014; 41: 121701
[6] Meng B, et al. Phys. Med. Biol. 2013; 58: 7777
[7] Gupta M, et al. In: 2013: 545–552
[8] Jecić S, et al. In: 2003
[9] Park J, et al. Colored Point Cloud Registration Revisited
[10] Gelfand N, et al. In: Fourth International Conference on 3-D Digital Imaging and Modeling: 3DIM 2003: proceedings: 6–10 October, 2003, Banff, Alberta, Canada. Los Alamitos, Calif: IEEE Computer Society; 2003: 260–267
[11] Krell G, et al. Computational and mathematical methods in medicine. 2017; 2017: 2938504
[12] Joung JH, et al. In: 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems: IROS 2009; St. Louis, Missouri, USA, 10–15 [i.e. 11–15] October 2009. Piscataway, NJ: IEEE; 2009: 3082–3088
[13] Korn M, et al. Color Supported Generalized-ICP
[14] Hoisak JDP, et al. Seminars in radiation oncology. 2018; 28: 185–193
[15] Tarnavski N, et al. Journal of Radiosurgery and SBRT. 2016; 4: 15–20

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