Nuclear Instruments and Methods in Physics Research A 827 (2016) 39–45

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Technical notes

Real-time optical tracking for motion compensated irradiation with scanned particle beams at CNAO

G. Fattori [a,*], M. Seregni [a], A. Pella [b], M. Riboldi [a], L. Capasso [c,1], M. Donetti [b,c], M. Ciocca [b], S. Giordanengo [c], M. Pullia [b], F. Marchetto [c], G. Baroni [a,b]

[a] Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy
[b] Centro Nazionale di Adroterapia Oncologica (CNAO), Strada Campeggi 53, 27100 Pavia, Italy
[c] Istituto Nazionale di Fisica Nucleare, Section of Torino, Torino 10125, Italy

ARTICLE INFO

Article history:
Received 25 August 2015
Received in revised form
5 April 2016
Accepted 18 April 2016
Available online 26 April 2016

Keywords:
Sotion monitoring
Optical tracking
Moving targets
Beam tracking
Gated treatments
Protons

ABSTRACT

Purpose: We describe the interface developed at the National Center for Oncological Hadrontherapy in Pavia to provide the dose delivery systems with real time respiratory motion information captured with an optical tracking system. An experimental study is presented to assess the technical feasibility of the implemented organ motion compensation framework, by analyzing the film response when irradiated with proton beams.

Methods: The motion monitoring solution is based on a commercial hardware for motion capture running in-house developed software for respiratory signal processing. As part of the integration, the latency of data transmission to the dose delivery system was experimentally quantified and accounted for by signal time prediction. A respiratory breathing phantom is presented and used to test tumor tracking based either on the optical measurement of the target position or internal-external correlation models and beam gating, as driven by external surrogates. Beam tracking was tested considering the full target motion excursion (25×18 mm), whereas it is limited to 6×2 mm in the gating window. The different motion mitigation strategies were evaluated by comparing the experimental film responses with respect to static irradiation conditions. Dose inhomogeneity (*IC*) and conformity (*CI*) are provided as main indexes for dose quality assessment considering the irradiation in static condition as reference.

Results: We measured 20.6 ms overall latency for motion signal processing. Dose measurements showed that beam tracking largely preserved dose homogeneity and conformity, showing maximal *IC* and *CI* variations limited to $+0.10$ and -0.01 with respect to the static reference. Gating resulted in slightly larger discrepancies ($\Delta IC = +0.20$, $\Delta CI = -0.13$) due to uncompensated residual motion in the gating window.

Conclusions: The preliminary beam tracking and gating results verified the functionality of the prototypal solution for organ motion compensation based on optical monitoring.

1. Introduction

Respiratory organ motion affects the precision of particle therapy delivered to thoracic and abdominal treatment sites [1–6]. Korreman et al. [7] reviewed the magnitude of organ motion observed in numerous previous studies, reporting maximal values of 31.9 mm, 24.4 mm and 10.0 mm in superior-inferior, anterior-posterior and left-right directions for the lungs and 30.4 mm, 5.2 mm and 4.6 mm for the liver. In the clinical routine, enlarged safety margins are coupled with the active control of beam delivery to preserve the patient dose conformity and homogeneity. The two main strategies for motion mitigation applicable in particle therapy involve gating [8,9] or continuous beam position adaptation (tumor tracking) [10,11] to compensate for anatomical changes occurring during treatment delivery. For this purpose, X-ray fluoroscopy images are acquired to track the motion of target and bony structures during treatment [12] and thus account for daily variations in the respiratory pattern [13]. Alternatively, non-invasive imaging techniques, such as ultrasound systems, have been investigated as monitoring device. Their application is however currently limited to measurements in experimental conditions [14,15].

Indirect motion monitoring, i.e., the estimation of the target motion based on the established correlation between target

* Corresponding author. Permanent address: Paul Scherrer Institute PSI, 5232 Villigen, Switzerland.
E-mail address: giovanni.fattori@psi.ch (G. Fattori).
[1] Permanent address: Istituto Nazionale di Fisica Nucleare, Section of Roma 3, Roma 00146, Italy.

http://dx.doi.org/10.1016/j.nima.2016.04.066
0168-9002/

position and the displacement of the patient surface, can provide non-invasive measurements at high frequency [16]. The accuracy of such approaches, however, is affected by the physiological instability of internal-external correlation. For this reason, hybrid methods were proposed and applied in photon radiotherapy [17,18], combining real-time external surrogate measurements with low-frequency X-ray imaging, to verify and update the targeting accuracy.

In this technical contribution, we describe the interface implemented at the National Center for Oncological Hadrontherapy in Pavia (CNAO) to provide the dose delivery systems [19] with real time motion information captured with an optical tracking system (OTS). Specifically, we tested tumor tracking based either on the optical measurement of the target position or hybrid strategies and beam gating, as driven by external surrogates. An experimental study is presented to assess the technical feasibility of the implemented organ motion compensation framework, by analyzing the film response when irradiated with proton beams delivered through pencil beam scanning.

2. Materials and methods

2.1. Respiratory phantom and setup

The experimental setup is shown in Fig. 1. A respiratory phantom was designed to combine the motion of a film holder on a planar trajectory with multiple independent elements mimicking the rib cage of a patient [20]. The phantom motion is driven by the NEMA-23 stepper motor (Phidgets Inc., Calgary, Canada) that, actuating on a cogwheel, pushes outwards the plastic rib sticks in the inspiration phase of the breathing cycle. Calibrated springs at the base of the phantom ensure the controlled return at rest position during the expiration, when the cogwheel is released. A system of pulleys moves the film holder to cover a hysteresis loop trajectory. The phantom structure was designed to provide stable mechanical coupling with the treatment couch and accurate alignment of moving components based on room lasers.

2.2. Motion monitoring and experimental protocol

The phantom motion was monitored by a commercial infrared optical tracking system (SMART-DX100, BTS Bioengineering, Garbagnate, IT) used to track the position of four spherical markers coated with reflective material. Three markers (two lateral – *A, B*; one frontal – *C*) were placed on the rib cage elements and used as external surrogates (Fig. 1). A fourth marker (*D*) was attached to the film holder.

Motion data were acquired at 100 Hz frame rate with high geometric accuracy, featuring sub millimeter (<0.5 mm) 3D localization error [21]. In order to provide motion trajectories in absolute room coordinates, a calibration phantom (Brainlab AG, Feldkirchen, Germany) was aligned at the treatment isocenter to derive the transformation matrix mapping the marker coordinates in OTS reference system to the room coordinates system (Fig. 2). Singular value decomposition was applied to solve for reference systems rotation following center of mass alignment.

The experimental protocol consisted of six subsequent deliveries in comparable setup conditions. First, a reference dose distribution was measured (i) without phantom motion, referred as *static* irradiation in the following. Then beam tracking experiments were performed either by (ii) *direct* localization of the target position with the OTS (marker *D*) or estimating its position from the motion of the phantom ribs using correlation models. Two approaches were compared, state augmented model – SSM [22] (iii) and artificial neural networks – ANN [23] (iv):

- The SSM was implemented as a linear function relating the position of the film holder with that of rib cage markers $s(t)$ considering two time-delayed observations $s(t-\tau/2)$ and $s(t-\tau)$, with $\tau=1.5$ s. The *z*-axis and *x*-axis projections of *A*, *B* and *C* markers trajectories were considered as inputs for three identical models and their outputs were averaged to obtain the film holder motion. The prediction was based on a training dataset acquired before the irradiation to sample 4.5 s of respiratory motion with 30 equispaced control points, consisting of simultaneous positions of rib cage and film holder surrogates.
- The ANN model was designed as single hidden layer network composed of five units featuring a hyperbolic tangent activation function and one output unit with a linear activation function. The position $s(t)$ and velocity $ds(t)/dt$ of each rib cage marker (*A*, *B*, *C*) were considered and provided as input to the network. Two distinct ANNs were used for the estimation of lateral and vertical motion of the film holder, separately. The same set of control points acquired for the SSM was used for the training of the network.

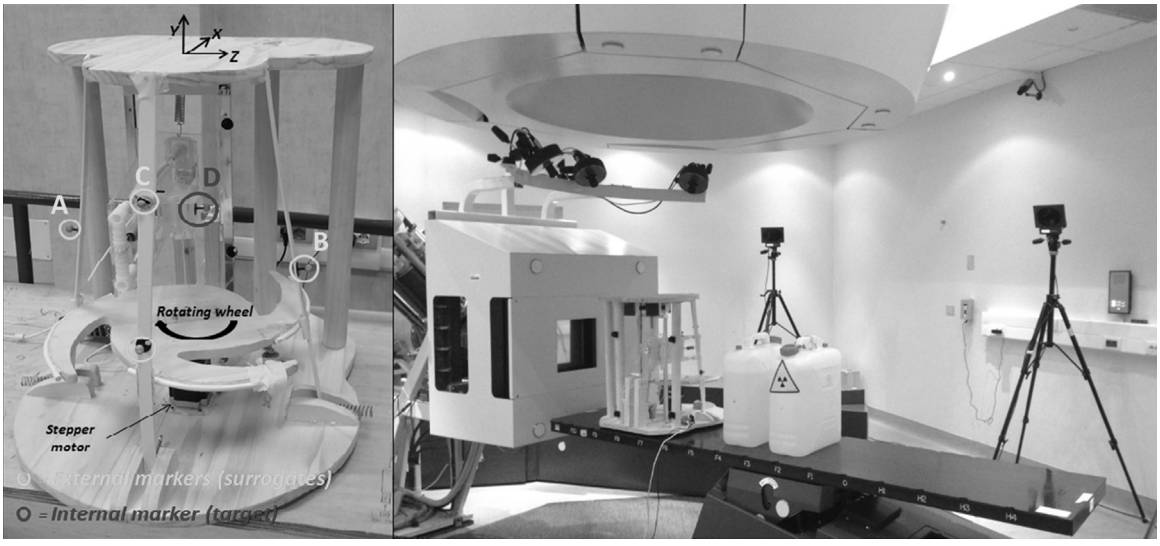

Fig. 1. Left panel: breathing phantom. Right panel: experimental setup at CNAO; a dedicated set of three free-standing video cameras was installed in addition to the clinical OTS mounted on the beam nozzle. The third camera is out of view at the foot end of the couch.