DYNAMIC DELIVERY PLANNING IN IBA PROTON PENCIL BEAM

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Abstract

Pencil Beam Scanning is a dynamic beam delivery system developed for proton therapy. The radiation field necessary to reach in a fast and robust way a prescribed 3D dose distribution is obtained by accurately controlling both the extraction of the beam from a 235 MeV accelerator and the motion of the beam spot thanks to scanning magnets. This paper focuses on the trajectory planning aspect of this control problem, i.e. the calculation of the desired time evolution of the beam current and scanning magnets voltages to reach a desired profile in minimum time while satisfying the actuator constraints.

1 INTRODUCTION

Proton therapy designates irradiation by protons for the treatment of cancers and related diseases. The medical advantage of protons over the more conventional use of photons or electrons has long been recognized due to the excellent physical properties of protons for dose localization. But the developments of proton therapy have also long been hampered by the technological challenges of producing very high energy beams (over 200 MeV) and reliable beam delivery systems.

Several proton beam delivery systems are currently developed at Ion Beam Applications S.A. *Passive* systems are designed to produce large flat fields (20 cm and above) from the well-focused beam spot (a few mm diameter) extracted from the accelerator. The dose field is then shaped to the tumor profile by means of various hardware components (collimator, aperture, compensator). In contrast, the Pencil Beam Scanning system discussed in this paper is an *active* beam delivery system aimed at directly controlling the trajectories of the beam spot and the beam intensity such as to accurately 'paint' the prescribed 3D tumor profile. The overall beam delivery system design is simplified but requires performant actuation and sophisticated control algorithms.

For a further explanation of the IBA Pencil Beam Scanning concept, the reader is referred to the companion paper [1]. The present paper focuses on the control algorithm needed to translate a 3D prescribed dose distribution into dynamic commands for the spot displacement and beam intensity.

2 DYNAMIC CONTROL OF PENCIL BEAM

To reach a uniform dose distribution within the tumor volume, the 3D tumor is divided into several 2D layers orthogonal to the beam axis. The irradiation of each layer is associated to a specific energy of the beam, calculated such as to adjust the position of the Bragg peak to the axial position of the layer. When irradiating a specific layer, the layers located upstream are also irradiated and receive part of their dose. It results that the dose to be delivered in a particular layer is no longer uniform (excepted for the most downstream layer). In upstream layers, the target dose profile exhibits high gradients and amplitude variations that can reach a ratio of 1 to 10.

Accurate tracking of the prescribed 2D dose profile in a specific layer is achieved by controlling the spot trajectory and the beam intensity, which involves the following three control variables:

- The beam current I_b is a normalized variable with range $[0, Imax]$ reflecting the $0 - 100\%$ utilization of the available beam flux in a given layer.
- The horizontal component V_x and the vertical component V_y of the spot velocity.

The control algorithm can be decomposed into three distinct components: the reference generator, the inner loops, and the outer loops.

The *reference generator* is a central component of the algorithm. Its task is to precalculate the desired time history (or time trajectory) of each control variable over a given time horizon in order to reach the target dose profile. The input of the reference generator is a two-dimensional dose field $D_c(r)$ that specifies the amount of charged particules to be delivered at each point $r = (x, y)$ of the considered layer. In our theoretical analysis, we treat $D_c(r)$ as a scalar field. In practice, the target dose is given in the form of a discretized 2D dose matrix. The output of the reference generator is a set of reference trajectories for the pencil velocity and beam intensity over the time interval $[0, T]$. Mathematically, the reference generator is an inverse of the dose model that calculates the delivered dose from the spot trajectories and the beam intensity.

The *inner loops* of the control algorithm produce the reference trajectories by means of physically controlled quantities: the beam current is regulated with a time constant

of about $50\mu s$ and a settling time below $500\mu s$. The control of magnet voltages by 8kHz PWM amplifiers makes it possible to regulate the spot velocity with a time constant of about $300\mu s$ and a settling time of about $500\mu s$. The slow magnet is ten time slower than the fast magnet, giving a velocity range v_x of $\pm 2000 cm/s$ and a velocity range v_y of $\pm 200 cm/s$.

The *outer loops* are correction loops that will compensate for the model uncertainties and external disturbances. Reliable outer loops are crucial for the safety of the Pencil Beam Scanning control algorithm but they are not discussed in the present paper. The reference generator is the feedforward (or open-loop) part of the algorithm. The inner and outer loops are the feedback (or closed-loop) parts of the algorithm. The separation of the feedback loops into inner and outer loops rests on a time-scale separation of their respective action. Typically, the time scale of the inner loops must be fast with respect to the time-scale of the reference generator, while the time-scale of the outer loops will be slower (quasi steady-state corrections).

3 REFERENCE GENERATOR

Let the variable $D(r,t)$, called the "dose", denote the amount of charged particles (protons) accumulated at time t at point $r = (x,y)$ of the irradiated plane. The reference generator must precalculate the time history (or reference trajectories) for the controlled variables $(v_x(t), v_y(t), I_b(t))$ over a time horizon $[0,T]$ in order to reach a certain dose field $D_c(r) = D(r,T)$. The instantaneous rate change or time derivative of $D(r,t)$ is the product of two variables: the beam flux, proportional to the beam current I_b, and a 2D gaussian profile centered at the pencil position $R = (X,Y)$, to model the beam spread-out (the value of σ depends on the spot size, typically a few millimeters). This leads to the following dose model:

$$\left\{ \begin{array}{rcl} \dot{D} = \frac{dD(r,t)}{dt} & = & I_b(t) \exp(-\frac{\|r-R(t)\|^2}{\sigma^2}) \\ \dot{R} = \frac{dR}{dt} & = & v(t) \end{array} \right. \quad (1)$$

To compute the current I_b and the velocity v that will produce the desired target $D(r,T)$, the dynamic relationship (1) must be inverted. Reference trajectories that achieve the desired objective are of course not unique. But they must satisfy a number of constraints arising from the inner loops that generate them and from various safety, robustness, and performance considerations. Among the reference trajectories that satisfy these constraints, the optimal reference trajectories will be those that minimize the time horizon T required for the complete dose delivery.

The crucial step of the path planning is the selection of a geometric path for the spot. This geometric path of total length L can be described by a one-parameter curve $\gamma : [0,L] \rightarrow I\!R^2 : s \rightarrow \gamma(s)$. Denoting by $|v|$ the norm of v and by e_v the unitary vector $\frac{v}{|v|}$, we obtain that the slope $\frac{d\gamma}{ds} = e_v$ determines the velocity direction along the path while the relationship $ds = |v(t)|dt$ induces a change of variables between the time variable t and the spatial variable s. We use this change of variables to convert the time integration of the dose model (**??**) into a path integration along $\gamma(s)$, which yields

$$D(r,T) = \int_0^L \frac{I}{|v|}(s) \exp(\frac{- \| r - \gamma(s) \|^2}{\sigma^2}) ds \quad (2)$$

The quantities $e_v(s)$, $|v(s)|$, and the ratio $\delta(s) = \frac{I}{|v|}(s)$ can be thought of as the three independent control variables of the model. The first control (velocity direction $e_v(s)$) determines the geometric path that will be described by the pencil as time evolves from 0 to T. The second control (dose density $\delta(s)$) then determines the dose field by the convolution operation (2). Finally, the third control (velocity norm $|v(s)|$) determines the speed at which the spot describes its path.

4 PATH PLANNING ALGORITHM

4.1 Basics

In accordance with the spatial reparametrization of the dose model, it is advisable to design the reference generator as an autonomous dynamical system, that is, a 'feedback rule' that specifies the rate of change of the control variables not as a function of time but as a function of the current position of the pencil beam. For instance, one will prefer the feedback rule 'invert the sign of velocity when reaching the next edge of the target profile' to the open-loop rule 'invert the sign of velocity at time $t = 3ms$'. The algorithmic construction of the reference generator can thus be rephrased as follows: given a dose field $D_c(r)$, design the corresponding feedback rule such that proper initialization of the generator produces the desired trajectories. The feedback rule consists of a unitary vector field $e_v(r)$ (that will dictate the geometric path of the pencil), a velocity scalar field $|v(r)|$ (that will dictate the speed at which the path is followed), and a beam current scalar field $I_b(r)$ (that will determine the dose density scalar field through the ratio $\frac{I_b}{|v|}$).

Modularity. The algorithmic complexity of the reference generator will clearly raise with the required performance –e.g. measured by the total delivery time and the precision in dose localization. A modular design will make it possible to provide the algorithm with additional functionalities as they are tested and experimentally validated. The most basic module of the algorithm will consist of a line by line scanning at constant low speed with beam modulation such as to follow the density field $\frac{I_b}{|v|}$. Additional modules will include speed modulation along a given geometric path and tracking of special contours.

4.2 Path selection

The selection of a geometric path is equivalent to the prescription of the vector field $e_v(r)$. Line by line scanning

limited to the 2D dose envelope is the most simple and the most generic geometric path to be included in the reference generator. It can be used for arbitrarily complicated dose targets and is implemented through very simple feedback rules. It is also the most favorable path with respect to the velocity constraints since it can be followed at the speed of the fast magnet, which is ten times faster than the slow magnet.

In layers that exhibit high dose gradients, it is advisable to track isodose contours prior to the line-by-line scanning. Contour sweeping is of course tumor dependent and considerably slower than line by line scanning because of the constraint on the slow magnet. But it makes it possible to obtain smoother contours and to achieve accurate tracking of high dose gradients. After the preliminary contour sweeping, fast line-by-line scanning can be used to complete the irradiation of the layer. If a line-by-line scanning is used directly, the fast scan must be slowed down (by a factor of ≈ 10) at each crossing of the high dose region. Contour sweeping thus not only results in improved contour smoothness but may also contribute to make the algorithm faster.

4.3 Deconvolution

The relationship (2) between the delivered dose $D(r,T)$ and the density field $\delta(r)$ is a consequence of the beam spread-out. In the case of a one-dimensional dose profile, the resulting dose is the true (1D) convolution of $\delta(r)$ with a gaussian. In the case of a two-dimensional dose profile, the relationship between D and δ depends on the selected path. However, we assume that the path is selected in such a way that (2) can be approximated by a true (2D) convolution. In the case of line-by-line scanning, this for instance imposes to choose the interline spacing such as to optimize the superposition effect of adjacent gaussians.

The density field $\delta(r)$ is thus obtained by deconvolution of the target profile $D_c(r)$. This deconvolution operation is important not only to ensure a sharp fall-off of the dose outside the tumor envelope but also because upstream layers impose sharp dose variations over intervals that are comparable to the size of the pencil (a few σ's).

4.4 Velocity and beam current fields

The scalar field $\delta(r)$ fixes the ratio $\frac{I_b}{|v|}$ to be followed along the selected geometric path. Neglecting the inner loops that regulate the control variables I_b and $|v|$, that is, assuming that the beam current and the spot velocities are the physical control variables, the calculation of I_b and $|v|$ from the scalar field $d(r)$ and the vector field $e_v(r)$ is the solution of a static (pointwise) optimization problem: at any point $r=(x,y)$, maximize $|v(r)|$ under the amplitude constraints on the maximal velocity and the maximal current.

The dynamics of the inner loops put limitations on the above optimal velocity and beam current fields. The time constant associated to the beam current regulation imposes to slow down when sharp dose gradients are encountered along the path. This velocity variation along the path can easily reach a factor of 1 to 10 and requires good synchronization between the current and velocity control loops.

5 EXPERIMENTAL RESULTS

A first version of the control algorithm has been tested experimentally at Ion Beam Applications. The target dose scalar field $D_c(r)$ is encoded as an 8-bits (256 colors) image. Deconvolution (with suitable filtering) is applied to this matrix to generate the density scalar field $\delta(r)$. Line-by-line scanning limited to the target envelope is then produced by the reference generator. In this first implementation, each line is swept at a constant speed, so that tracking of the dose gradients is accomplished by modulation of the beam current only. The velocity is limited to 500 cm/sec (1/4 of the maximal speed) to reduce the tracking error due to the time constant of the beam current inner loop. Radiographic films are used as a dosimetric support to evaluate the dose conformity. Several experimental results are illustrated in the companion paper [1], showing excellent qualitative conformity between the prescribed and the measured dose profile.

6 CONCLUSIONS

Pencil Beam Scanning is a promising dynamic delivery system to be used in proton therapy. The 3D irradiation is decomposed in a sequence of planar irradiations by adjusting the position of the Bragg peak. In each layer, active control of the spot trajectory and of the beam current modulation makes it possible to reach an arbitrary dose profile. The main part of the control algorithm is a reference generator for the spot velocities and for the beam current. The offline calculation of these reference trajectories is based on a dynamic inversion of the dose model subject to the actuator constraints. Preliminary experimental results demonstrate the feasability of the proposed approach.

REFERENCES

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