Paper Number: 50

Dynamic Tumor Motion Simulation Algorithm

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Abstract: This research project aims to improve cancer patient care by building a dynamic phantom which simulates tumor respiratory motion. A simulation model has been designed to represent the periodic motion of a point in 2-dimensional space. Different motion properties, such as velocity, amplitude, duration and random noise, are simulated and characterized based on statistical analysis of real patient data. Several motion simulation algorithms have been designed and implemented. In addition, a friendly graphical user interface (GUI) has been designed that will allow researchers to feed various types of data and provide different constraints for desired motion behaviors. The simulator is a good test bed for understanding tumor motion and will improve cancer radiation treatment outcome.

1. Introduction

Radiation therapy is one major method for cancer treatment, with the goal of delivering precise radiation dose to kill the tumor. Meanwhile the surrounding healthy and critical structures should be spared. However, especially for lung and lower abdominal tumors, the effectiveness of radiation treatment is compromised by tumor motion, due to respiratory and cardiac motion [1, 2, 3]. Understanding tumor motion characteristics and motion prediction are critical for advance radiation treatment methods, such as respiration gating and beam tracking [13].

Different methods have been used to model the complicated tumor motion. A modified cosine function has been proposed to model a breathing pattern [9, 10]. Similarly, a waveform model has been proposed based on the average tumor trajectory over many breathing cycles [11]. These methods are off-line simulations and are not suitable for a real-time analysis. A finite state model has been proposed to decompose the incoming tumor motion in line segments during real-time image guided radiation treatment based on the natural breathing action [12].

Tumor respiratory motion analysis and simulation are clinically useful. Different motion properties, such as amplitude, frequency, velocity, and stability of the motion must be quantified for designing margins [3, 4]. The breathing period and waveform characteristics are useful for planning treatments that use tumor motion tracking [5, 6, 7, 8, 9]. In addition, tumor motion simulation is an important input for testing dynamic multi-leaf collimation (DMLC) control algorithms, motion predicting algorithms, and for research involving predicting the convex hull around the tumor [8].

However, no systematic work of tumor motion has been undertaken to demonstrate different motion features under various conditions. In this work, we have designed an algorithm simulating the motion of a tumor. It also provides a realistic environment for an integrated phantom design. The simulation can be used as a test bed for control algorithms of radiation dose delivery, motion prediction algorithms during real-time treatment, and for the mechanical operation algorithm of a physical phantom. The motion simulation can also be used as an education tool to the public to understand the difficulty of radiation treatment and learn the various advanced treatment methods for moving tumors [14].

2. Methods

We have designed various simulation environmental constrains based on statistical results of tumor motion from real patients. The simulation works on a combination of rotation and translation of the tumor in the X/Y plane. In addition, the simulation algorithm has incorporated a set of random probability functions that creates the noise in the motion.

2.1 Requirements of the simulation algorithm

To design a realistic motion simulator, the following requirements have been considered in the design of the simulation algorithm.

First, although the basic motion of the tumor is periodic, realistic motion simulation, random noise must be included. There are several ways in which noise could be incorporated into the model. One is to use a random function and randomly to choose when the noise should occur. The second option is to use a Gaussian function, particularly for motion simulation based on velocity or amplitude of the tumor. Another is to apply probability distribution functions resulted from statistical analysis of real patient data.

Second, except periodical motion with random noise, the point of interest can rotate across an external point of reference (through a fixed angle), or it can be translated back and forth through a preset trajectory. In addition, random noise exists for different periods. Thus, the actual movement of the point of interest actually varies. For example, for lung tumors, there are multiple phases including inhale, exhale, and end-of-exhale [12].

There are special concerns of velocity changes for tumor motion. Smooth velocity oscillation prevents the simulation from making sudden changes in the trajectory. The velocity of tumor at the different breathing states can be pre-assigned to a values based on analysis of previous motion. However the actual velocity will change based on the random noise that will be included in motion simulation.

2.2 Development of the algorithm

Based on the requirement analysis, a phased simulation algorithm has been developed and evaluation of each phase has been performed. The details of each phase are described below:

1) *Motion generation based on simple repetitive patterns:* The basic motion of a lung is periodic. A sinusoidal function was used to simulate the motion. However, there are multiple stages in one cycle of tumor motion. Each of these stages has different velocities and trajectories. Our algorithm has been designed based on the finite state model proposed in Wu *et al* [12], which has three regular states in one breathing cycle. Thus, the algorithm was modified in order to incorporate these three segments. Thus a third order polynomial was used for each of the three stages in order to plan the trajectories. By setting arbitrary start and finish points and keeping the velocity constant for each stage, we could determine the coefficients of the polynomial. Hence from that the X/Y positions along the path of motion of the tumor could be determined.

2) *Motion generation based on simple repetitive patterns with random noise:* After the basic periodic motion using third degree polynomials was developed, randomness tumor motion was incorporated by randomly shifting the points along the trajectory at preset time intervals. When the tumor is at a particular point, the position of the next point after a given time interval is randomly chosen. Then the coefficients of the polynomial are recalculated and hence the velocity is recalculated.

3) *Motion generation based on statistical analysis of amplitude, duration and velocity variations*: The previous model was not realistic since it did not use real tumor amplitude, velocity constraints. Neither did it take into account the acceleration of a tumor, which causes the change in the velocity. In this phase of the development, the motion complexity is based on probability distributions from real patient data, not randomly generated.

   Random motion occurs because an internal or external force is applied to the tumor causing it to accelerate. Fifth order polynomials have been applied to different segments of the motion. Real life constraints of velocity accelerations have also been added to the motion. Thus, the values of the polynomials can only change by a certain amount. A Gaussian function was also used based on data from real patient to help determine the degree of randomness a tumor would be at a particular point.

   From these data, at a particular time instant, based on the data from the Gaussian function, the acceleration of the tumor would be changed. It would in turn change the velocity of the tumor. As a result the coefficients of the polynomials are different. From the coefficients, the location of the tumor at the next time instant will be determined.

4) *Motion simulation with mechanical constraints*: Mechanical constraints are added to avoid sudden change of the simulated motion since an instantaneous change in the velocity is physically impossible. The mechanical constraints make the change in the velocity gradual and the acceleration within the maximum value possible.

2.3 Development of a graphic user interface (GUI)

A Graphic user interface is developed to provide a friendly approach for setting up the simulation environment with different constraints. At the same time users can see the real time motion of the tumor and make corrections to it from GUI. The GUI is designed to perform the following functions:

- Set the number of stages of motion (minimum would be two with one for each direction).
- Set the velocity, amplitude, and acceleration constraints for the simulated motion. This would help create and set up the polynomials for different stages of the motion.
- Set up the mean time of each period.
- The dimensions of the grid to visual the simulated motion. (The position of the tumor will have to be with in these constraints.)

3. Performance:

Different motion generation algorithms have been implemented based on the methods described above. Simple motion of repetitive patterns with constant velocity and constant amplitude is tested first. Then rotation and transition with random noise has been simulated and evaluated. Sample simulating results are illustrated in Figure 1 and 2.

In Figure 1, the motion over a course three periods is tracked in the X and Y dimensions. In this chart the velocity of the point is kept constant, and random noise is added to the point as it moves between two points at each time instant. In Figure 2, the point of interest has been simulated over two periods. The velocity varies as it moves, depending on random noise and the changes in the trajectory. Towards the end of each cycle, the points are close together which represents slow movement of the point of interest. When the points are further apart, the point of interest is traveling faster. This velocity changing patterns in Figure 2 are based on statistical analysis of tumor motion data from real patients.

A prototype of the graphic user interface (GUI) has been developed for dynamically changing of different parameters to help users customize tumor motion as required, which is displayed in Figure 3. From the picture, it can be seen that the user has different options to customize the simulation in one of many ways. For instance, the screen shows the trajectory of the simulation real time. The grid (or max distance that the point of interest can move) can be entered in the grid dimensions section, where the max/min x-axis distance and the max/min y-axis distances can be entered respectively. The duration of each simulation can be entered. Finally the user can choose the type of random function used to create the noise and also choose the maximum angle value for the rotation and the maximum distance for the translation trajectory.

4. Conclusion and future work

This paper described our work in developing an algorithm that simulates the motion of a point in the lung in the 2-dimension space with different constraints. Simulation results and the auxiliary graphic user interface (GUI) have also been introduced in the paper. The next step would be to read the historical tumor motion data from a patient's tumor and use it to predict the future motion of the patient's tumor. Another work is to improve the GUI for more advanced functions.

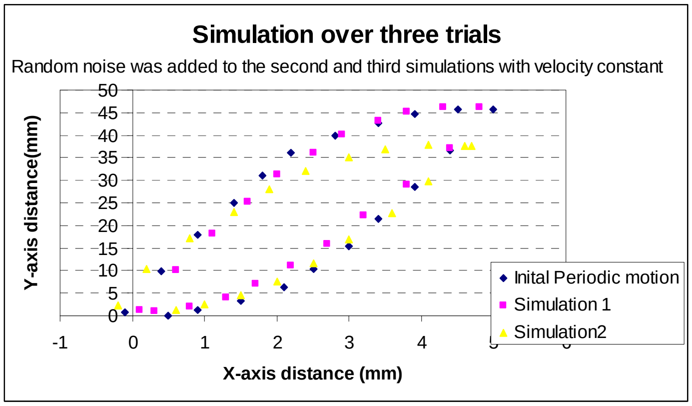

Figure 1: Trajectory of a point of interest over a course of three periods.

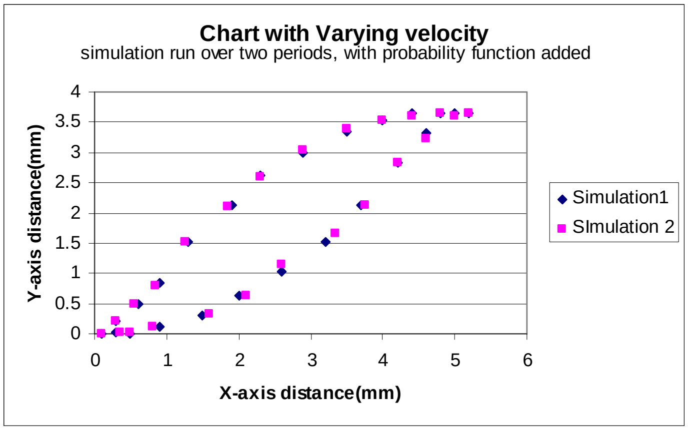

Figure 2: Trajectory of the point of interest with velocity variation and randomness added.

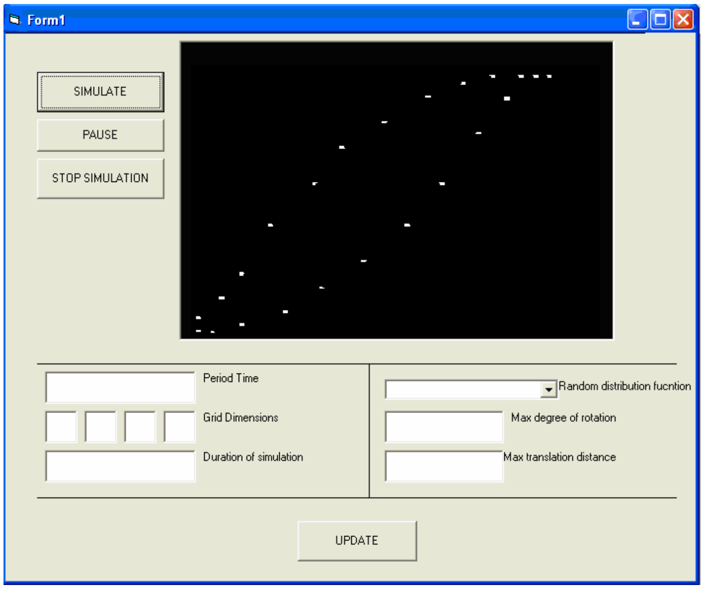

Figure 3: GUI User interface

Acknowledgement

Part of the work is supported by IUPUI Multidisciplinary Undergraduate Research Institute (MURI) grant.

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