33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Active Tracking and Dynamic Dose Delivery for Robotic Couch in Radiation Therapy

Ivan Buzurovic, *Member, IEEE*, Yan Yu, and Tarun K. Podder, *Member, IEEE*

Abstract—**Precise and accurate dose delivery is critically important in external beam radiation therapy. In many cases target-volumes are stationary, but the problem arises when the tumors move significantly due to cardiac and respiratory motions. This is a case for tumors in lung, esophagus, pancreas, liver, prostate, breast, and other organs in thoracic and abdominal regions. In the article we have described the Active Tracking and Dynamic Dose Delivery (ATDD) technique for real-time tumor motion compensation. In this approach, the robotic treatment table moves while delivering the radiation beam and compensates for breathing-induced tumor motion. Many parameters of the control system, such as patient mass or breathing pattern, are initially uncertain and may vary during the treatment. To solve these problems, feedforward adaptive control was adopted to minimize irradiation to healthy tissue and spare critical organs while ensuring prescribed radiation dose coverage to the target-volume.**

I. INTRODUCTION

USING traditional treatment techniques, radiation oncologists have to contend with variations in tumor position during the treatment by treating a margin of healthy tissue around the tumor. Significant tumor motion, which can be up to 5cm, has been induced mostly by cardiac and respiratory motion [1-6]. Recently, several research groups are investigating various aspects of tumor tracking and developing tools to deliver a precise dose to moving target-volume [5]-[17].

The latest reported research in the field of tumor tracking included fluoroscopic tumor tracking, error analysis using probability theory, prediction filter investigation and development of the different tracking algorithms. In [18] the accuracy of two-dimensional projection imaging methods in three-dimensional tumor motion monitoring was investigated. Geometric uncertainties were investigated as well. In [19] a method that can track a deforming lung tumor in fluoroscopic video using active shape models was presented. A fluoroscopic tumor tracking for image-guided lung cancer radiotherapy was proposed in [20]. In [21] authors performed 4D targeting error analysis represented by a motion probability density function. In the article, the statistical fluctuations of tumor trajectory were described. In [22], the evaluation of the use of multi dimensional linear adaptive filters and support-vector regression to predict the motion of lung tumors tracked at 30 Hz was performed. To predict tumor motion during irregular breathing cycles, in [23] a novel adaptive acceleration-enhanced normalized least mean squares prediction filter with a breathing acceleration prediction was proposed. The performances of the filter were compared with both artificial neural network and AE-nLMS filters. Article [24] proposed an algorithm that utilizes the on-board portal imager of the treatment machine to track lung tumors. The general framework of correlation-based tumor position estimation that is applicable to various imaging configurations, where instant 3D target positions cannot be measured, was introduces in [25]. In [26] the authors developed algorithms for direct tumor tracking in rotational cone-beam projections and for reconstruction of phase-binned 3D tumor trajectories. This work shows the feasibility of a direct tumor-tracking technique for rotational images. A dynamics-based robotic approach to tumor motion prediction and tracking was described in [27]. The proposed system was evaluated using 4D-CT real patient data.

The influence of the tumor tracking technique to the treatment outcome was analyzed in [28-29]. The purpose of the dosimetry studies was to investigate clinical benefits of tumor tracking and to evaluate changes of treatment volumes when the proposed tumor tracking technique is applied. The study includes the evaluation of dosimetric advantages of tumor motion tracking and the irradiation of normal lung and spinal cord. The dosimetric evaluation of tumor tracking was carried out on ten randomly selected patients who were scanned using a 4D-CT technique.

It was observed that during respiratory cycle, a tumor volume was changed by up to 20cm^3 depending on tumor size, location, and patient specific breathing pattern. The 3D tumor displacement for all investigated patients was more than 10 mm. Using the proposed active tracking technique it was found that for average tumor motion of 1.5cm the irradiated planning target volume (PTV) was 20-30% less which indicates a significant amount of healthy tissue to be spared. The average maximum dose was 110% of prescribed dose (PD) and the mean dose was 103.6% of PD. It was observed that average lung volumes that received absorbed doses of 5, 13, 20 and 30 gray (Gy), with tracking technique were about 17.4%, 19.3%, 18.3% and 22.7% lower than the

Manuscript received April 15, 2011

I. Buzurovic is with Thomas Jefferson University, Medical Physics Division, Philadelphia, PA, USA (phone: +1-215-955-0320; e-mail: ivan.buzurovic@jefferson.edu).

Y. Yu is with Thomas Jefferson University, Medical Physics Division, Philadelphia, PA, USA (e-mail: yan.yu@jefferson.edu).

T.K Podder was with Thomas Jefferson University, Medical Physics Division, Philadelphia, PA, USA. He is now with the Department of Radiation Oncology, Brody School of Medicine at East Carolina University, Greenville, NC 27834, USA (e-mail: poddert@ecu.edu).

978-1-4244-4122-8/11/$26.00 ©2011 IEEE

volumes without tracking, respectively. Calculating dose delivered it was concluded that approximately 20% of healthy lung received 4-8 Gy less dose when the tumor tracking technique was used. Spinal cord was the most important critical organ for the studied lung cases. Dose to the 5% of spinal cord (D5) with tracking technique was 17.5% lower compared to that of without tracking. D5 of the spinal cord received approximately 0.5-11 Gy less dose when tumor tracking technique was used; wide variations were observed due to differences in prescribed dose, tumor location and size. Investigation whether patients could tolerate the motion of the robotic couch that compensates for breathing-induced tumor motion was recently performed [30]. The authors concluded that most patients tolerated compensatory couch motion and that motion sickness should not pose a problem in the investigation of different tumor tracking methods.

Based on the clinical investigation, the importance of the efforts for developing the tracking techniques is understandable. Implementation of real-time tracking techniques can minimize irradiation to healthy tissues and improve sparing of critical organs. Consequently, quality of patient treatment potentially can be improved.

II. SYSTEM DESCRIPTION

The commercially available ELEKTA Precise Table^{TM} robotic couch is capable of positioning the patient with high level of accuracy; however, currently it does not have provision for compensating the tumor movement due to respiratory and cardiac motion. In [17] and [27], we have proposed a closed-loop dynamic controller for adjusting the 3 degree-of-freedom (DOF) robotic couch so that the tumor-volume appears to be stationary to the radiation beam and the beam can be delivered close to 100% duty-cycle. Prediction of the tumor motion has been incorporated in the system.

To apply the dynamic-based control of the system, we have developed dynamic equations-of-motion for the ELEKTA Precise Table^{TM}, as in [17]. The treatment table is an integral part of the system for radiation therapy (Fig. 1). The treatment table consists of a 2DOF tabletop and 1DOF vertical lift. The tabletop can move in the horizontal plane (laterally and longitudinally) using two Maxon 24V motors with gearbox combination. The vertical motion is obtained using robust 70V Rockwell Automation motor. For all motors we use Model 755A Accu-Coder encoders which have been connected to the Advance Motion Controls amplifier for robust vertical motion motor and to the Galil DMC-4133 onboard amplifier for horizontal plane motion and controller for all 3DOF. The system has two independent power supplies: Galil PS300 for vertical motor and Advance Motion Controls AMC Z6A8 for horizontal motion motors. The controller contains the developed control algorithms to close the desired loop (for position and velocity). The amplifier represents the electrical power converter that drives the motor according to the controller reference signals. Described parts have been mounted on the commercially available ELEKTA Precise Table^{TM} robotic couch (Fig.2).

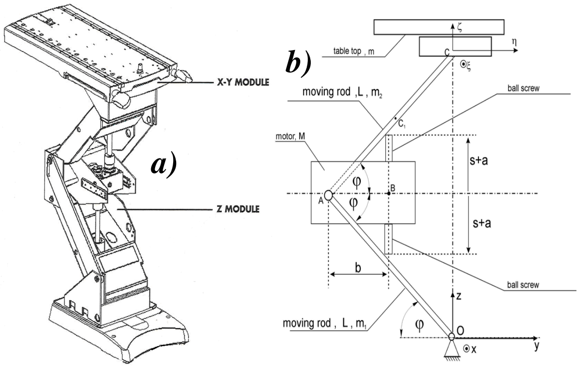

Fig. 1. a) Robotic couch used for radiation therapy treatment - ELEKTA Precise Table^{TM}, a) external isometric view; b) System model: vertical movement in s direction is achieved by motor installed in the holder A. Tabletop movement in ξ and η directions are achieved by two motors sitting under the tabletop

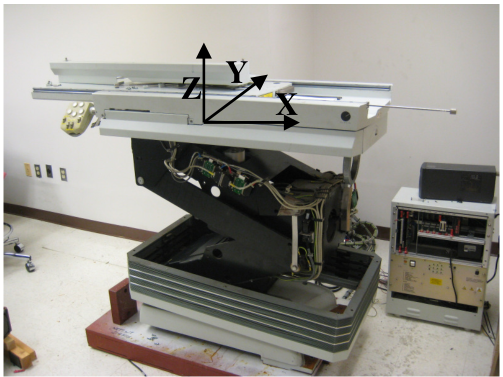

Fig. 2. ELEKTA Precise Table^{TM} robotic treatment couch – experimental setup with reference coordinate system.

The described system is in the integration phase. Before getting the experimental data using external radiation, it is of high importance to fully simulate the system behavior. The presented data are the simulation results.

For computer simulation, we have considered several masses of the patients, such as 55, 85 and 150kg; mass of the tabletop is m=25kg, mass of the moving rods $m_1 = m_2 = 50$kg, mass of the vertical motor with the holder M=50kg, length of the rod L=8cm, a=b=3cm, and the lead of the thread h=0.01m. The sampling frequency is ν=5Hz, and total time of simulation t = 20sec. For the simulation, we have derived the general equations-of-motion for this system, [27]:

$$\begin{aligned}
& m\ddot{\xi} = \tau_{\xi} \\
& m\ddot{\eta} = \tau_{\eta} \\
& -2(a+s)(a^2(3M+m_1+m_2)+b^2(18m+3M+m_1+10m_2)+ \\
& (3M+m_1+m_2)s(2a+s))\dot{s}^2+(a^2+b^2+2as+s^2)(a^2(3M+m_1+m_2)+ \\
& b^2(12m+3M+m_1+7m_2)+(3M+m_1+m_2)s(2a+s))\ddot{s} = \\
& = \frac{3(b^2+(a+s)^2)^4}{b^2L^2}\left(\frac{4\pi\tau_M}{h}-\frac{b^2gL(4m+2M+m_1+3m_2)}{2(b^2+(a+s)^2)^{3/2}}\right)
\end{aligned} \tag{1}$$

where ξ, η and s are generalized coordinates of motion, $\tau(.)$ is generalized torque for each axis. Other parameters from equation (1) are masses of moving parts and geometric characteristics of the system, as in (Fig1.b).

III. TRACKING AND ADAPTIVE CONTROL

In the following part, the two motion compensation techniques have been analyzed. The first is tumor tracking without knowing the tumor position in advance, and the second one is the adaptive contouring mode, when the trajectory is known before the treatment starts.

For tumor tracking the controller should be placed in the position tracking mode to support changing the target volumes of an absolute position move during the treatment. The provision for mutual tracking exists. That option is useful in the case when there are two targets (i.e. lung tumor and moving lymph nodes). New targets may be moved in the same direction or the opposite direction of the current target position. The controller will then calculate a new trajectory based upon the new target and the acceleration, deceleration, and speed parameters that have been set. The controller has provision to update the position information at the rate of 1msec. However, for the purpose of simulation, we have used a sampling frequency of 5Hz. The controller generates a profiled point at every other sample, and linearly interpolates one sample between each profiled point. Based on the tumor velocity and position, the controller will either continue in the direction it is heading, change the direction it is moving, or decelerate to a stop. The position tracking mode is suitable in the case when the internal markers give the real-time position during the motion compensation and tracking and the proposed system is able to generate a robotic couch trajectory on the fly. The simulation of the robotic table position when the tumor position is not known in advance is given in Fig.3.

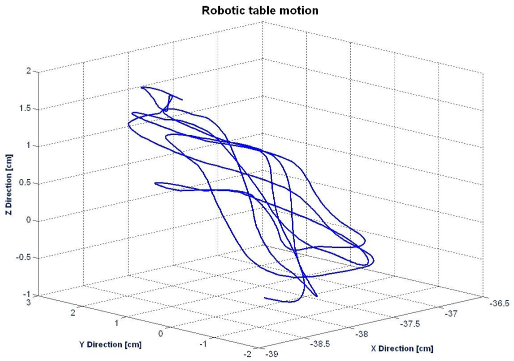

Fig. 3. Robotic table motion in the tracking mode. An internal marker gives the real-time position of the target volume and the system compensates the motion.

The adaptive contour mode allows the user to generate custom profiles by updating the reference position at a specific time rate or to have a predefined tumor trajectory. This approach was analyzed in [17]. To obtain real patient data we have used 4D-computer tomography (CT) image technique. A 4D-CT device is able to acquire images during ten phases of breathing cycle and to calculate tumor centroid displacement for each of the ten phases with respect to the treatment isocenter.

IV. RESULTS

To compare previously proposed [17], [27] tracking using a PID controller with an adaptive control strategy, we have analyzed different system errors, as a result of different patient mass. We have analyzed errors in the vertical direction, due to the fact that the biggest influence of the load to the system accuracy was observed for the vertical motion. This fact can be confirmed by analyzing equation (1). Due to the fact that adaptive control has provision for the control parameters to be self-tuned, it was observed that variations in loads (i.e. patient mass) have less influence on the system error comparing to the PID controller.

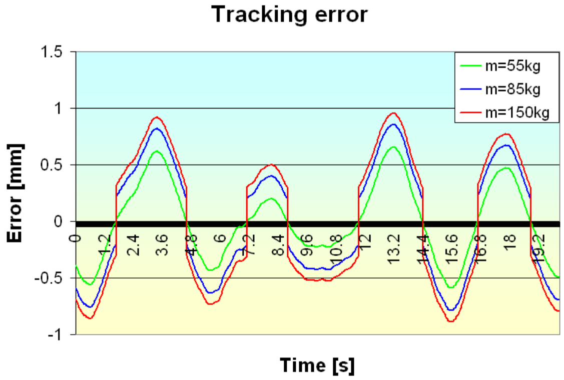

Fig. 4. Tracking error for the system when PID controller was used. for the different loads.

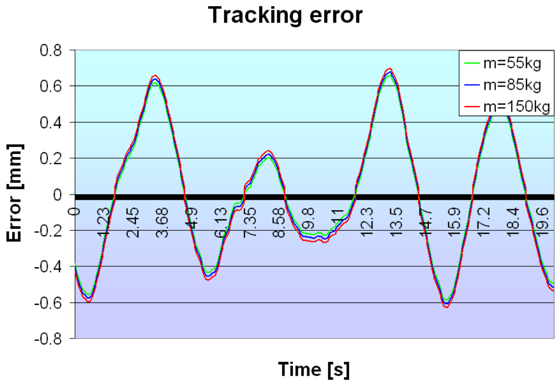

Fig. 5. Tracking error for the system when adaptive controller was used. for the different loads.

V. CONCLUSION AND FUTURE WORK

Implementation of the proposed technique can potentially improve real-time tracking of the tumor-volume to deliver highly conformal precise radiation doses, while minimizing irradiation to healthy tissues and sparing critical organs. This, in turn, will potentially improve the quality of patient treatment by lowering the toxicity level and increasing survival rates. With this new technique, it will be possible to administer radiation doses to the tumor faster than conventional methods like gating.

In this study, we have analyzed the implementation of the control strategy in the clinical radiotherapy procedure. The closed-loop PID controller was compared with feedforward adaptive control to asses the influence of the different patient mass to the system accuracy. Adaptive control shows to be a suitable choice because of the variability in the payload on the system, i.e., the weight of the patient. Maximal tumor tracking errors for PID control were less than 1mm, and based on the results in [27] it will not compromise patient treatment, i.e. dosimetric coverage. For the adaptive control, maximal tracking errors were less than 0.7mm. The PID controller can be suitable as well, but in some cases, it is necessary to adjust the controller's gains, depending on the patient weight.

The future work is to be full system integration and rigorous mechanical and dosimetric tests using external beam radiation.

ACKNOWLEDGMENT

This research study is partly supported by the ELEKTA Ltd, Crawley, UK.

REFERENCES

[1] S. Hiroki, S. Keishiro Suzuki, G.C. Sharp, *et al.*, "Speed and amplitude of lung tumor motion detected in four-dimensional setup and in tumor-tracking radiotherapy", *Int. J. Radiation Oncology Biol. Phys.*, Vol. 64, No. 4, pp. 1229–1236, 2006.

[2] Q.S. Chen, M.S. Weinhous, F.C. Deibel, J.P. Ciezki, and R.M. Macklis, "Fluoroscopic study of tumor motion due to breathing: Facilitating precise radiation therapy for lung cancer patients," *Med. Phys.*, 28(9), 1850–1856, 2001.

[3] E.A. Barnes, B.R. Murray, D.M. Robinson, L.J. Underwood, J. Hanson, and W.H. Roa, "Dosimetric evaluation of lung tumor immobilization using breath hold at deep inspiration," *Int. J. Radiat. Oncol., Biol., Phys.* 50(4), 1091–1098, 2001.

[4] S.C. Erridge, Y. Seppenwoolde, S.H. Muller, M. van Herk, K. De Jaeger, J.S. Belderbos, L.J. Boersma, and J.V. Lebesque, "Portal imaging to assess set-up errors, tumor motion and tumor shrinkage during conformal radiotherapy of non-small cell lung cancer," *Radiother. Oncol.* 66(1), 75–85, 2003.

[5] C. Ozhasoglu, and M.J. Murphy, "Issues in respiratory motion compensation during external-beam radiotherapy," *Int J Radiat Oncol Biol Phys* 52(5):1389–1399, 2002.

[6] P.J. Keall, G.S. Mageras, J.M. Balter, et. al. "The management of respiratory motion in radiation oncology report of AAPM Task Group 76", in the *J. Medical Physics*, Vol. 33, No. 10, pp. 3874-3900, 2006.

[7] G. Benchetrit, "Breathing pattern in humans: diversity and individuality," *Respir Physiol* 122(2-3):123–129, 2000.

[8] S.S. Vedam, P.J. Keall, A. Docef, D.A. Todor, V.R. Kini, and R. Mohan, "Predicting respiratory motion for four-dimensional radiotherapy." in the *J. Medical Physics,* Vol. 31, No. 8, pp. 2274–2283, 2004.

[9] G.C. Sharp, S.B. Jiang, S. Shimizu, and H. Shirato, "Prediction of respiratory tumour motion for real-time image-guided radiotherapy," in the *J.Phys Med Biol*. Vol. 49, No. 3, pp. 425–440, 2004.

[10] A. Schweikard, G. Glosser, M. Bodduluri, M. J. Murphy, and J. R. Adler, "Robotic motion compensation for respiratory movement during radiosurgery," in the *Comput Aided Surg* 5(4):263–277, 2000.

[11] Y. Kamino, K. Takayama, M. Kokubo, *et al*. "Development of a four-dimensional image-guided radiotherapy system with a gimbaled x-ray head", *Int. J. Radiation Oncology Biol. Phys.*, Vol. 66, No. 1, pp. 271–278, 2006.

[12] W. D'Souza, and T.J. McAvoy, "Analysis of the treatment couch and control system dynamics for respiration-induced motion compensation", in the *J. Medical Physics*, Vol. 33, No. 12, pp. 4701-4701, 2006.

[13] P.J. Keall, H. Cattell, D. Pokhrel, et al., "Geometric accuracy of a real-time target tracking system with dynamic multileaf collimator tracking system", in the *Int. J. Radiation Oncology, Biology and Physics*, Vol. 65, No. 5, pp. 1579-1584, 2006.

[14] W. D'Souza, S.A. Naqvi, and C.X. Yu, "Real-time intra-fraction-motion tracking using the treatment couch: a feasibility study", in *Phys. Med. and Bio.*, Vol. 50, pp. 4021-4033, 2005.

[15] T.K. Podder, I. Buzurovic, Y. Hu, Galvin J.M., Y. Yu, "Partial transmission high-speed continuous tracking multi-leaf collimator for 4D adaptive radiation therapy" in the *IEEE Int. Conf. on Bioninformatics and Bioengineering (BIBE)*, pp. 1108-1112, Boston, MA, USA, 2007.

[16] T.K Podder, I. Buzurovic, J.M. Galvin, Y. Yu, "Dynamics-based decentralized control of robotic couch and multi-leaf collimators for tracking tumor motion" in the *IEEE Int. Conf. on Robotics and Automation (ICRA)*, pp. 2496-2502, Pasadena, CA, USA, 2008.

[17] I. Buzurovic, K. Huang, Y. Yu, and T.K., Podder, "Tumor Motion Prediction and Tracking in Adaptive Radiotherapy", *Proc. of 2010 IEEE Int. Conf. on Bioinformatics and Bioengineering (BIBE)*, pp.273-278, Philadelphia, PA, USA, 2010.

[18] Y. Suh, S. Dieterich, and P.J. Keall, "Geometric uncertainty of 2D projection imaging in monitoring 3D tumor motion", *Phys. Med. Biol.* Vol.52, pp.3439-3454, 2007.

[19] Q. Xu, R.J. Hamilton, R.A. Schowengerdt, and S.B. Jiang, "A deformable lung tumor tracking method in fluoroscopic video using active shape models: a feasibility study", *Phys. Med. Biol.,* Vol.52, pp.5277-5293, 2007.

[20] T. Lin, L.I. Cerviño, X. Tang, N. Vasconcelos, and S.B. Jiang, "Fluoroscopic tumor tracking for image-guided lung cancer radiotherapy", *Phys. Med. Biol.*, Vol.54, pp.981-992, 2009.

[21] N. Riaz, P. Shanker, R. Wiersma, O. Gudmundsson O, *et.al.*, "Predicting respiratory tumor motion with multi-dimensional adaptive filters and support vector regression", *Phys. Med. Biol.*, Vol.54, pp.5735-5748, 2009.

[22] M. Ribold, G.C. Sharp, G. Baroni, and G.T.Y. Chen, "Four-dimensional targeting error analysis in image-guided radiotherapy", *Phys. Med. Biol*., Vol.54, pp.5995-6008, 2009.

[23] K. Huang, I. Buzurovic, Y. Yu, and T.K. Podder, "A Comparative Study of a Novel AE-nLMS Filter and Two Traditional Filters in Predicting Respiration Induced Motion of the Tumor", *Proc. of 2010 IEEE Int. Conf. on Bioinformatics and Bioengineering (BIBE)*, pp.281-282, Philadelphia, PA, USA, 2010.

[24] J. Rottmann, M. Aristophanous, A. Chen, L. Court, and R. Berbeco "A multi-region algorithm for markerless beam's-eye view lung tumor tracking", *Phys. Med. Biol.*, Vol.55, pp.5585-5598, 2010.

[25] B. Cho, P.R. Poulsen, and P.J. Keall, "Real-time tumor tracking using sequential kV imaging combined with respiratory monitoring: a general framework applicable to commonly used IGRT systems", *Phys. Med. Biol.*, Vol.55, pp.3299-3316, 2010.

[26] J.H., Lewis, R. Li, W.T. Watkins, J.D. Lawson, *et.al.*, "Markerless lung tumor tracking and trajectory reconstruction using rotational cone-beam projections: a feasibility study", *Phys. Med. Biol.*, Vol.55, pp.2505-2522, 2010.

[27] I. Buzurovic, K.Huang, Y.Yu, and T.K. Podder, "A Robotic Approach to 4D Real-time Tumor Tracking for Radiotherapy", *Physics in Medicine and Biology* (PMB), Vol. 56(5), pp.1299-1318, 2011.

[28] I. Buzurovic, M. Werner-Wasik, T. Biswas, J. Galvin, A.P. Dicker, Y. Yu, T. Podder, "Dosimetric Advantages of Active Tracking and Dynamic Delivery", *Med. Phys.*, Vol.37, p.3191, 2010.

[29] I. Buzurovic, K. Huang, M. Werner-Wasik, T. Biswas, A.P. Dicker, J. Galvin, Y. Yu, T. Podder, "Dosimetric Evaluation of Tumor Tracking in 4D Radiotherapy", *Int. J. Radiat. Oncol. Biol. Phys.* 78(3), Suppl.1 S689, 2010.

[30] R.A. Sweeny, W. Arnold, E. Steixner, M. Nevinny-Stickel, P. Lukas, "Compensating for Tumor Motion by a 6-Degree-of-Freedom Treatment Couch: Is Patient Tolerance an Issue?", *Int. J. Radiat. Oncol. Biol. Phys.*, Vol.74(1), pp.168-171, 2009.