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Motion compensation for robotic lung tumour radiotherapy in remote locations: A personalised medicine approach

Clara M. Ionescu[a,*], Cosmin Copot[b], Dirk Verellen[c]

[a] Ghent University, Faculty of Engineering and Architecture, Research group on Dynamical Systems and Control (DySC), Technologiepark 914, 9052 Ghent, Belgium
[b] University of Antwerp, Department of Electromechanics, Op3Mech, Groenenborgerlaan 171, 2020 Antwerp, Belgium
[c] Vrije Universiteit Brussel, Faculty of Medicine and Pharmacy, Translational Radiation Oncology and Physics and Supportive Care (TROP), Laarbeeklaan 101, 1090 Brussel, Belgium

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ABSTRACT

The purpose of this work is to integrate the concept of patient-in-the-closed-loop application with tumour treatment of cancer-diagnosed patients in remote areas. The generic closed loop control objective is effective synchronisation of the radiation focus to the movement of a lung tissue tumour during actual breathing of the patient. This is facilitated by accurate repositioning of a robotic arm manipulator, i.e. we emulate the Cyberknife Robotic Radiosurgery system. Predictive control with disturbance filter is used in this application in a minimalistic model design. Performance of the control structure is validated by means of simulation using real recorded breathing patterns from patients measured in 3D space. Latency in communication protocol is taken into account, given telerobotics involve autonomous operation of a robot interacting with a human being in different location. Our results suggest that the proposed closed loop control structure has practical potential to individualise the treatment and improves accuracy by at least 15%.

1. Introduction

Nowadays, radiation therapy is a major modality for treating cancer patients. Stereotactic Body Radiotherapy (SBRT) is an overarching term addressing cancer treating radiotherapies that exploit the principle of hypo-fractionation with high precision tumour localisation and image guidance [1–7]. This technique sequences a high radiation dose over multiple non-coplanar beams that only intersect at the cancerous target location, thereby creating a so called localised radiation hot-spot. Tumours nestled in lung tissue or near thoracic organs are often found to describe a spatial trajectory as a result of respiration induced lung movement [9]. The phenomenon is referred to as *respiratory* (*induced*) *tumour motion* and the spatial path described by the tumour as the *tumour trajectory*. Hence, precise target localisation and accurate dose delivery cannot be guaranteed if this complex motion is not taken into account.

Respiratory gated radiotherapy (RGR) represents a static perspective on motion-adaptive therapy. The technique exploits the periodic nature of the breathing cycle and administers a cyclic radiation exposure. Therefore the radiation source can remain fixed in space and is only switched on when the target moves into a predefined window or gate. Position and width of this gate depend on the specific behaviour of the target movement, the current angle of incidence and consequently the exposed adjacent healthy tissue [7,10].

Real-time tumour tracking (RTTT) is a recent addition to the SBRT family, that caters to the respiratory induced tumour movement [12,11,13,14,7]. The technique entails active compensatory motion to counteract any wandering of the tumour, such that the relative position between radiation beam and target is kept constant. This motion compensation can be realized either by manipulating the collimating system, the entire linac or using the patient support system [10]. In the Cyberknife approach the source is mounted on a six degree of freedom robotic arm to facilitate sufficient manoeuvrability. Individual beams are directed precisely to the target while the patient is exposed to the radiation [8].

In practice, surrogate breathing signals that exhibit strong correlation to the actual tumour trajectory are measured, and fed to a *correlation function* which then estimates the true tumour position. Surrogate signals can be obtained by use of implanted fiducial markers, however this requires an invasive procedure [15,16]. Alternatively, surrogate signals can be provided by external markers such as infrared reflectors interwoven into a vest worn by the patient during treatment [17]. Recently, a new technique arose that completely circumvents any direct contact to the patient. Continuous-wave (CW) radar sensors

* Corresponding author.
E-mail addresses: claramihaela.ionescu@ugent.be (C.M. Ionescu), cosmin.copot@uantwerpen.be (C. Copot), dverelle@vub.ac.be (D. Verellen).

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measures the periodic motion of the body itself thereby minimizing the discomfort experienced by the patient. The technique however is yet in its infancy but shows great potential in motion-adaptive radiotherapy [18].

Using any of these surrogate techniques will heavily influence the quality of the estimates given by the correlation functions. These consist of patient specific mathematical algorithms apriori designed based on the surrogate signals and tumour trajectory signals obtained through conventional imaging. As the surrogate signals are correlated to an accurate estimate of the tumour trajectory and these motion patterns change during treatment, the accuracy of the correlation model needs to be verified. This verification is performed online by comparison of intermediate tumour images and their positional estimates [4,19]. Whenever accuracy would fall short, treatment is interrupted and the function revised, which is to be avoided as much as possible in clinical practice.

In the context of telemedicine, virtual presence of a medical supervisor and remote delivery of treatment have a significant role in today's healthcare. Telemedicine has several advantages, the main being economic cost effective, and in restricted access situations (i.e. space) it may play an unique role. In today's framework of cyber-physical systems, long distance teleoperations are common control problems. Some of the main challenges for control are: latency, nonlinear dynamics and constraints. For instance, the communication delays may vary from 0.08 s to as much as 600 s depending on the distance from Earth communication base to various places in Space [20]. A schematic overview of the remote robotic radiotherapy system is given in Fig. 1. The potential for biomedical applications of telemedicine in remote areas has already been recognized [21,22] and suggestions for surgical robotic support in space missions has been proposed in [23]. Furthermore, procedures to circumvent any potential faults for space robotic systems have been proposed in [24]. An important challenge remains the presence of time delays, which may deteriorate significantly the performance if not suitably tackled [25].

The original contribution of this paper stands in the following. Firstly, we introduce and tailor the use of closed loop control algorithms for motion compensation in robotic radiotherapy. Inverse kinematics of the robotic motion are used to partially compensate dynamic motion profiles during radiotherapy and simplify the closed loop control complexity, but dynamic models of the robotic system are also used in the control algorithm. Secondly, we employ the use of 3D patient-breathing profiles into a model based predictive control methodology to ensure a patient-specific motion compensation. The above described steps aim at moving away from the current state of art in clinical practice, which uses solely robot inverse kinematics and open loop compensation based on motion sensor systems. Additionally, we employ the proposed predictive control scheme in a Smith Predictor form, such that it can naturally deal with varying time delays. The use of breathing profiles as disturbance profiles introduces a feedforward-like action in dynamic motion compensation. The purpose of the entire methodology is to increase accuracy in the position of the robotic radiotherapy system to maintain to a minimum the percent of healthy tissue radiation.

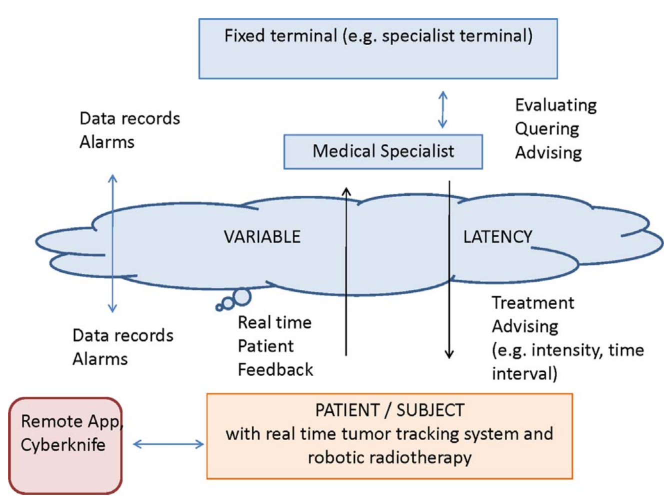

Fig. 1. Conceptual scheme of various elements of remote robotic radiotherapy system.

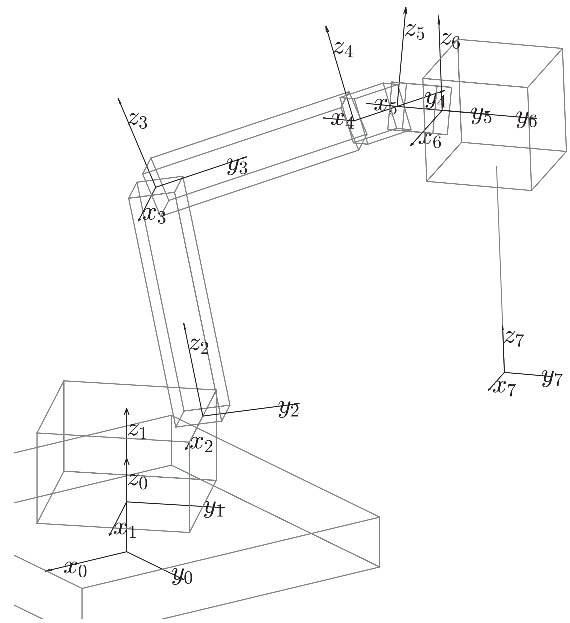

Fig. 2. Visualisation of the coordinate frames fixed to each link body on the Cyberknife robot.

The paper is organized as follows: next section introduces the robot kinematics and our specific approach to this problem. Section 3 presents the proposed control methodology followed by results and discussion in section 4. A conclusion section summarizes the main outcome of this work.

2. Robot models

A simplified representation of the robotic manipulator that is employed in the Cyberknife Robotic Radiosurgery system is given in Fig. 2.

A *serial-link manipulator* consists of a chain of links interconnected with a set of joints, each DOF, either rotational or translational. A robot consisting of n joints, numbered from 1 to n, compromises $n + 1$ links, 0 and $n + 1$ respectively corresponding to the robot base and the end-effector [12,26]. The full state of a robot can thus be captured by a generalised joint variable vector $\bar{q}(t) = [q_1(t) \; \dots \; q_n(t)]^T$ containing the joint variables. Notice that a seventh coordinate frame is attached to the radiation focus point in Fig. 2.

Each transformation matrix consist of a rotation matrix ${}^{i-1}R_i$ and a translation vector ${}^{i-1}T_i$. Assembling into one transformation matrix ${}^{i-1}DH_i$ and concatenating frame $i - 1$ to frame i gives:

$$ {}^{i-1}_{4\times4}R_i = \begin{bmatrix} {}^{i-1}_{3\times3}R_i & {}^{i-1}_{3\times1}T_i \\ {}_{1\times3}0 & 1 \end{bmatrix} \tag{1} $$

This formulation obeys the transition law presented in Eq. (2), which demonstrates its ease of use when describing the transformation between consecutive coordinate frames:

$$ {}^{j}G_i = {}^{j}G_{i-1}\,{}^{i-1}DH_i \tag{2} $$

whereas the matrix ${}^{n}DH_R$ specifies the position of the beam that is to be