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Control methods for robot-based predictive compensation of respiratory motion

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ABSTRACT

Robot-based tracking of spontaneous respiration-triggered motion of human tissue becomes increasingly important in robot-guided imaging, interventional radiology, surgery and radiotherapy. This work provides a first general comparative assessment of the tracking performances that can potentially be achieved by common control schemes under realistic conditions.

Cartesian exemplary spontaneous respiratory motions of 185 min duration were recorded from a healthy male subject and transformed into reference trajectories for tracking experiments. Prediction error was modeled by random perturbation of these trajectories with increasing amplitude over the prediction horizon. The controlled system, an industrial robot, was represented by an identified ARX model. A repetitive (RC), adaptive (ALC), feedforward (FFC) and model-based predictive controller (MPC) were implemented. ALC adaptively identifies robot latency and compensates this latency by according time-shift of reference coordinates. Control performance was assessed based on the control error as well as this errors' estimated worst case dosimetric consequence in a radiotherapy application. Deviations from periodicity in reference trajectories were statistically quantified and reproduced for simulation-based assessment of RC. ALC, FFC and MPC were assessed experimentally.

Realistic deviations from periodicity made performance of RC unprofitable, even with ideal function of controller and period-robustness techniques. The same applies potentially to related methods such as iterative learning control. ALC, FFC and MPC performed comparably for ideal prediction. Despite realistic prediction error, FFC and MPC achieved submillimeter control error, significantly outperforming ALC.

Thus, FFC or MPC should be employed, RC and ALC should not be employed in robot-based tracking of spontaneous respiration-triggered motion of human tissue.

1. Introduction

Tracking of respiratory motion by a robot becomes increasingly important in radiotherapy as well as in any other context that involves the synchronization of the motion of a robot with respiration-triggered physiological motion such as e.g. in robot-guided imaging, interventional radiology and surgery.

Radiotherapy processes like intensity modulated radiotherapy (IMRT) comprise imaging, planning and dose application with high spatial precision. This allows conformal irradiation and thus effective treatment of stationary tumors. If the irradiated anatomical structures are subject to temporal changes, e.g. as a result of respiration, 4D radiotherapy processes are required. Such processes imply measurement of aforementioned changes by imaging, consideration of these changes during planning and compensation of these changes during dose application [1]. Four-dimensional radiotherapy processes are increasingly addressed in research and introduced into clinical routine [2].

Respiratory motion is generated primarily by abdominal and breast breathing modes [3] and effects a dynamic location of organs such as lung, esophagus, pancreas, liver, prostate and breast [4]. Spontaneous respiration-triggered motion of a lung tumor features irregular quasiperiodic character with a range of up to 2.5 cm (in rare cases up to 5 cm) [5] and a frequency between 0.15 and 0.3 Hz [3] (in rare cases up to 0.52 Hz [6]).

The main approaches to account for respiration-induced tumor motion in radiotherapy are motion inhibition and motion compensation. Motion inhibition reduces tissue motion e.g. by mechanical retaining devices or breath hold techniques. Motion compensation realizes an adaption to tissue motion by either gating or track-

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ing. Gating [7] restricts the beam-on-time to phases of predefined margins of motion-correlated sensor data (surrogates). As a result, a trade-off between residual motion and duration of the treatment fraction is required. Tracking realizes continuous beam-on by determining and compensating changes of anatomical structures in realtime during dose application. Such compensation can be obtained e.g. by robot-based and respiration-synchronized positioning of the linear accelerator [8,9], or the treatment couch [10], or by dynamic reconfiguration of the multileave collimator [11]. Each aforementioned approach employs feedback control with the aim of fixing the position of the moving tumor with respect to the treatment beam.

Published control schemes for robot-based tracking respectively compensation of respiratory motion address among others the fields of radiotherapy, surgery and osteotomy. The "HexaPod"[1] [12–14], the "Precise Table"[2] [15,16], the "Lightweight Robot"[3] [17] the "AESOP Robot"[4] [18–20], the "PHANToM Premium"[5] [21–23] and several robot prototypes were employed as controlled systems. The "Cyberknife" system[6] [24] is already used in clinical practice and employs industrial robot technology.

The aforementioned systems utilize PID controllers with different approaches for motion prediction to overcome deadtimes [25], model-based predictive controllers [12,13,26,27] and iterative learning controllers [17], among others. Gangloff et al. [18] include the repetitive properties of the respiratory signal in the ARIMAX equation of a general predictive control (GPC) to achieve a better compensation of the respiratory movement of organs in a surgical application.

Despite the high and increasing relevance of tracking of spontaneous respiratory motion by a robot, associated basic control methods that might be considered for this task, have not yet been systematically assessed and compared. This work aims at providing such assessment based on the representative example of patient couch tracking in radiotherapy by a serial industrial robot. Two analyses are presented:

1 Simulation based assessment of repetitive control

Repetitive control (RC) [28] has the potential of eliminating the tracking control error for the case of a periodic reference trajectory. Moreover, RC is a causal control scheme, i.e. solely measured samples of the reference trajectory are required as controller inputs; prediction of the reference trajectory is avoided. Period-robust repetitive control (PRC) allows a small tracking control error even if the reference trajectory displays slight deviations from periodicity. In this analysis, the degree of deviations from periodicity in spontaneous respiration-triggered motion is statistically quantified based on experimental data. Using this quantification, realistic reference trajectories are constructed and used to determine simulatively the principal suitability of PRC.

2 Experimental assessment and comparison of non-causal control schemes

Non-causal tracking control schemes require measured and predicted samples of the reference trajectory as controller inputs. In this analysis, three different non-causal control schemes, an adaptive control scheme (ALC), feedforward control (FFC) and model-based predictive control (MPC), are assessed and compared quantitatively based on physical experiments. These experiments account for the specifics of the motion tracking application by:

a) Use of reference trajectories that represent measured spontaneous respiratory motion.
b) Distortion of the used reference trajectories by a simulated prediction error.
c) Use of a KR16 industrial robot[7] as exemplary controlled system.
d) Quantification of the control error in terms of the worst case clinical consequence in a tracking application in radiotherapy.

The inclusion and assessment of prediction schemes are not part of this work. Preliminary results of this work have been published previously [29].

2. Methods

2.1. Nomenclature

In this work, vectors and matrices, which hold multiple numeric components, are marked by bold face lower and upper case letters respectively. Cartesian vectors are denoted as **r** accompanied by up to three indices

- Lower left hand side index: Name of the start point of the vector.
- Lower right hand side index: Name of the end point of the vector.
- Upper left hand side index: Name of the coordinate system the vector components refer to.

An index that is omitted indicates the inertial system respectively its base point. Values in discrete-time domain are represented by using the argument $\{t\}$ where t denotes the integer-valued time step. Values in z-domain are represented by using the argument $\{z\}$.

2.2. Acquisition of respiratory motion

Twenty-seven infrared reflecting markers were homogeneously distributed over the chest and abdomen of a healthy male subject lying in dorsal position. The Cartesian motions of these markers were optically tracked, while the subject performed spontaneous regular breathing. Recorded tracking data were low-pass filtered and scaled by a factor of two (in order to reach motion ranges which are realistic for a lung tumor). Measurement errors (especially pairs of spontaneous jumps in opposite direction attributed to (partial) marker occlusion) were corrected, if that was possible. Records (or parts thereof) noticeably disturbed by measurement errors (e.g. measurement noise amplitudes noticeably greater than movement amplitudes) were excluded. Total duration of the recorded Cartesian motions is 185 min.

2.3. Quantification of variability of respiratory motion

In order to quantify the deviations from periodicity in the recorded motions (Section 2.2), the recorded Cartesian motion trajectories were first projected onto their principal axes yielding a reduction into according one-dimensional trajectories. The time dependent shape parameters (duration, amplitude, offset and shape of one period) and the time dependent variation parameters (change of the shape parameters from one to the subsequent period) were extracted from the one-dimensional trajectories for

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