UNIVERSITÄT ZU LÜBECK
INSTITUT FÜR ROBOTIK
UND KOGNITIVE SYSTEME

Algorithms for Compensation of Quasi-periodic Motion in Robotic Radiosurgery

Floris Ernst

supervised by Prof. Dr.-Ing. Achim Schweikard

Dissertation

Universität zu Lübeck
Institut für Robotik und Kognitive Systeme

IM FOCUS DAS LEBEN

In modern societies, the second most prevalent cause of death—after cardiopulmonary disease—is cancer. And while fighting cancer has been very high up on the agenda for many years, successfully treating aggressive neoplasms, such as tumours of the lung, bronchus, or pancreas, remains a challenge.
One major challenge in radiotherapy for treating these cancers is the presence of respiratory and pulsatory motion. Different concepts for detecting and compensating for this motion exist and have been or are in the process of being introduced into the clinic. While, in theory, most radiotherapeutic devices can be modified such as to allow for motion compensation, only two feasible approaches exist. The first method, which has not yet been fully adopted clinically, makes use of metallic leaves shaping and moving the treatment beam. The other approach, clinically available since the early years of the 21^{st} century, uses a robotic arm to move the radiation source. In this work, the main focus is placed on algorithms needed to improve motion tracking using this robotic device, the CyberKnife.
Robotic radiosurgery suffers from two problems: first, real-time acquisition of the tumour position is difficult or strenuous on the patient. Second, even if the position of the tumour is known, synchronously moving the radiation source is impossible due to systematic latencies from signal processing and mechanical inertia. These problems are currently handled by two independent approaches, being *correlation* to determine the tumour's position from externally measured surrogates, and *prediction* to reduce effects of the system's latency. These two approaches are the main topic of this work.
To be able to better evaluate and quantify errors of the system as well as the sources of these errors, multiple measures for describing prediction and correlation errors are discussed. The standard metric, the RMS error, is introduced as well as new measures focusing on signal stability (the *jitter*), the frequencies present in the error signal (the *frequency content*), and probable error ranges (the *confidence interval*). Additionally, a signal smoothing method well suited to real-time processing of quasi-periodic signals sampled at high frequencies is introduced and evaluated. It is shown that noise can be removed from respiratory and pulsatory motion traces with high reliability given that the acquisition frequency is sufficiently high (at least 100 Hz). Another artefact commonly seen when using electromagnetic tracking systems or IR tracking systems with line cameras, called *frequency leakage*, is also investigated. It results from the fact that these tracking systems must collect multiple measurements—which cannot be done simultaneously—to completely determine an object's pose. If the object moves in between these measurements, the resulting pose is distorted. By using interpolation or one of the prediction methods investigated for respiratory motion prediction, it was possible to reduce the effects of this artefact by more than 60 % when using interpolation and by more than 35 % when using prediction.
The main part of this work is centred around developing and evaluating algorithms suitable for prediction of quasi-periodic signals. Eight algorithms are introduced, the LMS, nLMS, RLS, wLMS, MULIN, SVRpred, EKF frequency tracker, and FLA-nLMS methods. Three methods, the LMS, nLMS, and RLS algorithms, are merely slight variations of standard textbook algorithms. The other algorithms have been newly developed for this work. The MULIN family of algorithms is based on a Taylor-like expansion of the difference between the real signal and the delayed signal. In its simplest form, it is a simple linear extrapolation method. The EKF frequency tracking approach models the respiratory motion trace as a sum of finitely many sinusoidals and tries

to track their frequencies, amplitudes, and phases. The wLMS algorithm is a combination of Wavelet-based multiscale decomposition and regression on the individual Wavelet bands. The FLA-nLMS algorithm is a modification of the standard nLMS algorithm which dynamically adapt the algorithmic parameters M and μ to produce an optimal prediction algorithm. The SVRpred algorithm tries to model prediction as a high-dimensional regression problem in kernel space, with the possibility of incorporating additional surrogates like the ECG for the prediction of pulsatory motion traces. All methods have been thoroughly evaluated on a database of 304 real respiratory motion traces recorded during CyberKnife treatment and on 41 pulsatory motion traces from various acquisition modalities (external optical tracking, 3D ultrasound template matching, NavX catheter data). On both respiratory and pulsatory data, no single algorithm proved to be ultimately superior to the other methods. On the respiratory motion data, however, it could be determined that the algorithms currently in use in the clinic (algorithms based on LMS or pattern matching) are significantly outperformed by the wLMS, MULIN, and SVRpred algorithms: on average, the nLMS algorithm was outperformed by 25 % by the MULIN, by 31 % by the wLMS, and by 22 % by the SVRpred algorithm. In individual cases, the increase in accuracy was as much as 52 %, 58 %, and 84 %, respectively. In all but two cases, there was at least one prediction algorithm resulting in an improvement in relative RMS, in 90 % of the cases, a reduction by at least 21 % was possible, in 50 % of the cases, a reduction in error by more than 50 % was achieved. On the pulsatory motion traces, the results showed a somewhat different picture: the SVRpred algorithm performed best in 28 of the 41 cases, the EKF algorithm in 7 cases, the nLMS algorithm in three cases, the wLMS algorithm in two cases and the MULIN algorithm in one case. In all cases, prediction improved reduced the error from latency, by at least 10 % and as much as 75 %.
The second problem, correlating chest surface motion to the internal target's motion, was investigated using data acquired in a porcine study (high-resolution and high-frequency biplanar fluoroscopy and external optical tracking) and with data from human volunteers (3D ultrasound and external optical tracking). Comparing the clinically used algorithms (simple polynomial models) to our newly developed correlation algorithm based on SVR showed that the state-of-the art clinical algorithms can be outperformed by as much as 78 %. The main difference between our correlation method and the classical polynomial models is that now all dimensions of the external motion signal are used (instead of just the main axis of motion), that information about speed and, if desired, acceleration is incorporated, and that it is possible to simultaneously use the information from multiple external points.