**Abstract:** This paper summarizes the work carried out at Coventry University on video tracking and patient motion compensation during the MAESTRO European project. A novel combination of motion prediction, couch control and couch non-linearities compensation was developed and implemented in real time to control an Elekta AB (Publ) ‘Precise’ patient support system or ‘couch’. The reference trajectory was obtained from a video tracking system implemented using LabVIEW. A new anthropomorphic robotic system was used to generate target motions which were captured with a video tracking system that provided a reference to the PSS control system implemented using Matlab® Simulink® and dSPACE. The PSS with its new control system reduced the vertical and longitudinal motion of a surrogate marker located on a robotic arm to less than 1mm RMS and 2mm 95% confidence interval. The motion compensation resulted in significant dosimetric improvements compared to irradiating a moving target. Irradiation of Gafchromic films produced dose distributions with no noticeable differences between fixed target and a motion compensated moving target.

1. INTRODUCTION

Motion management in radiotherapy aims to accommodate organ and patient motion to maximize treatment effectiveness. This paper summarises the work carried out during the Methods and Advanced Equipment for Simulation and Treatment in Radiation Oncology (MAESTRO) FP6 European project (Haas, 2010) on motion management using an active motion compensation/tracking strategy. It is based on the Elekta AB (Publ) ‘Precise’ patient support system (PSS). To accommodate motion it is necessary to accurately locate and then track the shape and position of the treatment volume. Four-dimensional (4D) computed tomography, 4D cone beam and 4D magnetic resonance imaging can provide tumour size, shape, volume and motion information. However, actively accommodating the tumour motion during radiation delivery is still a challenge from the image processing perspective. Current solutions involve the monitoring of surrogate markers which position can be related to the actual tumour (Hoogeman et al, 2009). This paper assumes that the surrogate motion measured is representative of the tumour motion. Clinical solutions involve monitoring of external surrogates located on the chest and/or abdomen together with surgically implanted fiducial markers detected using stereoscopic kV imaging techniques. In this work a 2D video tracking system is used to monitor the position of surrogate markers with sub millimetre accuracy.

The following techniques and devices can actively manage motion using robotic devices. All the techniques track surrogate motion and correlated with the internal fiducial markers located near the tumour. Cyberknife uses a robotic manipulator to aim a radiation onto a target (Hoogeman et al, 2009). VERO is a ring based machine which uses a set of gimbals to move the radiation beam (Depuydt et al, 2011). Multileaf collimator tracking synchronises tungsten leaves motion with surrogate motion (Keall et al, 2006, Sawant et al, 2008, Tacke et al, 2010). PSS compensation aims to move the PSS in opposite direction to the measured motion (D’Souza and McAvoy, 2006, Skworcow et al, 2007, Wilbert et al, 2008). The aim of this paper is not to advocate a particular active motion management method, as PSS compensation can be used together with beam tracking, but to highlight the possibilities of making the most of existing devices by adapting their control systems.

The paper is organized as follows: Section 2 describes the PSS. Section 3 describes the control system, Section 4 the material used to evaluate the system’s performance, Section 5 the results before giving overall Conclusions in Section 6.

2. PATIENT SUPPORT SYSTEM

The Elekta precise PSS is a robotic device used to position the patient under a radiation beam at each fraction of a radiotherapy treatment. PSS were originally designed to be operated manually using a set of joysticks. In this work, manual control was replaced by computer control. Two electronic interfaces were constructed by Coventry University Hospital’s technicians to connect a dSPACE 1104 rapid prototyping card (dSPACE, 2011) to the PSS, enabling a Simulink® based control system to operate the PSS. The first interface bypassed the joysticks and measured the currents directly from the PSS. The second interface, used in this work, enabled the connection of the dSPACE 1104 to the linear accelerator control cabinet. The latter reduced the amount of processing done to the signal sent to the PSS drive system and removed the activation of the brake for low velocity. Whilst the logarithmic joystick response was
overcome, the dead zone was found to increase. The non linearities inherent to the system due to stiction and friction were not affected by the interfaces. The PSS position was obtained from two sets of sensors per axis referred to as the coarse and fine potentiometers. The resolution of these sensors was determined experimentally. The coarse potentiometers made one turn over the whole range of motion resulting in a resolution of the order of 0.6 mm. The fine potentiometers made a turn every 100 mm with a resolution increased to 0.06 mm.

Positional, velocity and acceleration tests under no load and up to 70 kg load demonstrated that the Elekta PSS was capable of compensating typical organ motion. To model the PSS non linearities a series of ramp, sine wave and other input signals such as pseudo random binary sequences were adopted. More recently a set of trajectories were designed to represent typical as well as extreme chest motion. The derivative of the position was calculated, modified by a dead zone compensator and sent as a reference to the PSS via the dSPACE interface to obtain open loop system responses, see Fig 1. The non linearities identified include stiction, friction, hysteresis and slightly varying gains. The most significant nonlinearities are i) uneven dead zone and ii) saturation due to the maximum velocity and acceleration the PSS is capable of. The uneven dead zone causes the PSS to drift and follow a distorted sine wave pattern when a sine wave is sent to the PSS. Stiction and friction result in larger control actions being required to start the PSS than to make it stop. Whilst it was observed that the PSS deflected due to the load on the table top, such effect were assumed to be negligible due to the small amplitude of motion during the compensation phase. The deflection can however be taken into account when the patient is initially positioned.

The system was then modelled as a type 1 second order system in series with a look up table mapping the PSS drive voltage against the PSS velocity. In addition input saturations and output saturations were used to reflect the range of operation of the PSS. The sensor noise was also modelled as a statistical distribution and implemented in Simulink® as an embedded Matlab® function. A model was obtained for each axis and the model fit is illustrated for the longitudinal axes in Fig 2. Average sum of absolute of the modelling error of the order of 1 to 2 mm were achieved. The nonlinear and bilinear models offered similar performances, however the bilinear model did not use a look up table of gains resulting in a smaller number of free parameters to identify. The reference was obtained from one of the specifically designed benchmark trajectories (Sahih, 2010).

Having modelled the system the next phase was to design and tune the controller using simulation studies and then progressing to real time software in the loop simulation before deploying the controller on the actual clinical PSS.

3. CONTROL SYSTEM DESIGN

Five controllers were evaluated on simulation, a proportional + integral + derivative (PID) controller, a Smith predictor, a model predictive controller (MPC) and a constrained model predictive controller (cMPC) with both velocity and acceleration constraints and a bilinear Generalised Predictive controller (bGPC). The cMPC was found to offer the best performance on simulation (Skworcow et al, 2007; Skworcow, 2008) and was subsequently implemented in real time. The constraints implemented took into account the maximum PSS velocity as well as ‘sensible’ acceleration values to calculate the control action sent to the PSS. To enable the user to interact with the controller settings during the experimental work the MPC together with the quadratic programming solver were coded in Matlab® C S-function. MPC minimizes a two terms cost function using quadratic programming. The first term relates to the error between the predicted reference and the predicted position and the second term the future control actions. The MPC performance can be adjusted via two parameters that weight the relative importance of accurate machine motion and smooth control action. Active control action may lead to ‘shaky’ motion but precise tracking whereas enforcing a smoother control action leads to a more comfortable ‘ride’ for the patient. To reduce the likelihood of the controller becoming ‘hyperactive’ due to noise, the signal received from the camera was filtered and sent to the control system which operated with frequencies in the range 33 Hz to 80Hz. Whilst in simulation the controller was able to cope with the nonlinearities the real time hardware implementation required the use of a compensator realised as the inverse model of the non linearities. Such compensator reduced the effect of nonlinearities from the controller perspective, enabling a linear controller to control a non linear system by making the combination of compensator
together with the PSS almost linear. Fig. 2 (top) illustrates the action of the compensator which creates sharp amplitude changes to overcome the dead zone and then multiply the reference by a scalar to accommodate for asymmetrical gains. Fig. 3 illustrates the overall control strategy. The target horizontal and vertical motion is measured using an IEEE1394 camera. Each direction of motion is controlled independently with a constant acceleration Kalman filter providing a set of reference position to the MPC controller which uses measured position and estimated velocity together with the predicted position to calculate its next control action (the PSS velocity).

Fig. 3. Overall control strategies for video feedback PSS control for the purpose of patient motion compensation

4. SYSTEM EVALUATION

To evaluate the feasibility of motion compensation using a standard Elekta PSS, criteria based on the positioning accuracy as well as on simulated and actual radiation delivery were adopted. The MAESTRO phantom, developed in collaboration with the University Hospital, the University of Warwick and Coventry University, was designed to evaluate active motion management. It is a 3 degrees of freedom robotic arm aimed to replicate tumour motion within the lungs and a 2 degrees of freedom rib cage covered with latex, see Fig. 4. It can be filled with water to replicate soft tissues densities and has different types of bone equivalent material for the ribs and the spine (Land, 2009). Dosimetric studies have shown that it is accurate within 3% between calculated and measured dose.

Fig. 4. Dosimetric evaluation of MAESTRO phantom (left) with radiotherapy treatment planning system (right).

A LabVIEW based video tracking system was developed to track two patterns, one fixed to the PSS and one fixed onto the moving target. Initially a pattern matching technique was used (pattern matching VI in LabVIEW). Subsequently in an attempt to speed up the code mathematical morphology was employed. The latter was however slightly less robust in low light conditions experienced in the linear accelerator bunker. To demonstrate motion compensation, the anatomical part of the phantom was removed such that it was possible to use a second camera to film the target motion. The results shown in the next sections were obtained using such set up.

An IEEE1394 camera was used to track two surrogate markers with the aim to immobilise the film holder with respect to the radiation beam. Such set up is realistic as similarly to a clinical set up it is normally not possible to measure the organ position directly and surrogates have to be used. The video tracking system was capable to indicate the reference and target surrogate positions 20 times per second. Three dosimetric studies were carried out, each one measuring the amount of radiation received by a Gafchromic film inserted in the film holder attached onto the flexible robot arm (see Fig. 5). During the first experiment the phantom remained static and the target was irradiated. This constituted the reference dose distribution which is the best achievable. In the second experiment the target moved according to a motion pre-programmed in the robotic arm whilst the irradiation was taking place. This constituted the worst case scenario when motion is not taken into account. In the last experiment, the same robotic arm motion was programmed, however this time its motion was monitored by a camera and compensated by the PSS. Ideally the motion compensation scheme should move the PSS to immobilise the target with respect to the beam, resulting in an identical dose distribution compared to the static case.

Fig. 5. Illustrating dosimetric and video based assessment of motion compensation. When tracking is used the laser indicating the beam isocentre remains within the 5mm central disk. When tracking is off it moves by 15mm at a 45° angle.

To evaluate the dosimetric consequence of positioning errors without using radiation, a simulated irradiation was generated using image processing techniques. A video camera with a resolution 640×480 at 30 frames per seconds was used to record the position of 5 white dots representing external markers located on the film holder and aligned with respect to the room lasers, see Fig. 5. The position of the central dot
The isocentre was recorded in each frame and used to locate the centre of a black disk of 5 cm radius onto a white background. The resulting images of the disk on a white background created for each frame were added together simulating the amount of dose received per 0.033 s (30 Hz sampling), using a simplified model assuming a flat homogeneous field without penumbra.

The motion compensation accuracy was expressed by the root mean square error (RMSE) and the 95% confidence interval (CI95). CI95 describes the fact that the error will be less than the stated value 95% of the case. The tracking errors were given by the difference between reference and PSS position recorded by both the PSS sensor and a camera that served as an independent measurement device. To identify and visualize the spread of the tracking errors histograms were used. The performance of the control system should be evaluated not only in terms of resulting tracking error but also in the manner with which such performance is achieved. The ‘controller activity’ criteria which gives the average of the sum of the difference between successive control actions, was adopted to highlight the importance of limiting the change in control action between two successive samples.

5. RESULTS

The first part of this Section describes the control of the PSS using known signal reference. Such an approach was adopted to evaluate the best performance that could be achieved assuming perfect video tracking: e.g. no target loss or computational delay. The second part describes the demonstration of the overall video feedback system.

5.1 PSS feedback control

The prediction and overall control scheme were evaluated using a number of realistic signals. The constant velocity KF algorithm leads to errors of the order of at best 1 mm in terms of RMSE and 1.7 mm for 95% confidence interval. The constant velocity KF consistently overshoots when the motion changes of direction. This behaviour is taken into consideration by tuning the controller to be smooth and hence slower to react, than an aggressive controller.

![Fig. 6. Illustrating the ability of the controller to make the PSS follow a realistic patient motion trajectory](image)

The ability of the controller to make the PSS follow typical patient trajectory was demonstrated by loading a typical patient trajectory from file. Such an approach removes errors due to variable delays, sampling rate and target loss exhibited by the imaging system. Despite a prediction error around 2 mm RMS, the tracking error was 0.42 mm RMSE and 0.85 mm 95% CI with the prediction position RMSE = 1.97 mm and a controller activity of 0.023 V, see Fig 6.

5.2 Video feedback motion compensation

In the case where the reference is given by a video camera additional challenges arise due to target losses and additional delays which require an increase of the prediction horizon, resulting in increased overshoot. Fig. 7 (top) illustrates the trajectory followed by the PSS to counteract the phantom motion measured by camera. It exploits the predicted position such that it moves in opposite direction than the observed target motion. The PSS motion is symmetrical to the reference. The controller performance is not affected by the voluntary tracking interruption between 113 s and 137 s. Fig. 7 (bottom) shows the surrogate marker position and PSS position sent to the controller by the video tracking system. The surrogates markers displacement (grey line) is shown together with the PSS motion (black line). The motion of the target with respect to the beam is reduced from 15 mm peak to peak (without tracking) to less than 2 mm peak to peak (with tracking) resulting in RMSE < 1 mm and 95% CI < 2.0 mm. In some instances, difficulties were encountered with the video tracking system and target losses were witnessed. The strategy adopted to accommodate such target loss was to send the last known good signal to the motion predictor and controller. The loss of tracking did however degrade the system performance.

![Fig. 7. Illustrating the motion compensation along the longitudinal axis from the controller perspective as well as the tracking camera perspective](image)

Fig. 8 (top) is a zoomed version of Fig. 7 (top) giving the robotic arm trajectory (plain grey); the predicted position (plain black) and the mirror image of the PSS trajectory measured by the PSS sensors (black dotted line). The mirror image of the signal is used to facilitate the comparison with
the tracked reference. The control action required to make the PSS follow such trajectory is depicted in Fig. 8 (bottom). The sharp changes of magnitude are caused by non linear compensator which artificially increases the control action.

![Control action sent to the PSS](image1)

**Fig. 8.** Illustrating the ability of the controller to compensate organ motion.

Fig. 9a illustrates the image processing simulation of irradiation using an idealized circular field and the dosimetric evaluation of the motion tracking using film (Fig. 9b). A video of the experiments can be downloaded from (Haas, 2010) and Coventry University MAESTRO project web site.

![Simulated irradiation based on target motion video](image2)

**a) Simulated irradiation based on target motion video**

![Films located in the film holder](image3)

**b) Films located in the film holder represented in a) and irradiated for a moving target without compensation, a fixed target and the moving target with PSS compensation from left to right.**

![Motion compensation along the horizontal (X1) and vertical (Y1) axis](image4)

**Fig. 10.** Dose profile in the direction of motion (bottom) and perpendicular to the direction of motion (top) (see Fig. 9).

![Motion compensation along the horizontal (X1) and vertical (Y1) axis](image5)

**Fig. 11a** shows the simulated films that would have resulted from the residual target motion shown in Fig. 11b. The error distribution corresponding to the five phases: tracking, tracking with significant camera issues, tracking, no tracking and tracking is given in Fig. 12. Whilst the error histograms are shown for the horizontal axis, similar results were obtained for the vertical axis. Note that zone 2 is characterised by frequent losses of video tracking resulting in the target position sent by the camera to be held constant until tracking could be resumed. The large peaks observed are due to the reaction of the motion predictor to ‘catch up’ with the target when tracking is resumed.

![Motion compensation along the horizontal (X1) and vertical (Y1) axis](image6)

**Fig. 11b** shows the motion in the five phases: tracking, tracking with significant camera issues, tracking, no tracking and tracking. The histograms show for the horizontal axis, similar results were obtained for the vertical axis. Note that zone 2 is characterised by frequent losses of video tracking resulting in the target position sent by the camera to be held constant until tracking could be resumed. The large peaks observed are due to the reaction of the motion predictor to ‘catch up’ with the target when tracking is resumed.

**Fig. 11.** Motion compensation along the horizontal (X1) and vertical (Y1) axis (b) with the simulated irradiation (a) corresponding to the five zones identified according to their tracking performance.

Note that the simulated dose shows that intermittent loss of tracking which resulted in a few large tracking errors did not have a significant effect on the overall dose distribution. This is due to the fact that most of the time the PSS compensation...
did track the target with high accuracy. To further reduce the effect of temporary loss of tracking a method to change the dose rate of the linear accelerator was studied in (Haas et al., 2010). It was shown that whilst reducing the dose rate when the tracking performance is degraded does improve the overall dose distribution and overcome the effects due to loss of tracking, it did increase simulated treatment time and increased the treatment complexity and hence risk of failure.

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Fig. 10. Motion compensation error distribution of the x-axis

6. CONCLUSIONS

This paper has demonstrated the feasibility of motion compensation with a standard Elekta patient positioning system or ‘radiotherapy treatment couch’. Whilst motion compensation error of the order of 10 mm have a significant impact on the resulting dose distribution, tracking errors about 1mm RMS are not significant from a dosimetric perspective.

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