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Optimal marker placement in hadrontherapy: Intelligent optimization strategies with augmented Lagrangian pattern search

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ABSTRACT

Purpose: In high precision photon radiotherapy and in hadrontherapy, it is crucial to minimize the occurrence of geometrical deviations with respect to the treatment plan in each treatment session. To this end, point-based infrared (IR) optical tracking for patient set-up quality assessment is performed. Such tracking depends on external fiducial points placement. The main purpose of our work is to propose a new algorithm based on simulated annealing and augmented Lagrangian pattern search (SAPS), which is able to take into account prior knowledge, such as spatial constraints, during the optimization process.

Material and methods: The SAPS algorithm was tested on data related to head and neck and pelvic cancer patients, and that were fitted with external surface markers for IR optical tracking applied for patient set-up preliminary correction. The integrated algorithm was tested considering optimality measures obtained with Computed Tomography (CT) images (i.e. the ratio between the so-called target registration error and fiducial registration error, TRE/FRE) and assessing the marker spatial distribution. Comparison has been performed with randomly selected marker configuration and with the GETS algorithm (Genetic Evolutionary Taboo Search), also taking into account the presence of organs at risk.

Results: The results obtained with SAPS highlight improvements with respect to the other approaches: (i) TRE/FRE ratio decreases; (ii) marker distribution satisfies both marker visibility and spatial constraints. We have also investigated how the TRE/FRE ratio is influenced by the number of markers, obtaining significant TRE/FRE reduction with respect to the random configurations, when a high number of markers is used.

Conclusions: The SAPS algorithm is a valuable strategy for fiducial configuration optimization in IR optical tracking applied for patient set-up error detection and correction in radiation therapy, showing that taking into account prior knowledge is valuable in this optimization process. Further work will be focused on the computational optimization of the SAPS algorithm toward fast point-of-care applications.

1. Introduction

In high precision photon radiotherapy and in hadrontherapy (HT), the theoretical geometrical selectivity of the treatment (particularly enhanced in charged particle therapy) requires specific technological and methodological efforts to minimize the occurrence and size of geometrical deviations with respect to the treatment plan at each treatment session. In HT, in particular when active scanning beam delivery is applied, inter- and intra-fractional uncertainties may produce severe consequences in dose deposition patterns, thus frustrating highly conformal treatment plans designed to treat deep-seated solid tumor in critical sites.

Beside in-room X-ray imaging and image registration methods, valuable tools for inter- and intra-fractional deviations mitigation consist of infrared (IR) optical tracking and point-based registration [1–4]. Surface tracking methods have also been used in radiotherapy [5–7] but in HT, patients are usually immobilized with a thermoplastic mask that prevents the tracking camera from visualizing the patient's surface directly. In this case, surface-based methods are not suitable for the target registration and this is why we focused on point-based tracking.

Point based IR optical tracking in radiation oncology is based on the real-time detection of the 3D position of a set of external markers placed on patient's skin. Fast iterative estimation of the 6° of

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freedom rigid transformation is obtained by minimizing the measured marker displacements with respect to corresponding references coming from the treatment plan dataset obtained with Computed Tomography (CT): this technique allows the compensation of geometrical deviation mainly due to patient set-up errors. The root mean square (RMS) of the distance between corresponding markers, defined as fiducial registration error (FRE) [8] represents the metric for the estimation of the corrective transformation of patient position, under the usual assumption that FRE minimization implies minimizing geometrical deviations affecting the target of the treatment. The distance between the real target position and its corresponding reference position is defined as target registration error (TRE) [9]. TRE cannot be directly calculated, since it is not possible to know the real position of the target. However, statistical predictors can be applied to estimate TRE size as a function of residual FRE and of the geometric distribution of markers on patient surface. Under the hypothesis that optical tracking is efficacious in registering corresponding surface surrogates of the target achieving a minimum FRE, there is the need to identify, by means of appropriate optimization methods, the optimal marker configuration that minimizes the corresponding value of TRE. The final goal is to obtain a higher accuracy in target repositioning [10].

Several authors have faced the issue of optimal marker placement by proposing different optimization methods.

Liu et al. [11] described a floating optimization based on genetic algorithm and obtained a 50% TRE reduction with respect to a random marker configuration. Nevertheless, the methods turned out to be computational expensive, due to the large number of parameters to be optimized and to the continuity of the search space that slows down the execution of the algorithm. Moreover, marker visibility constraints imposed by the optical tracking system (OTS) were not taken into account.

An interesting strategy to deal with complex optimization problems is to resort to methods that are able to incorporate prior knowledge in the search of the best solution, usually by adding a suitable set of constraints. This is typically possible by applying algorithms belonging the AI and to the statistical learning tradition, such as neural networks, genetic algorithms and simulation annealing [12,13].

These strategies lie at the intersection of data analysis and knowledge-based system, an area that is known as “intelligent data analysis” or IDA [14–17]. IDA, since the late 90s, has produced several interesting studies and tools with a noteworthy number of applications in medicine and biology [18–21].

In the area of optimal marker placement, an IDA approach has been implemented by Riboldi et al. [22], who combined genetic algorithm (GA) with Taboo search (TS) in a method called Genetic Evolutionary Taboo Search (GETS). They proposed a permutation encoding with the goal to characterize candidate solutions and make the search space discrete. Consequently, the execution time of the algorithm turned out to be reduced with respect to the approach described in [11]. Taboo search allowed the algorithm to reject marker configurations, which would have featured critical visibility for the OTS cameras and to exclude irradiation field areas from the surface available for marker placement. The results obtained on data coming from ten prostate patients showed an average 26.5% reduction of TRE (compared to a random marker configuration), against the 19.4% obtained when a quasi-Newton method was applied. Limitations of the GETS algorithm reside in the fact that possible overlap of markers, commonly occurring when a high marker number is used, is not taken into account. As another example of knowledge-driven approaches, in the frame of image-guided neurosurgery, Shamir et al. [23] described a collaborative framework that allows the surgeon to optimally plan marker location on routine diagnostic images before preoperative imaging, and to select during surgery the fiducial markers and the anatomical landmarks that minimize the target registration error (TRE). The optimal fiducial marker configuration selection can be performed on diagnostic image dataset interactively, by monitoring target selection on a visual Estimated TRE (E-TRE) map, which is automatically updated when the surgeon adds and deletes candidate markers and targets. Data coming from five patients were used and results showed a reduction of the average TRE from 4.7 mm to 3.2 mm.

As a whole, methods previously described exhibit limitations related to a long execution time [11] incomplete constraints about marker placement [22] and the requirement of invasive procedures for the selection of additional anatomical landmarks [23].

The current spread of the clinical centers dedicated to the hadrontherapy and the increasing availability of this therapy worldwide demands new approaches, more accurate and repeatable than the previous ones, with the aim of identifying a standard procedure that ensures the highest precision in tumor localization.

In this paper, we present a novel IDA algorithm that answers to these issues by integrating two different optimization methods: simulated annealing (SA) and pattern search (PS). We have named the algorithm “SAPS”. Simulated annealing was selected for its capability of avoiding the entrapment in local minima; pattern search provides reduction of execution time required by SA to converge to a global minimum. Some knowledge-based features of the GETS algorithm [22] have been included in the SAPS algorithm: marker visibility constraints, a priori definition of the surface allowed for marker placement and permutation encoding of candidate solutions. In addition, we have introduced specific constraints that prevent markers overlapping. Table 1 summarizes how the prior knowledge has been converted in specific constraints for the marker placement.

SAPS has been tested on data collected on thirteen head-and-neck and pelvic cancer patients who were treated with proton therapy. Results show that constrained optimization allows us to improve TRE minimization with respect to random fiducial configurations and to those obtained by the GETS algorithm, especially when the number of markers is high. The SAPS algorithm lends itself as a valuable and clinically applicable alternative to improve the accuracy of target localization when IR optical tracking is applied.

2. Methods: data registration techniques and optimization algorithms

2.1. Patient population

The SAPS algorithm was tested on a set of clinical data collected at the National Centre of Oncological Hadrontherapy (CNAO Foundation) in Pavia, Italy [24]. The patient cohort included 6 head and neck and 7 pelvic cancer patients, who were fitted with external

Table 1
The table shows the prior knowledge incorporated into the search, represented by the constraints imposed on the marker placement.

	Prior knowledge	Constraints	Effect
Spatial constraints	Irradiation field areas on the mask surface Marker dimension (cm)	Boundaries for the search space Marker spatial constraint	Avoiding markers placement that affect the treatment Preventing markers overlap
Visual constraints	Marker dimension (pixel)	Marker visibility constraint	Preventing incorrect marker recognition by the OTS system