Continuous path optimization for non-coplanar variant SAD IMRT delivery using C-arm machines

Innovation/Impact This work provides the first automatic solution to sequencing and traversing non-coplanar beams with variant source-to-axis distances. The generated continuous path ensures freedom from collision over the entire delivery process, minimizes potential patient motion due to couch movement as well as machine travel time for efficiency. Supported by latest-generation programmable robotic C-arm machines, this novel development can automatically orchestrating the couch/gantry system to complete the whole treatment safely and efficiently. As such, it promises to lift the practical obstacles preventing wide application of non-coplanar treatment due to its current request of intensity manual effort.

Introduction and motivation The use of non-coplanar beam geometry has been demonstrated to achieve superior plan conformality compared to coplanar plans. The major obstacle in harvesting such dose benefit and making non-coplanar treatment widely available lies in the practicality in (1) automatic beam selection, (2) collision avoidance in the more complex space, (3) risk in patient setup error and uncertainty, and (4) prolonged treatment time. Both (3) and (4) are caused by manually maneuvering the couch, gantry, and possibly re-setting up patient between beams.

A few methods exist for beam selection, and the current project addresses issues (2)-(4) with by devising a full operation path for the machine control over the whole delivery process to ensure collision avoidance, minimal couch (thus) patient motion and short delivery time.

Methods We represent the the collision/avoidance zone definition and the planned beams in a motion control space \( \mathbb{R}^N \), parameterized by couch translation, couch rotation, gantry rotation, and collimator rotation. Denoting the collective avoidance zone as \( C \subset \mathbb{R}^N \) and planned beams as \( y_k \), \( k = 1, 2, \ldots, K \), we seek a path \( \gamma(s) \subset \mathbb{R}^N \), \( s \in (0, 1) \) such that (i) \( \gamma \) does not cross \( C \), (ii) \( \gamma \) covers \( y_k \) for \( k = 1, 2, \ldots, K \), and (iii) \( \gamma \) requires as little control motion as possible.

We formalize the optimization framework as

\[
\text{minimize } \sum_i \lambda_i E_i = \sum_i \lambda_i \int_0^1 |\gamma_i'(s)| ds
\]

subject to

\[
\begin{align*}
& y_k \in \gamma, \text{ for } k = 1, 2, \ldots, K. \\
& \gamma \cap C = \emptyset.
\end{align*}
\]

where the \( E_i \) characterizes the accumulative variation for the \( i \)th control and \( \lambda_i \) balances the penalties. Couch rotation risks patient motion and is penalized heavily with large weight while collimator rotation has minimal impact on delivery accuracy or efficiency, and is assigned with a small weight.

The couch translation to achieve a SAD can be uniquely determined given the couch/gantry angle, and is treated as a dependent variable. We further assume collimator motion has negligible impact on delivery time. The optimization is performed in a level set framework with variational flow. The most “costly” segment is removed from the contour to generate the final open path.

Results and Validation We used the proposed method to optimize the delivery path for a 14-beam non-coplanar, variant SAD plan. The clearance geometry was generated based on a patient model obtained with high-resolution 3D optical cameras and treatment room/machine geometry - for each couch/gantry angle combination, the minimal SAD without collision was computed (Fig. 1(a)). Collision zone was declared when this value exceed 1m, based on which the path optimization was performed (Fig. 1(b)). Fig. 1(c) illustrates the path in patient-centric view.
The proposed method is the first one to generate a continuous collision-free path on an arbitrarily pre-defined collision domain. In the absence of existing methods for benchmarking, we relax the path-wise continuous collision-free and variant SAD requirement so that all beams reside on a spherical control space. We compare the path from our optimization (Fig. 2) to that generated from solving three variations of the traveling-salesman problem (TSP):

<table>
<thead>
<tr>
<th>TSP scheme</th>
<th>path</th>
<th>pairwise distance calculation</th>
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<tbody>
<tr>
<td>TSP: crow-fly</td>
<td>Fig. 3</td>
<td>length of the connecting great circle arc (shortest spherical distance)</td>
</tr>
<tr>
<td>TSP: couch-shift</td>
<td>Fig. 4</td>
<td>difference in corresponding couch angle (&quot;patient-motion&quot; distance)</td>
</tr>
<tr>
<td>TSP: weighted</td>
<td>Fig. 5</td>
<td>the offset in each direction is weighted to mimic the setup in Eq. (2).</td>
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**Table 1: Comparison of integrated machine motion to traverse each path: couch and gantry movement reported in degrees.**

<table>
<thead>
<tr>
<th></th>
<th>Proposed</th>
<th>TSP</th>
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<tbody>
<tr>
<td></td>
<td>Opt. path</td>
<td>crow-fly</td>
</tr>
<tr>
<td>couch</td>
<td>116</td>
<td>260</td>
</tr>
<tr>
<td>gantry</td>
<td>880</td>
<td>572</td>
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**Discussion** Under the relaxed setting where TSP is applicable, Table 1 demonstrates that the our solution prioritizes patient-motion-control without significantly increasing gantry movement - it achieves a good balance between the time-minimizing crow-fly TSP and the patient-motion-minimizing couch-shift TSP. When the distance is carefully tuned, TSP yields beam sequence coinciding with our approach and the same accumulative couch/gantry movement, with slightly different trajectory. This special case validates the optimality of our approach.