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Deformable Surface Registration for Automated Patient Positioning in Head and Neck Radiation Therapy

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ABSTRACT

Conventional iterative closest point (ICP) algorithms capable of 3D surface registration perform best with non-deformable surfaces. Such methods are not efficient in head and neck (HN) RT, where one part of the surface is rigid (head) while another part is deformable (neck). A novel ICP algorithm was developed to enable surface registration across both rigid and semi-deformable surfaces, in which points on a surface are permitted to move relative to one another. The algorithm was applied to automation of patient positioning in head and neck radiation therapy, where registration must account for skin stretching and soft-tissue deformation in regions such as the neck. Accuracy is quantified using the root-mean-square (RMS) distance between registered surfaces. The algorithm demonstrated accurate registration of patient positioning while accounting for clinically relevant surface deformations. Using a digital phantom with representative head and neck surfaces, the algorithm successfully matched surfaces across a range of initial misalignments. Registration converged to an RMS distance of <1mm. This work demonstrates the feasibility of a semi-deformable ICP algorithm for registration of semi-deformable anatomical surfaces, such as 3D HN patient surface data, with potential application to automated patient positioning.

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INTRODUCTION

- Head and neck (HN) RT requires accurate patient positioning for proper dose delivery.
- The positioning process can be time-consuming and involves immobilizing the patient using a thermoplastic mask, shown in Figure 1 (a).
- This work presents a system to allow for efficient and maskless patient positioning using a novel iterative closest point (ICP) algorithm and robotic six degree of freedom (DOF) correction platform.
- ICP algorithms, used for surface registration, perform well when surfaces are rigid bodies[1].
- In HNRT, the neck is subject to deformations that cannot be captured by a rigid surface[2].
- This algorithm solves this by treating the head as rigid and the neck as semi-deformable, in order to achieve registration across the entire HN anatomy.

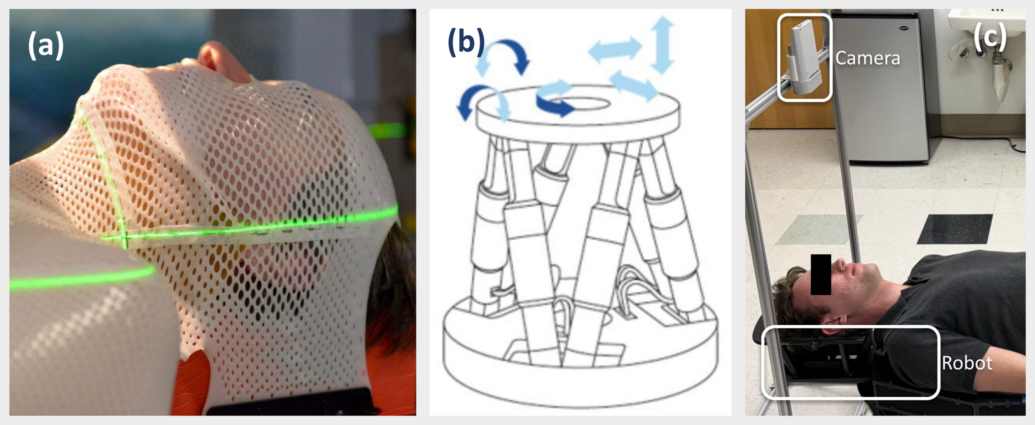

Figure 1. (a) A HNRT patient immobilized using a thermoplastic mask[3]. (b) A robotic positioning system with correction along 6 DOF. (c) Patient supine on a treatment couch with their head on a robotic positioning platform.

METHODS

- The developed ICP algorithm partitions the patient surface into three regions: the head, a rigid body; the neck, a semi-deformable region; and the shoulders, a rigid region which is fixed.
- Total surface registration is performed by applying a rigid transform to the head, while neck points are permitted to move relative to one another through a weighted deformation scheme.
- Initial testing of this system was done on a digital HN phantom, Figure 3, which is sampled to mimic data collected by a depth mapping camera.
- A multi-resolution pyramid downsampling framework, shown in Figure 4, is used to reduce computation time while preserving accuracy.
- The algorithm outputs a 6 DOF correction which can be executed by a robotic positioning system to adjust patient posture, shown in Figure 1 (b, c).
- The primary metric used to evaluate registration accuracy is root-mean-square (RMS) distance, with a target benchmark of sub 1 mm accuracy[4].

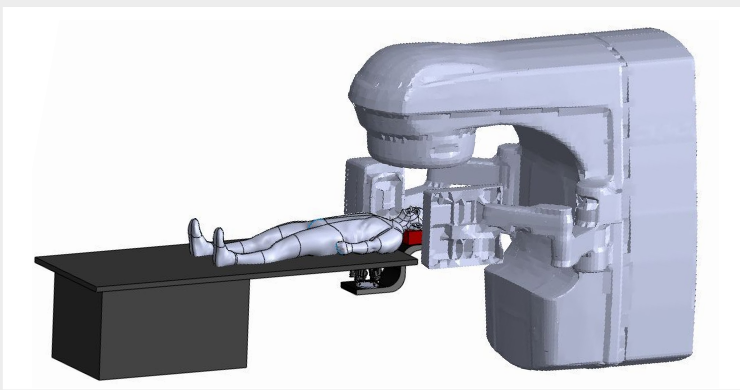

Figure 2. A rendering of the clinical setup of the proposed positioning system. A patient lies supine on the treatment couch with their head on the robotic positioning system while allowing for full LINAC rotation.

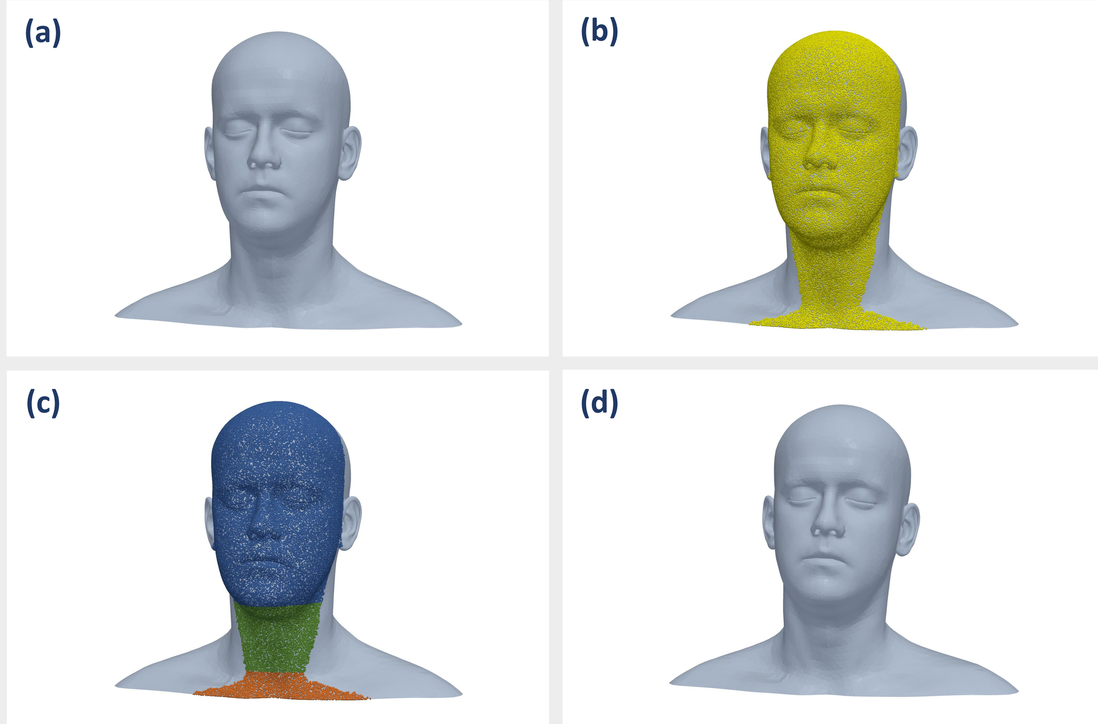

Figure 3. Digital HN phantom. (a) The neutral reference position. (b) The surface is sampled within the capture region to replicate data capture from a depth mapping camera. (c) The capture region is broken down into head, neck, and shoulder regions. (d) The HN digital phantom in a perturbed position to be corrected.

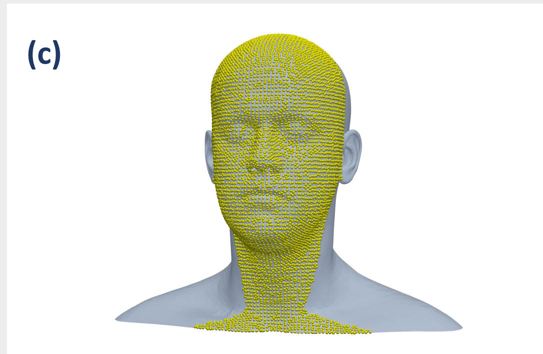

Figure 4. Pyramid ICP downsampling layers. The final transform from each layer is used as the initial transform of the next. (a) 10 mm voxel size layer. (b) 5 mm voxel size layer. (c) 1 mm voxel size layer.

RESULTS

- Testing of this algorithm has shown its ability to perform accurate surface registration on the total HN surface, taking into account deformations occurring on the neck region, shown in Figure 5.
- The algorithm was able to correct patient positions within the target accuracy threshold across a range of different initial misalignments.
- ICP calculations were performed in under 0.1 seconds, allowing patient monitoring at a rate above 10 fps.
- Initial validation of this system on a fully rigid physical head phantom shows similarly good results, with registration being performed within 1 mm, Figure 6, and a computation time of under 0.1 seconds.

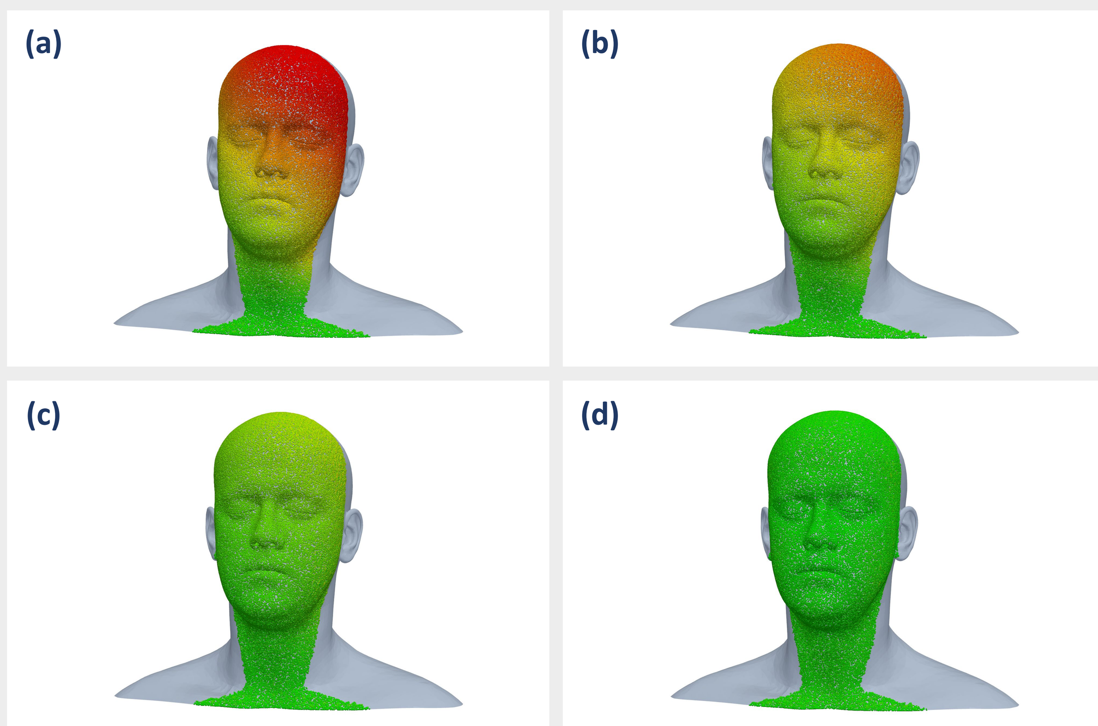

Figure 5. With each step of ICP algorithm, patient position is corrected from the initial perturbation to match the reference. Points within the capture region are colored based on their RMS proximity to the reference position, with points closer to the reference position colored green and points further colored red.

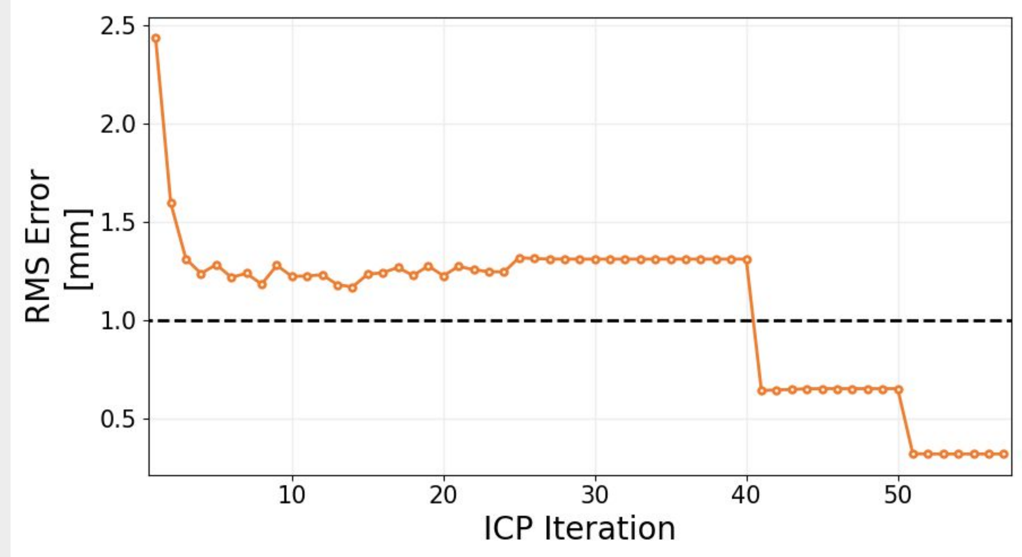

Figure 6. As the ICP algorithm matches the surfaces, the RMS error declines to below threshold. Changes in pyramid voxel sizes can be seen in sharp drops of RMS at certain iterations.

DISCUSSION

- The results demonstrate that the proposed ICP algorithm is capable of accurate registration across a surface composed of both rigid and semi-deformable regions.
- Achieving sub-millimeter positional accuracy across a range of initial misalignments suggests the algorithm is robust.
- Validation has, to this point, been primarily performed on digital phantom data, which may not fully capture real anatomical behavior.
- Real patient surfaces exhibit greater anatomical variability, more complex neck deformations.
- Future work will focus on validation using clinical scan data across a volunteer cohort.

CONCLUSIONS

- The presented novel ICP algorithm is capable of performing accurate, real-time surface registration across surfaces composed of both rigid and semi-deformable regions.
- Initial validation on digital and physical head and neck phantoms demonstrates <1mm accuracy at frame rates suitable for real-time monitoring.
- These results support the potential of this approach as a foundation for improved HN SGRT, where conventional methods are not sufficient.
- Ongoing work will focus on validation in a volunteer dataset, as well as increased anatomical accuracy through vertebral motion modeling.

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