MR Image Overlay Adjustable Plane System for Musculoskeletal Interventions

Paweena U-Thainual[1,2,3], Jan Fritz[4], Tamas Ungi[2], John A. Carrino[4], Gabor Fichtinger[1,2,3,4], Iulian Iordachita[3]

[1]Department of Mechanical and Materials Engineering, Queen's University, Kingston, ON; [2]Laboratory for Percutaneous Surgery, School of Computing, Queen's University, Kingston, ON; [3]Laboratory for Computational Sensing and Robotics, Johns Hopkins University, Baltimore, USA; [4]Russell H. Morgan Department of Radiology and Radiological Science, Johns Hopkins University School of Medicine, Baltimore, USA

Introduction

The 2D MR image overlay system (IOS) concept is effective in a variety of musculoskeletal procedures (Figure 1) [1, 2, 3]. Because of the vertical orientation of the image plane, insertions are currently limited to the axial plane. However, for obliquely oriented anatomic targets (disc spaces, vertebral bodies, hypogastric plexus) and for biopsy targets, optimal percutaneous access often requires oblique insertion.

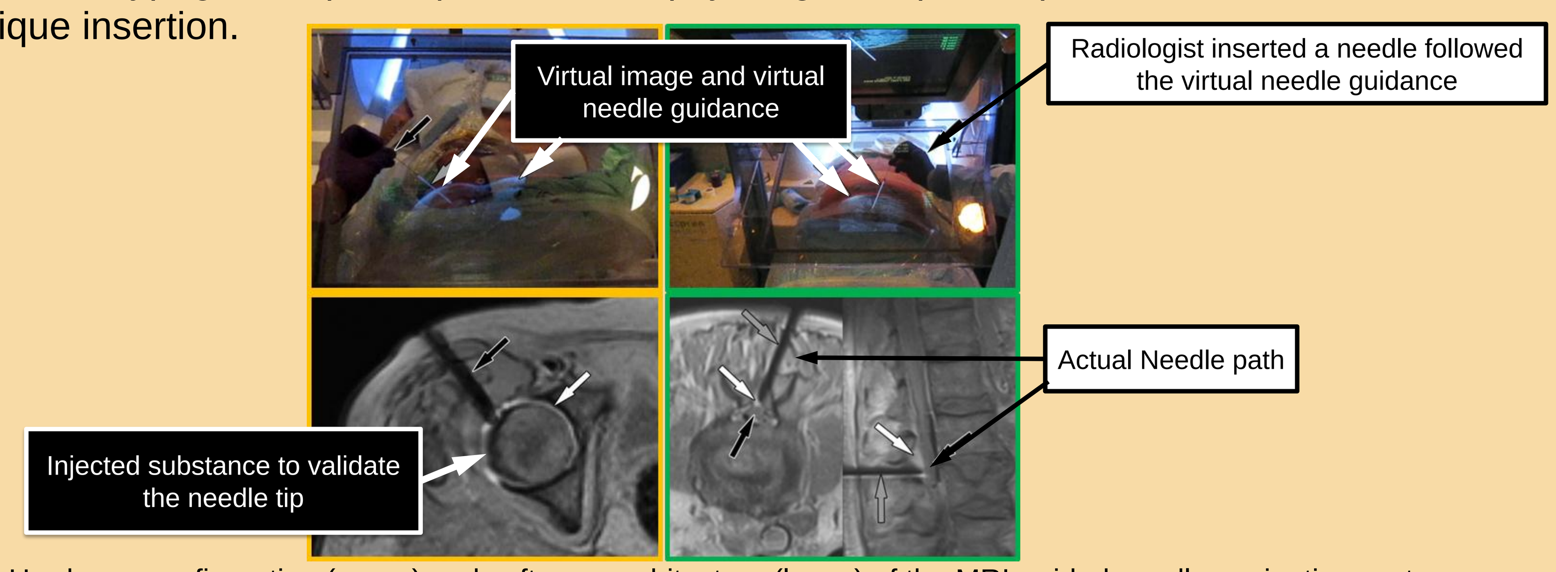

Figure 1. Hardware configuration (upper) and software architecture (lower) of the MRI-guided needle navigation system.

To allow for image-guided needle insertions in oblique planes, we have:

1. developed the "MR image overlay adjustable plane system (IOAPS)"
2. proposed an intraoperative calibration method.
3. assessed the motion characteristics of the 4-DOF for intraoperative calibration and tested the encoders functionality.

Methods

System overview

The IOAPS consists of two main units (Figure 2): In-Room Unit and Out-of-Room Unit.

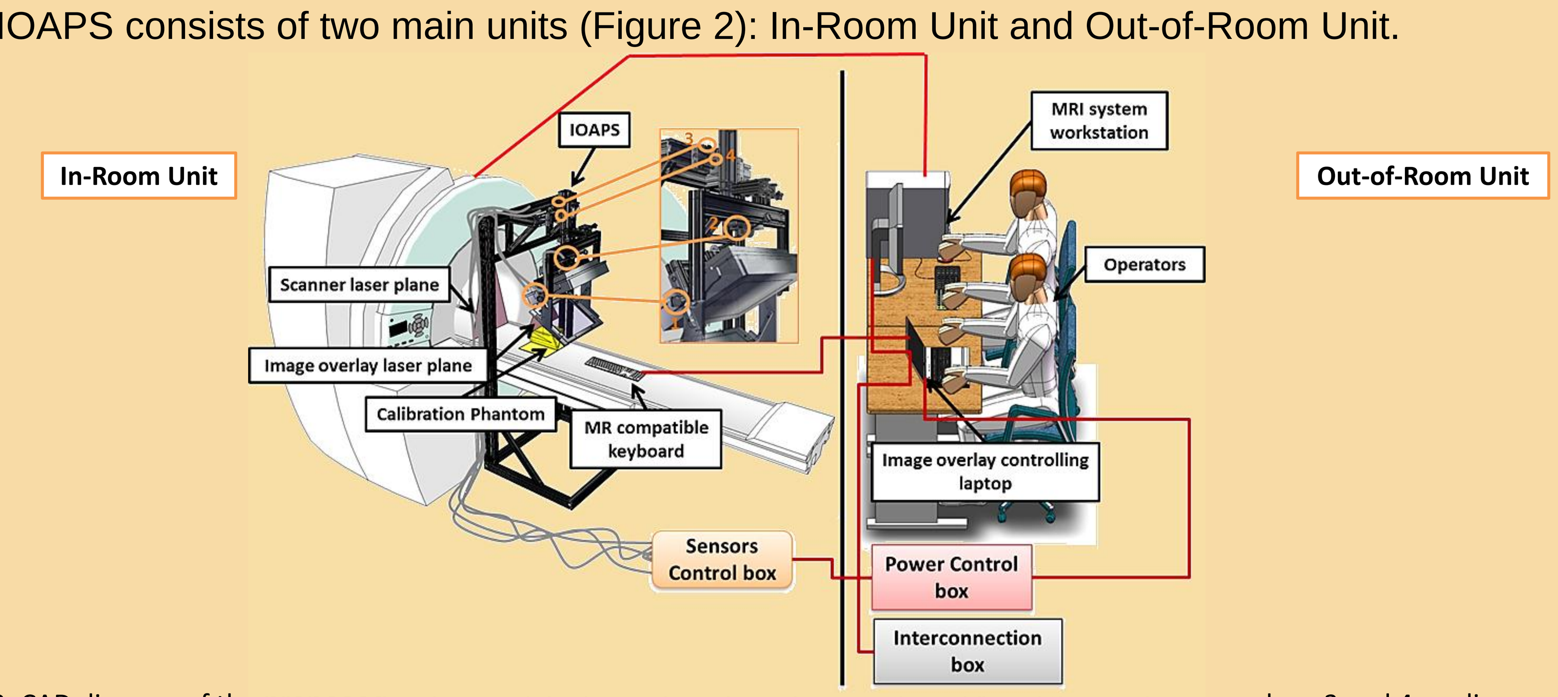

Figure 2. CAD diagram of the proposed system and its description. Encoders numbered 1 and 2 are rotary encoders, 3 and 4 are linear encoders.

- IOAPS has 4 -DOF (two translations and two rotations), manually actuated (Figure 3 left).
- Encoders attached to the moving joints indicate the motions.
- The aluminum frame carries the weight of all devices and provides motions of ±100 mm (in *X-Y* directions) and ±25° (around X-Y axes).

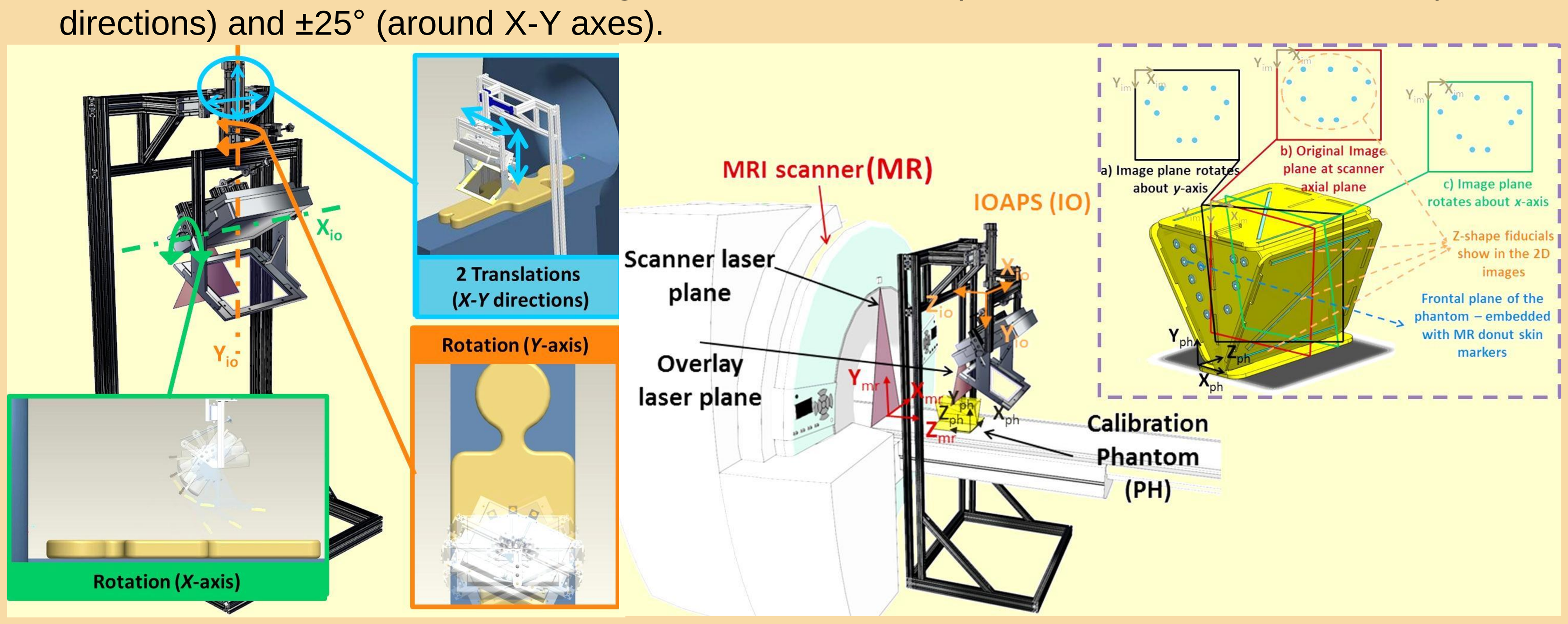

Figure 3. (Left) Diagram of the IOAPS and its DOFs, (right) IOAPS coordinates system and diagram of calibration phantom with Z-shaped fiducials in each image motion (a-c) and frontal plane of the calibration phantom with MR-donut skin markers, where the laser plane cut through.

Calibration Procedures

The proposed calibration method is based on the assumption that the virtual image plane is superimposed upon the target plane.

- Constructive Calibration: Align the virtual image plane to coincide with the overlay transverse laser plane; this is performed during the built-up of the IOAPS device.
- System Calibration: Align the laser plane parallel to the scanner laser plane; this is a preoperative calibration and uses the calibration phantom (Figure 3 right) to define the home position.
- Motion Calibration: Calibrate system motion indicated by encoders to 2D image motion using the calibration phantom (Figure 3 right); this is intraoperative calibration. To simplify the calibration procedures, the translation joints will be fixed at a distance and assumed motionless during the procedure.
- Software Calibration: The radiologist moves the virtual image plane until the real fiducial markers on the phantom and their virtual images overlap perfectly on the phantom; this is performed after acquiring MRI data from the calibration phantom.

Calibration Phantom

The triangular phantom is designed for:

- *System Calibration* – Frontal plane of the phantom indicates the alignment of laser planes (Figure 3 right).
- *Motion Calibration* – Z-shaped markers show different patterns through out the hardware motions (Figure 3 right).

Methods

Motion Characteristics

We performed the preliminary motion characteristics to assess the intraoperative calibration workflow and to test the functionality of the encoders. The experimental setup and protocols are shown in Figure 4. The study consisted of two parts; translations (n=16) and rotations (n=16). To measure the accuracy of the encoders, all the motions were tracked by the optical tracking system.

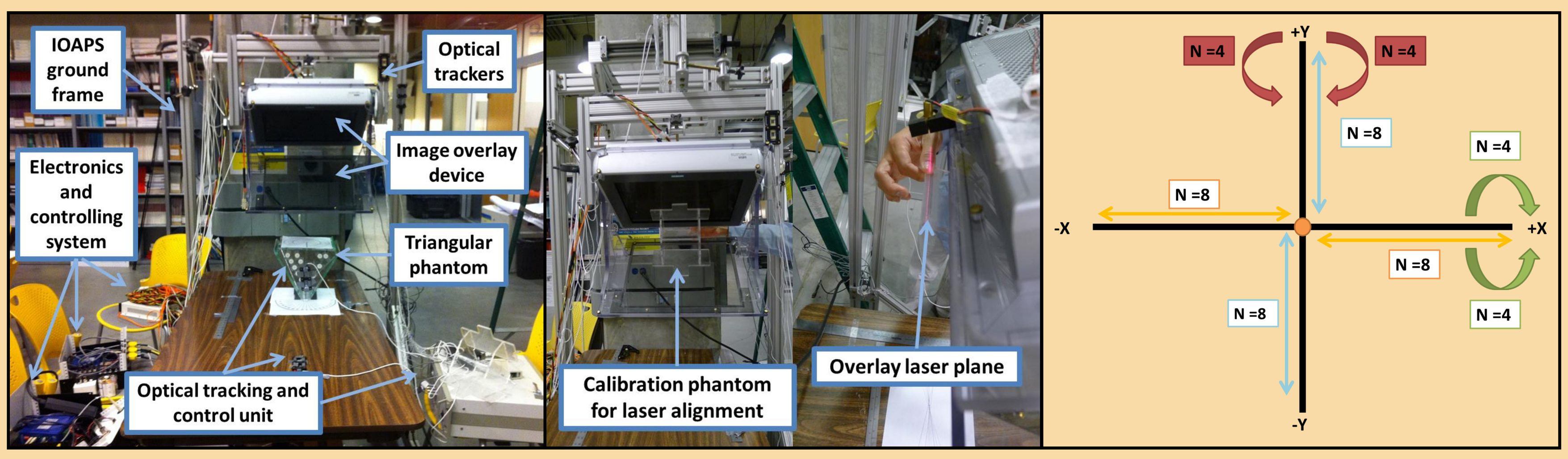

Figure 4. (Left) Experimental setup including the current prototype of MR-IOAPS, calibration phantom, electronics and control boxes, and optical tracking system with five rigid body; (center) matching the overlay laser plane to the image plane by using the calibration phantom; (right) experiment protocol for translation and rotation around X- axis and Y- axis; N represents the number of translations and rotations in each axis.

The assessed preliminary parameters of the motion characteristics included:

1. Absolute position errors of the encoders relative to the optical tracking.
2. Absolute angle errors of the encoders relative to the optical tracking.
3. Motion plots for translations
4. Motion plots for rotations.

Results

The IOAPS has been designed, built and motion analysis experiments have been performed. The IOAPS was translated (back and forth) and rotated (clockwise and counterclockwise) to different positions along one axis at a time. All motions (32/32) were carried out. The ranges of translations are ±55 mm and ±40 mm about the *X*-axis and *Y*-axis respectively. The ranges of rotations are ±5 ° (deg) and ±10 ° (deg) about the *X*-axis and *Y*-axis respectively.

Table 1. The average absolute error of the motions in *X*-and *Y*-axes

X – Axis, Absolute Error	*Mean ± SD*	*Min – Max*	*Y– Axis, Absolute Error*	*Mean ± SD*	*Min – Max*
Translation	0.7±0.6 mm	0.1–1.9 mm	Translation	1.8±2.1 mm	0.1–4.9 mm
Rotation	0.6±0.6 deg	0.0–1.5 deg	Rotation	0.0±0.0 deg	0.0–0.0 deg

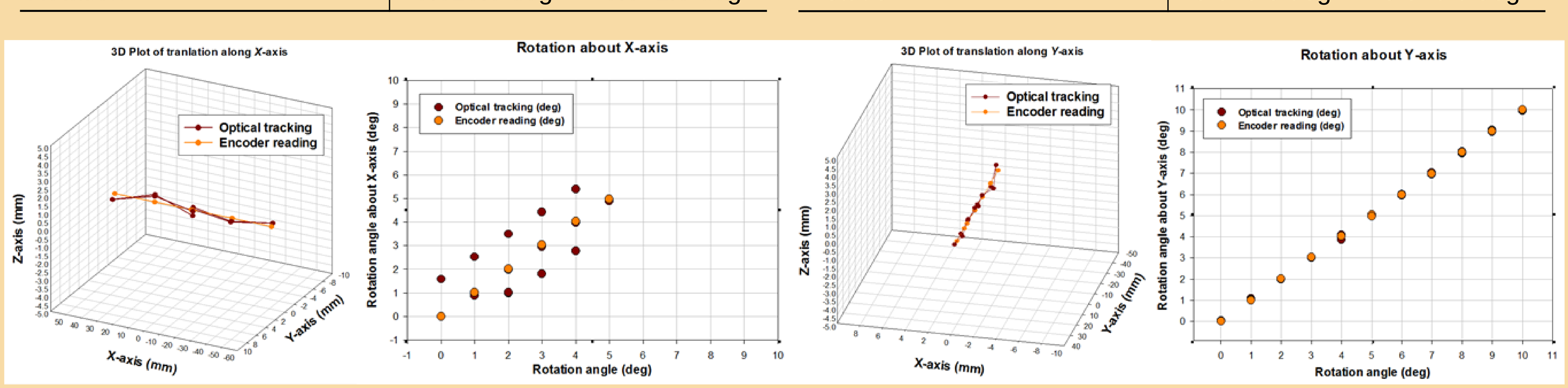

Figure 5. (Top) Rotational plot results about *X*- and *Y*-axes; (bottom) translation plot results along *X*- and *Y*-axes.

Conclusion

- The IOAPS system was design and built. A calibration method was developed and a workflow was proposed. A preliminary motion characteristic analysis was performed and the encoder functionality was assessed.
- Preliminary data currently suggest considerable translations errors due to elastic deformation from vibration during the motion. However, those appear fixable and are thus not expected to substantially affect the system performance.
- The rotations around the *X*-axis and *Y*-axis are stable within the ±5 deg and ±10 deg limits, respectively.
- Our results support further evaluation of the IOAPS system with optical tracking, which affords assessments through real-time tracking and real-time registration.

References

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Acknowledgements

This project is funded by National Institutes of Health grant #R01 CA118371 A2.
Paweena U-Thainual was supported by the Natural Sciences and Engineering Research Council of Canada. Gabor Fichtinger was supported as a Cancer Care Ontario Research Chair. Tamas Ungi was supported as an Ontario Ministry of Research and Innovation Fellow.

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