Accuracy of Intra-operative Quantitative Imaging with a Low-cost TC-arm Retrofit Tracking System

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Introduction: Fluoroscopic C-arms have been widely used in operating rooms, mainly for qualitative assessments and obtaining a visual reference for guiding tools in a wide range of intraoperative applications including orthopaedic surgery, interventional radiology and brachytherapy. Quantitative imaging can be performed with a C-arm if the position of the arm relative to the body part being imaged is known with substantial accuracy. This will provide very powerful intraoperative technical capabilities for the surgical staff for accurate 2D and 3D assessments, localization of the bone and device positions, and panoramic radiographic visualization of large size portions of the anatomy (e.g. long bones and spine) that do not fit within the limited field of view of a C-arm. In spite of the great potential, quantitative C-arm imaging has not been widely accepted because of extra cost, interference with the surgical work-volume, and technical complexities in tracking, registration and calibration. The objective of this work is to describe a novel method for producing an inexpensive tracked C-arm (TC-arm) using inertial measurement units (IMUs) and laser distance sensors, and to assess the accuracy of the system in 2D-3D registration, landmark localization, and 2D image stitching.

Methods: We developed a low-cost upgrade system that can convert any C-arm fluoroscope to a tracked C-arm (TC-arm), which enables intraoperative quantitative assessment.

To develop the system, we first designed and constructed a low-cost sensor-tracking module (Figure 1) that can be retrofitted to any conventional C-arm to track the position of the gantry, assuming that the base of the device is kept at a locked position during imaging, while the desired multiple imaging views can be reached by moving the joints of the C-arm. This sensor tracking module included both inertial measurement units (IMUs) (incorporated with custom drift-cancellation algorithms) and laser distance sensors, which allowed the gantry’s full position to be assessed without requiring line-of-site measurement with optical sensors. We then developed software and protocols to register and track the kinematics of the C-arm in near real-time, with flexibility to support C-arms of different joint configuration constructs. Next we developed calibration protocols to optimize the accuracy of the tracking and to provide the full 3D position information for each of the acquired radiographic images, along with feature-based registration software and user interface for quick intraoperative localizations [1,2]. Finally we developed image stitching procedures, which allowed us to generate parallax-free panoramic radiographic views of large regions of the body (such as full long bones) by registering together multiple calibrated images. The registration and offline calibration methods developed for this system provide accurate pose-estimation of the gantry and report the estimated intrinsic and extrinsic parameters of the imaging system for any fluoroscopic shot. The acquired images and the calibration data generated by the system can then be processed collectively to provide advanced quantitative 2D and 3D assessments.

We assessed the system’s accuracy for tracking, localization, and panoramic views by comparing to measurements from an Optotrak motion tracking system and by conducting a series of experiments on highly accurately-built (<10 microns) ball-bearing phantoms. Validation of the functions of the tracked C-arm included: a) evaluating accuracies in tracking the device, by comparing to Optotrak measurements of a target point on the gantry for 12 different positions spread across the imaging volume; b) evaluating the accuracies of 2D-3D registration through tests on a two-part ball-bearing phantom; c) evaluating the accuracies of localizing three-dimensional landmark positions across the field of view by conducting tests on an accurate ball-bearing phantom placed over a radiolucent operative table; d) determining accuracies of two-dimensional measurements on stitched two-dimensional images in comparison to ground-truth references from a flat ball-bearing phantom; and e) testing the image stitching mode on synthetic models of the knee and lumbar spine.
Figure 1. The TC-arm setup consists of the Sensor Box and two inertial measuring units (IMU-1 and IMU-2) which communicate through a USB port and wireless communication to a tracking PC.

**Results:** The system was able to track a target point on the gantry with an accuracy of $1.5 \pm 1.2$ mm. The 2D-3D registration accuracies of the test phantom were $2.3 \pm 1.1$ mm and $0.2 \pm 0.2^\circ$, and the three-dimensional landmark localization accuracies were $3.1 \pm 1.3\%$ of the lengths (or $4.4 \pm 1.9$ mm) on average. The overall accuracies of the two-dimensional measurements conducted on the stitched images were $2.5 \pm 2.0\%$ of the measured lengths (or $3.1 \pm 2.5$ mm on average) and $0.3 \pm 0.2^\circ$, respectively. The system was successfully tested for acquiring sample panoramic views of the long bone of the femur (Figure 2), and the lumbar spine.

**Discussion:** These results demonstrate excellent potential for the introduced TC-arm system in adding sophisticated quantitative fluoroscopy assessment capabilities to an existing imaging modality that is widely available. A simple estimation of error in a clinical application shows the utility of the TC-arm for estimating the orientation of the pelvis on the operating table in a total hip arthroplasty surgery as suggested in a previous work [2]. Assuming an average-size pelvis, the resulting error in calculating the anterior pelvic tilt due to errors in localizing landmarks positions is only $\pm 1.2^\circ$ (much lower than the $10^\circ$ cutoff threshold of error suggested in the literature). For the examples of panoramic view imaging of the long femoral bone and lumbar spine (Figure 2), the system had the acceptable accuracy of $<0.56^\circ$ for measuring the angle between the mechanical axis and the long axis of the femur. This study was limited to synthetic models and further cadaveric and clinical tests are required for full assessment of localization accuracies for specific orthopaedic applications. The system has a number of advantages. It offers a low-cost approach to quantitative imaging because it can be packaged as an upgrade kit that can be retrofitted to any.
conventional C-arm to add the capability to produce calibrated multi-planar X-ray projections and generate large panoramic radiographic views.

**Significance:** This work suggests that our inexpensive upgrade system for conventional c-arms is sufficiently accurate to expand their utility to more applications in orthopaedics where accurate intraoperative three-dimensional landmark localization, and large panoramic radiographic views of the patient’s anatomy can be highly beneficial for improving the quality of treatments.

![Figure 2](image)

Figure 2. Sample panoramic views of the long bone of the femur and tibia (a) and the lumbar spine (b) from a synthetic model generated from stitching multiple radiographs and conduct measurements.

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