600.446 CIS II: Seminar Paper Critical Review

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1 Background and Project Overview

Orthopaedic surgeries involve surgeons placing tools and fixtures in complicated positions inside the patient. X-ray imaging is used to confirm and guide such placement, but hundreds of scans may be required for a single procedure, lengthening procedure time and exposing the physician and patient to high doses of radiation.
The Camera Augmented Mobile C-Arm (CAMC) project aims to augment the commonly used cone beam computer tomography (CBCT) with Red-Green-Blue-Depth (RGBD) camera information to create a live mixed-reality visualization, thus reducing the number of x-rays required. A manual calibration algorithm[1] between CBCT and RGBD was developed to create the visualization. This project aims to automate this calibration process with minimal dependencies. A key difference is the use of a double mirror system in the system described in the paper that is not used in the more recent system in this project.

2 Paper Selection

The original paper for this augmentated visualization concept using a double mirror system was by Dr. Nassir Navab's Computer Aided Medical Procedures (CAMP) group at Johns Hopkins University and Technische Universitat Munchen in "Camera Augmented Mobile C-Arm (CAMC) Calibration, Accuracy Study, and Clinical Applications"[2]. This paper was selected for greater understanding of the background and motivation for the calibration portion of the project. Additionally, the maximum deliverable calls for improvement of the accuracy of the calibration; exploration into previous and alternative methods has proved useful in evaluating potential improvements.

3 Significance

3.1 Problem

As explained in the project overview, the large number of x-ray images taken during orthopaedic surgeries result in high radiation dosage for the physicians and patient. However, they are necessary in guiding and confirming the surgeon's placement of tools and fixtures. Improved live visualization of the patient in orthopaedic surgery without the use of external markers would greatly reduce the number of x-rays and thus radiation dosage, also improving the overall surgical workflow.

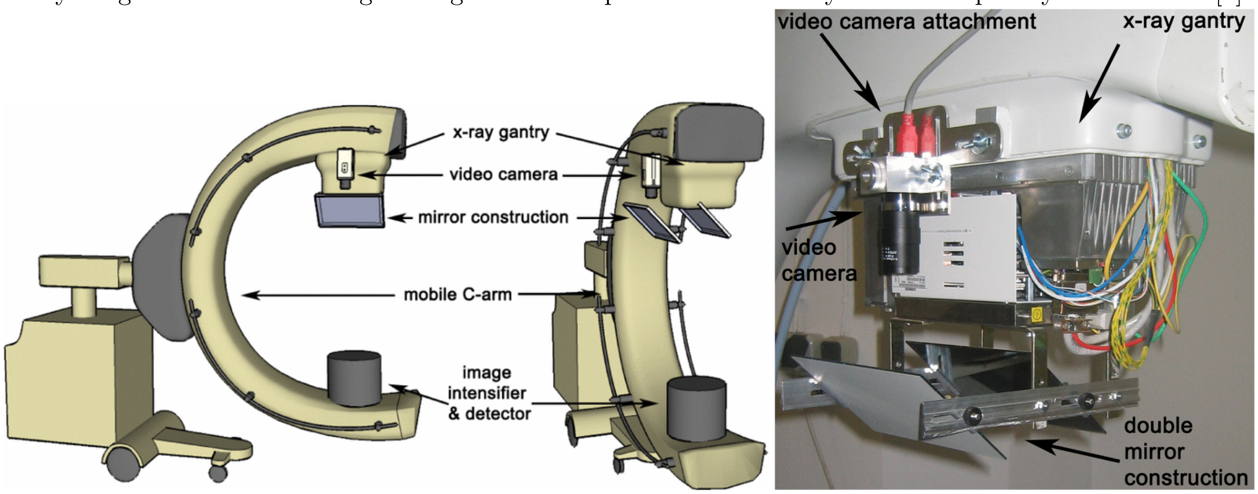
3.2 Key Result

After successful calibration of the CBCT and RGBD using a double mirror construction, pre-clinical applications of this visualization in simulations and cadavers show promising results. The number of x-ray images required was dramatically reduced, and radiation time and dose was also considered to be less compared to the original procedure.

4 Methods

4.1 System Overview

The CAMC system mounts a RGBD video camera onto a common intraoperative mobile C-arm with a double mirror system "such that the X-ray source and the camera optical center virtually coincide. To enable an image overlay of the video and X-ray image in real time a homography has to be estimated that maps the X-ray image onto the video image taking the relative position of the X-ray detector implicitly into account" [2].



The C-arm used is a Siremobile Iso-C 3-D from Siemens Medical Solutions, and the video camera is the Flea from Point Grey Research, Inc. connected by a Firewire connection. The mount and mirrors construction was custom made.

4.2 System Calibration

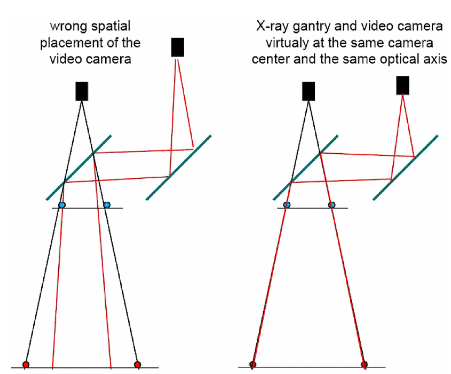
A one-time initial calibration is required to register the optical camera and x-ray. The three step calibration procedure first corrects distortion in each imaging, then aligns the two images, and finally estimates the homography for the image overlay.

4.2.1 Distortion Correction

Both the optical video camera and the X-ray imaging have distortions. The optical camera distortion is estimated and corrected using a nonlinear radial distortion model. The vendor provides look-up tables for geometrical X-ray distortion for most common poses of the C-arm.

4.2.2 Alignment of X-Ray Source and Camera Optical Center

To align the x-ray source and camera optical center with the double mirror construction, markers are viewed in each modality then the video camera is adjusted until the pairs of markers align. A two-plane calibration pattern of rings and spherical markers such that upon perfect alignment, the spherical markers will be centered in the ring markers.



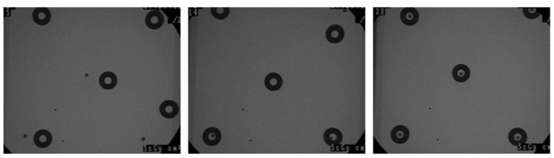
4.2.3 Homography Estimation for Image Overlay

The homography H from the image of the video camera to the X-ray image allows visualization by superimposing the X-ray image onto the video image. H is computed by four to 16 corresponding points simultaneously detected by solving the linear equations system and QR Decomposition.

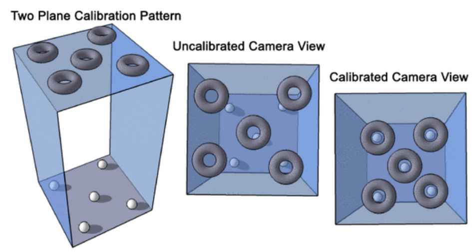
5 Evaluation and Results

5.1 Accuracy Evaluation

A pattern used for geometrical X-ray calibration and distortion measurement is attached to the image intensifier to detect the accuracy of the image overlay. The markers of the pattern are visible in both X-ray and video images, and the distances between the corresponding points were calculated. The mean error was calculated to be approximately 0.5mm on the plane of the calibration pattern. An accurate image overlay required per-pose re-estimation of the homography. These figures from the paper are of the calibration patterns and results.



(a) (b) (c)



5.2 Marker Tracking Evaluation

A mechanical device was rigidly attached to the detector plane and moved in 0.5mm steps to detect the accuracy of marker detection. The results indicated that movement of 1mm or more could be detected. The threshold for non-valid overlay was set to 1.5 pixels to alert the surgeon of misalignment.

5.3 Radiation Dose Evaluation

The radiation dose with and without the mirror construction was evaluated with external radiation dose measurement device Unfors Xi from Unfors Instruments GmbH. The setup was adjusted such that the mirror has no impact on the image quality of the final X-ray image.

It is important to note that conventional C-arm X-ray imaging places the source underneath the table to reduce scattering radiation, but in the CAMC configuration, the source is oriented above the table. This testing also evaluated the radiation dose with the X-ray source above the patient. The table absorbs 30% of the radiation in standard configurations but the upside-down configuration provides a slightly increased distance between the patient and X-ray source. 31μGy is the approximate measured dose to be received by the patient. No scattered radiation of the mirror construction that would threaten the safety of the surgical team was detected.

5.4 Pre-Clinical Evaluation

5.4.1 Interlocking of Intramedullary Nails

A cadaver study was performed for the interlocking of intramedullary nails. The procedure with CAMC "shows advantages over standard techniques"[2].

5.4.2 Pedicle Screw Placement

Two cadaver studies were performed for percutaneous pedicle approach - one lumbar and one thoracic. The experiments shows that CAMC provides a "reliable and robust two dimensional visualization for guided pedicle insertion"[2]. Each procedure required a maximum of three X-ray images, a reduction in radiation time and dose compared to standard procedures. The one-time calibration was stable during the whole series of both experiments.

5.4.3 Simulated Vertebroplasty

A series of experiments analyzing the duration and radiation time of a lumbar vertebroplasty were conducted with spine phantoms covered in foam. The procedure required the insertion of a guiding wire and filling canulla through the pedicle of the vertebra. The system automatically detects movement between the patient and C-arm greater than 1mm, and prompts for a correction by requiring an updated X-ray image.

6 Conclusions

6.1 Review

Pros: Explanation of the motivation, medical procedures, and system setup were very thorough and easy to understand. Each of their conclusions were supported by background information explaining its significance. There were many clear and helpful diagrams in addition to well-written explanations. In particular, the explanation of the three step calibration was very comprehensive and beneficial for my understanding of the current slightly different calibration algorithm.

Cons: There could have been more robust testing of the calibration accuracy. There was no comparison to similar methods, or the required margin of error that would constitute their accuracy sufficient for clinical applications. There was much emphasis on the application of CAMC, important for this proof of concept but not much evaluation of the error measurements. Also, analysis of the results of the pre-clinical applications was not very detailed or quantitative. All resulted in a general statement about CAMC improving the process, but no details about by how much. Lastly, explicit surgeon feedback and suggestions for improvement would make the discussion stronger.

6.2 Next Steps

This proof of concept has since been improved and expanded to the current project, which now does not require the double mirror construction, nor the markers. It was very helpful to understand the origin of the current project, and many of the other papers mentioned in the background have provided a starting ground for ways to improve the current calibration. The accuracy evaluation process discussed can be used for the current project as well.

References

[1] Sing Chun Lee et al. "Calibration of RGBD camera and cone-beam CT for 3D intra-operative mixed reality visualization". In: *Int J CARS* (2016). DOI: 10.1007/s11548-016-1396-1.

[2] Nassir Navab, Sandro-Michael Heining, and Joerg Traub. "Camera Augmented Mobile C-Arm (CAMC): Calibration, Accuracy Study, and Clinical Applications". In: *IEEE Transactions on Medical Imaging* 29.7 (2010), pp. 1412–1423. DOI: 10.1109/tmi.2009.2021947.