Frameworks for Evaluating Accuracy in CAOS

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INTRODUCTION

One goal of Computer-Assisted Orthopaedic Surgery is to improve the accuracy with which a given surgical procedure can be performed compared to conventional methods. Improved surgical accuracy can result in improved clinical outcomes, reduced long-term costs and less invasive surgical procedures. However, achieving high accuracy in computer-assisted surgery is a difficult task which requires attention to the technical details of component and system design. There are many potential sources of inaccuracy within a computer-assisted surgical system. A single source of inaccuracy can degrade the performance of the entire system, since inaccuracy in CAOS obeys the adage: "a chain is only as strong as its weakest link". Accuracy evaluation of CAOS systems is an important and very challenging technical problem. While component and system inaccuracies can often be characterized in-vitro, it is much more difficult to characterize these inaccuracies under more realistic in-vivo conditions, ideally performed in parallel with actual CAOS procedures.

Any discussion of accuracy in CAOS would be incomplete without mention of the complex problem of specifying accuracy *requirements*. An understanding of accuracy requirements for a given surgical task is crucial, since there is a trade-off between accuracy and associated monetary costs. In today's managed care environment, it is best to strive for the least expensive (read: least accurate) system which is capable of satisfactorily achieving the desired task. Unfortunately, in some cases it is difficult to know how much accuracy is sufficient. For example, in computer-assisted total hip replacement surgery, there is clearly a relationship between the orientation of the acetabular implant and the associated range of femoral motion and subsequent potential for dislocation. However, it is difficult to precisely quantify this relationship in order to establish a bound on the accuracy required by a CAOS system used to position the acetabular component.

This abstract explores several issues related to accuracy evaluation in CAOS, and presents some accuracy evaluation frameworks which have been successfully employed within our group.

SOURCES OF INACCURACY IN CAOS

Figure 1 outlines the components of a typical CAOS system. Pre-operatively, patient-specific medical images are acquired, and a pre-operative plan is constructed from these images. Shape extraction or fiducial localization are performed to enable subsequent intra-operative registration (for additional information on registration, see the abstract in this proceedings entitled "What is 'Registration' and Why is it so Important in CAOS?"). Intra-operatively, part of the patient's anatomy is either rigidly fixed or spatially tracked relative to an intra-operative sensing device. This sensor is then used to acquire data for performing registration, and based on this data the registration transformation is computed. Once registration is complete, intra-operative guidance or robot motion

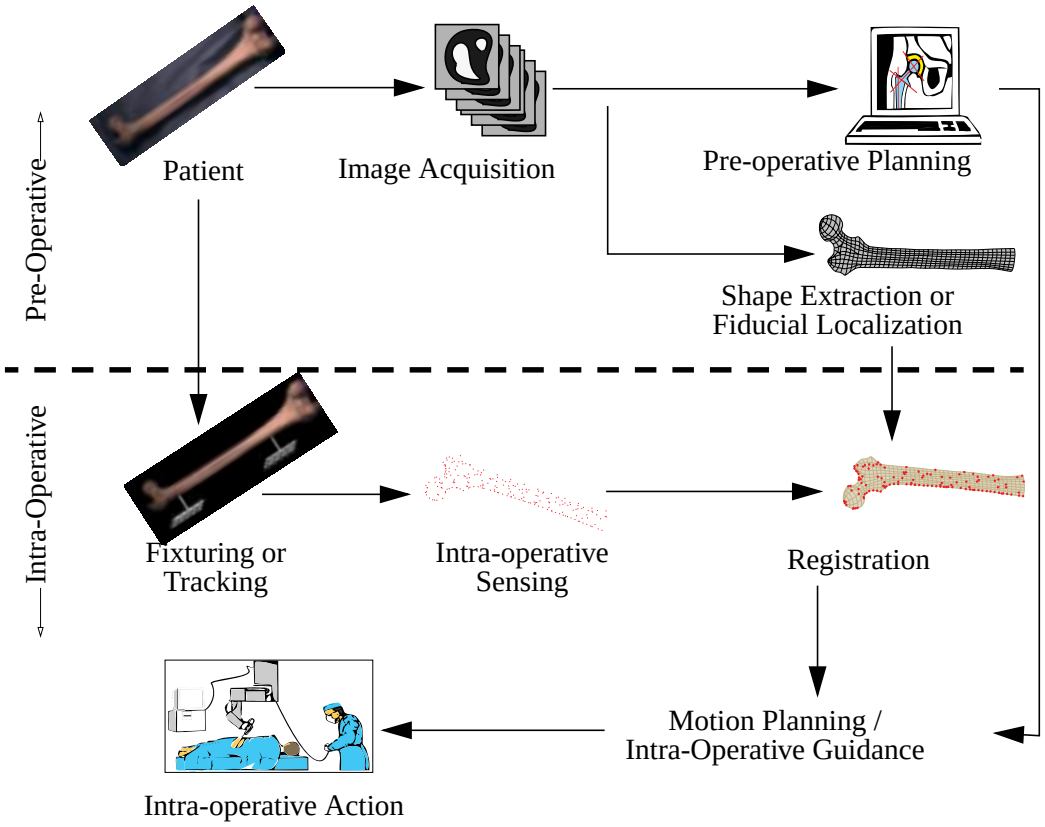


Figure 1: Sources of inaccuracy in CAOS.

planning is performed to enable the surgical action which achieves the pre-operatively planned goal. Each of the components in this framework are potential sources of inaccuracy, and the accuracy of the final surgical action is dependent upon each of the component inaccuracies. Potential sources of inaccuracy may include: image acquisition noise caused by artifacts, patient motion, etc.; pre-operative plan generation errors in which the plan does not replicate the surgeon's intent due to poor user interfaces, etc.; errors in anatomical object shape extraction or fiducial localization; deformations of the anatomy induced by the fixturing process, or errors in spatial tracking; noise in the intra-operative sensor measurements; errors in the registration process due to numerical or computational factors; misinterpretation of guidance information by the surgeon due to poor intra-operative user interfaces; errors introduced by the tools or processes performing the surgical action (e.g., robot positioning errors).

Given the large number of potential error sources in CAOS systems, it is important for the system designer to thoroughly understand the potential sources of inaccuracy, as well as the expected magnitudes of these inaccuracies. During the system development process, accuracy evaluation should be done on both the component and system levels. It is also important to have safeguards built into any CAOS system to ensure that individual component or operational failures during routine use of the system do not result in undesirable behavior. System designers should carefully heed the words of Hippocrates: "First, do no harm."

ACCURACY EVALUATION FRAMEWORK DESCRIPTIONS

Within a typical CAOS system, one component which has significant potential for inaccuracy is the intra-operative registration process. Our group has used the framework outlined in Figure 2 to better understand potential errors introduced by shape-based registration [5]. Via careful engineering, it was possible to design a highly accurate fiducial-based registration method which was used as a *ground-truth* to which other registration methods were compared. Using this process, fiducial- and shape-based registration were performed in parallel, and the results directly compared. In the above paper, we demonstrated that shape-based registration is accurate and reliable when tested on cadaver specimens and artificial bone phantoms. In the future it is desirable to replicate this evaluation process on live patients in clinical trials. The major technical challenge to achieve this goal is to design a highly reliable and accurate fiducial-based registration method which is biocompatible and minimally invasive. In addition to evaluating registration accuracy during the system design process, it is also possible to estimate registration accuracy during surgery on a case-by-case basis [4].

Two other components of CAOS systems which may introduce inaccuracies are medical image acquisition and anatomical shape extraction. There are many parameters which must be specified during image acquisition and shape extraction which can influence the accuracy of the resulting shape model, and therefore the resulting registration accuracy. Figure 3 outlines a framework for studying the effects of these parameters upon the accuracy of the resulting shape models. The difficult part of this process is to construct reliable ground-truth models for anatomical specimens which have been scanned in-vivo. In the past, our group and others have built ground-truth models using highly accurate industrial measuring equipment. While such measurements are feasible for specimens which have been scanned in-vitro, it is impossible to use such equipment on live patients. While animal studies might be possible, it would be important to ensure that the anatomical

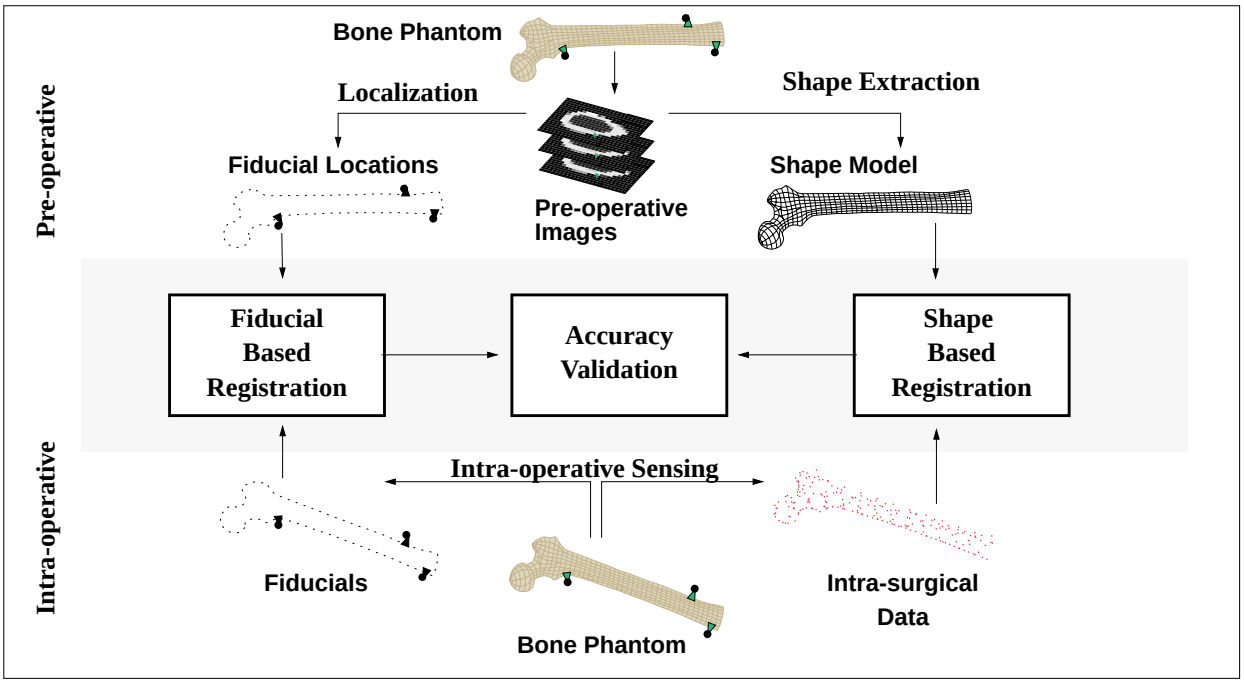


Figure 2: A framework for registration accuracy evaluation.

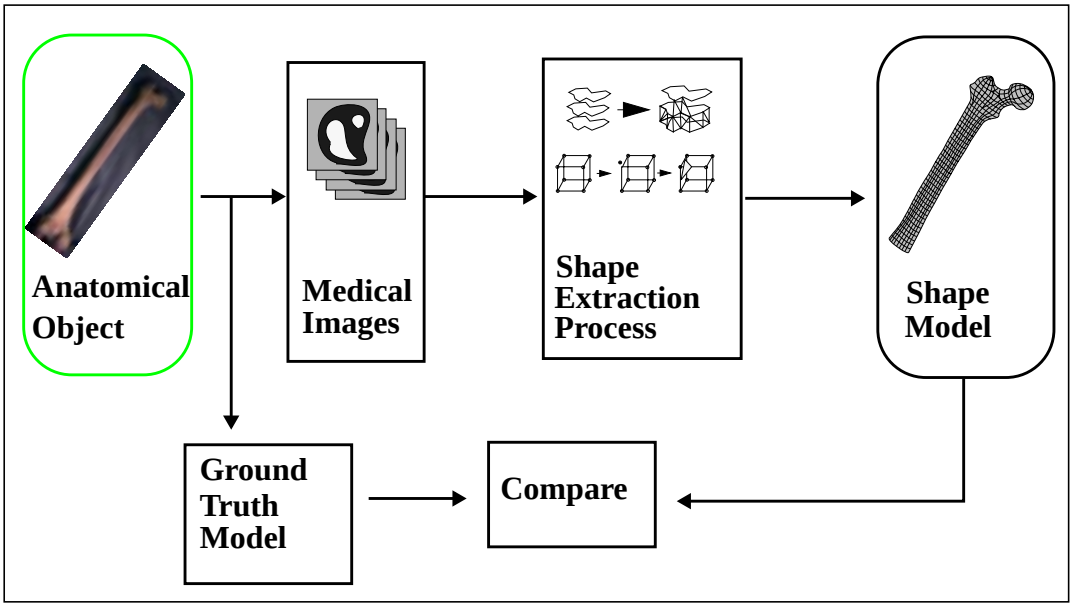


Figure 3: A framework for validating the anatomical object shape extraction process

specimens do not deform as a result of the soft-tissue removal process, or due to changes in temperature, humidity and loading conditions. This problems remains an area for future research.

CONCLUSION

To date, almost all accuracy validation work has concentrated on rigid anatomical structures (i.e., bones). As computer-assisted surgical techniques begin to incorporate soft-tissues, it will be necessary to expand accuracy validation techniques to deal with these non-rigid structures. From a technical perspective, the non-rigid case is significantly more difficult than handling rigid structures, and thus the field of accuracy validation will remain an important and challenging research area for years to come. The references below provide an initial set of pointers into the accuracy validation literature for the interested reader.

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