Development of Tools for Measuring the Performance of Computer Assisted Orthopaedic Hip Surgery Systems

Nicholas G. Dagalakis, Yongsik Kim, Daniel Sawyer, Craig Shakarji

Manufacturing Engineering Laboratory
National Institute of Standards and Technology
100 Bureau Dr. Stop 8230
Gaithersburg, MD 20899-8230

Abstract— In the late seventies a sensor was invented, which could track the movement of athlete body parts. In the early eighties an improved version of this sensor was introduced, by a group of NIST researchers, for the calibration and the performance testing of industrial robots. In the late eighties people experimented with the use of these sensors for human brain operations and in the early nineties these sensors were introduced to orthopaedic operations and the field of Computer Assisted Orthopaedic Surgery (CAOS) was born. Although significant progress has been made in the design and use of these sensors for medical applications, there are still sources of accuracy errors that must be addressed. This paper describes our work on the development of tools for the calibration and performance testing of CAOS systems, which can be used inside operating rooms.

Keywords: computer assisted surgery, computer assisted orthopaedic surgery, hip arthroplasty, phantom, artifact

I. INTRODUCTION

In the early eighties a group of National Institute of Standards and Technology (NIST) researchers, working for the NIST/Center for Manufacturing Engineering, the predecessor of the NIST/Manufacturing Engineering Laboratory, modified an athlete body tracking sensor [1[1]], so that it can be used for robot calibration and performance measurements [2]. An extensive study of the sources of measurement errors of this sensor and its controller was performed. Soon this sensor became a commercial product and it has been used by manufacturers and users of industrial robots, for their robot calibration and performance measurements, for the last 20 years. In the early nineties Nolte L.P. [3] used this type of

---

[1] Certain commercial products and processes are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products and processes identified are necessarily the best available for the purpose.

tracking sensor for precision enhancement in spine surgery. Spine surgery tools were equipped with probes holding three or more target Light Emitting Diodes (LEDs), that were tracked to determine the surgical tool position and orientation. A Dynamic Reference Base (DRB) coordinate frame, equipped with three or more target LEDs, was attached to the vertebra undergoing surgery. Appropriate mathematical transformations converted the surgical tool's position and orientation to DRB frame coordinates, thus facilitating the insertion of screws at the right position and orientation in the overwhelming majority of cases. At about the same time Lavallee S. [4] performed spine surgeries using a similar tracking sensor system. Lavallee experimented with surface registration for the identification of characteristic bone landmarks, instead of simple point registration. He also experimented with a robot carrying a laser beam for surgical drill tool alignment. Soon these techniques were extended to total hip and knee arthroplasties and the field of Computer Assisted Orthopaedic Surgery (CAOS) was born.

The market for the use of CAOS systems inside an operating room in order to guide orthopaedic operations has evolved significantly from the original Selspot athlete body tracking sensor system. The Selspot system used two lateral effect photodiode camera tracking sensors, while most of the modern CAOS systems use two or three Charge Coupled Device (CCD) cameras with active LED targets or passive sphere targets illuminated by infrared light. People have also experimented with electromagnetic tracking sensors, with electrical coil targets and other technologies. Although these types of targets do not require line of sight with the sensor and thus can operate inside the human body, they are susceptible to interference from electromagnetic waves reflected by metal surfaces inside the operating room. Computer Assisted Orthopaedic Surgery systems consist of tracking camera sensors, tracking markers (targets), a computer and other relevant electronics [5]. During an operation the markers are attached to bones, surgical tools and implants. The three dimensional space position of the markers is determined with

respect to a reference frame and based on that information the position and orientation of tools, bones and implants is calculated and used to generate useful surgery information. Comparison of conventional versus CAOS assisted arthroplasty operations have demonstrated that CAOS systems show significant improvement in the desired surgical result. In particular CAOS systems help reduce the variability of the positioning of prosthetic components from the desired optimum position and orientation, thus permitting a more consistent placement of the prosthetic components [6, 7].

It did not take very long though for the users of CAOS systems to recognize that the tracking sensors have accuracy problems, which may jeopardize the outcome of the surgical operation. The original NIST study identified several sources of errors. Some of them could still be relevant and can introduce positioning errors for the modern CAOS systems. Here is a list of these possible sources of errors:

1. Camera optics.
2. Detector irregularities.
3. Target operating conditions, like temperature, non uniform radiation field, distance from the camera sensors, etc.
4. Camera position and orientation determination with respect to the tracking sensor system reference coordinate frame.
5. Sampling rate frequency of multiple targets.

The image generated by each target on the camera tracking sensor is usually an irregular blob with non-uniform intensity distribution. It is up to the controller of each tracking system to decide how to assign XY coordinates to this type of image. A simple rotation of the target, with no position change, could alter the value of the measured XY coordinates. In the case of slow sampling rate tracking systems the target might move while its position is still being sampled. The general conclusion of the NIST study was that these tracking systems have a sweet region of low error for target positions located within the 80 % of the camera detector field of view. This error increases as the target moves away from this central region.

The focus of the work reported in this paper is to address the accuracy problems associated with the use of Computer Assisted Orthopaedic Surgery (CAOS) systems, by implementing well calibrated artifacts, called phantoms by most medical professionals.

II. BRIEF REVIEW OF TOTAL HIP ARTHROPLASTY OPERATION

Various human diseases and activities can damage the hip joint and lead to severe pain and loss of mobility. Surgery to replace the damaged joint with an artificial one, prosthesis, is usually the last resort in order to alleviate pain and restore mobility [8]. This operation was invented by Dr. Charnley, a British surgeon, in the sixties who was honored with knighthood for his contribution. During the operation the head of the femur (thigh bone) is removed with a saw and the pelvis socket is reshaped in to a hemisphere with a scraping tool called a reamer. There are two major categories of joint prostheses, the cemented and the uncemented ones. The cemented are attached to the bone with an epoxy cement, while the uncemented have a porous external surface where bone can grow in order to attach the prosthesis to the skeletal bone. The hip prosthesis consists of two major parts; the femoral component and the acetabular component (see images in Figure 1 and 2). The femoral component is made of a metal stem and a metal or ceramic ball head and is intended to replace the upper part of the femur bone. The acetabular component is usually made of a concave metal shell cup, and a plastic inner liner. During the operation the pelvis socket, is reshaped before the acetabular prosthesis head can be inserted. The initial step before the operation is to determine the coordinates of the center of rotation of the hip and ankle joints in order to calculate the length of the leg. This test must be repeated before the conclusion of the operation and adjustments must be made in order for the patient to exit the operating room with the proper length leg, since a portion of his femur bone and pelvis have been removed. Another critical step of this operation is the attachment of the acetabular component of the prosthesis. It has been found that the metal shell cup must be placed with precise angular orientation otherwise the prosthesis could fail due to dislocation, impingement and premature wear. The angles that define the correct angular orientation are defined with respect to the patient pelvis frontal (coronal) and transverse coordinate planes, which are difficult to locate while the patient is lying on the operating table.

After the acetabular component has been inserted the femur bone cavity is reshaped in order to accept the stem of the femoral prosthesis. The size and shape of the stem can vary from one patient to another. The femur bone cavity is usually shaped with manual tools although orthopaedic surgeons are also experimenting with robotic milling tools [9]. The robotic tool creates a smooth surface cavity, which should be less prone to stress concentrations that can lead to bone fractures. After a brief stay at the hospital and sometimes a rehabilitation facility, the patient will walk briefly with the help of a walker, crutches or a cane and finally the great majority will walk freely without assistance. This operation together with the total knee arthroplasty operation, are considered by some to be the greatest surgical developments of the twentieth century, because of the number of patients who have benefited and the severity of the pain that has been alleviated.
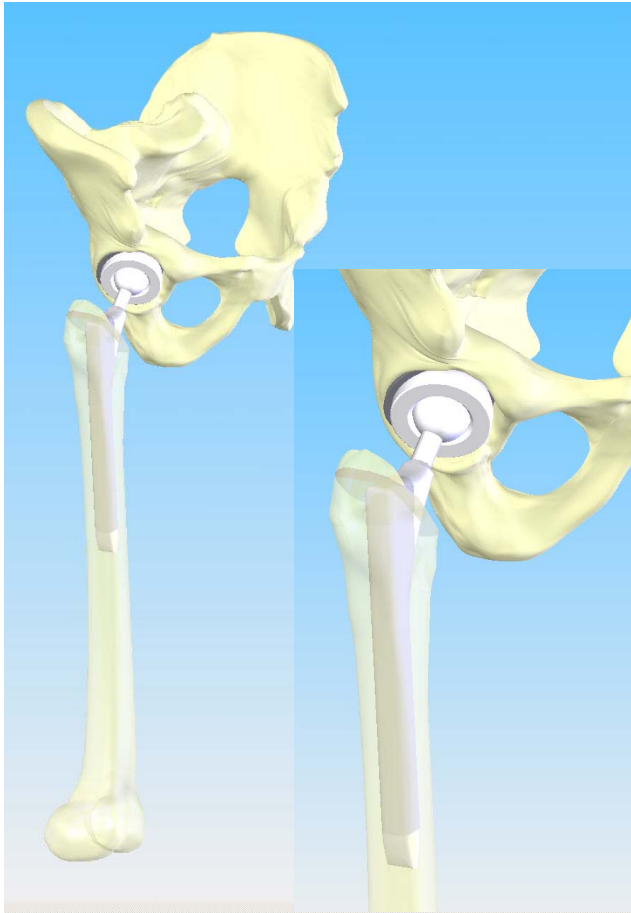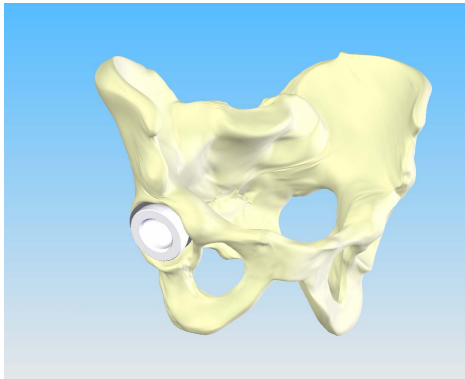
Figure 1. Femoral part of hip prosthesis

Figure 2. Acetabular part of hip prosthesis

III. PRECISION ENGINEERING TOOLS FOR TESTING COMPUTER ASSISTED ORTHOPAEDIC HIP SURGERY CAOHS SYSTEMS

Precision and robotic engineers have a need for high performance ball and socket joints, which have no backlash and low friction, so they invented the magnetic ball and socket joint shown in Figure 3. The basic component of this device is the magnetic socket shown in Figure 4 [10]. This device is usually made of magnetic stainless steel and has a cylindrical hollow cavity at its center. A cylindrical magnet is fitted in that cavity and secured at the desired position with plastic shims and epoxy glue. The image at the top of Figure 4 shows a socket fitted with a magnet, while the image below shows a socket before the attachment of the magnet. This design allows for the control of the magnetic force by selecting the proper magnet and shim thickness for the application. The shims control the size of the gap between the top of the magnet and the surface of the ball. The ball touches the rim of the socket at three small arcs located 120^0 from each other (see images on Figure 4). These arcs are created by pressing hard another ball on the rim of the socket. The socket joint ball is usually made of magnetic stainless steel and it is attracted to the socket by the force of the magnet. This force should be strong enough to keep the ball always in contact with the socket, but not very strong which might generate excessive wear on the ball surface.

Figure 3. Precision magnetic ball and socket joint
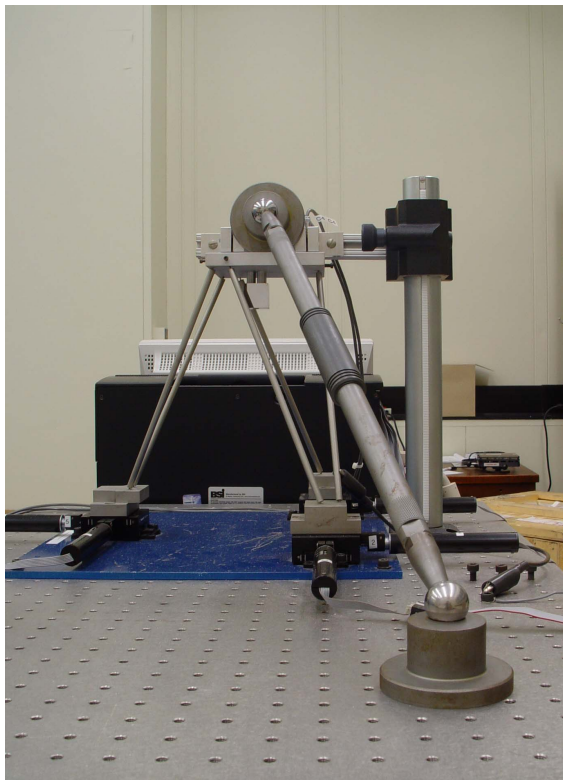
Figure 4. Precision magnetic sockets

The magnetic ball and socket device offers a convenient precision joint tool, but many precision and robotic applications require fixed or adjustable length links. To meet that need people have invented the ballbar shown in Figure 5. A ballbar can have fixed or adjustable length and has magnetic balls at both ends, mounted on its tips. In the case of Coordinate Measuring Machines (CMMs), these artifacts can be employed to perform a subset of performance tests that are described in an American National Standard. Although not required these artifacts are frequently calibrated for center-to-center distance. That is, the distance between the centers of the two magnetic balls is independently calibrated. These artifacts are then measured, by the CMM, in several locations and orientations, which were selected because of their sensitivity to error sources associated with the geometrical construction of the particular class of CMM.

For the calibration of the phantom described in this paper, a Direct Computer Controlled (DCC) CMM was employed. This class of machine is error corrected using a high accuracy laser interferometer, electronic levels and precision straightedges. After error correction of the CMM, ballbars are then employed, as described in the American National Standard, to highlight possible problems in the CMM performance before measurement of critical parts are performed.

IV. THE COMPUTER ASSISTED ORTHOPAEDIC HIP SURGERY (CAOHS) ARTIFACT

For best clinical results our artifacts (phantoms) are designed to resemble the skeletal joint or organ, which is the subject of the operation and the suggested performance tests resemble important tasks of the actual surgical operation. In order to reduce the fabrication and maintenance cost of these devices, we use commercially available precision parts wherever possible in the phantom structure design.

The most important component of the hip joint is the ball and socket joint, which we decided to add to our artifact (phantom). Most ordinary mechanical ball and socket joints have backlash and are difficult to clean and inspect for wear, because they are sealed. However precision engineers use magnetic ball and socket joints (see Figure 3) and bars (see Figure 5), which have none of the above mentioned drawbacks and are commercially available for reasonable prices and are used for the calibration and testing of precision measurement machines, like CMMs and Industrial Robots (IRs). Furthermore these joints can be fitted with various strength small size magnets, which can be selected for the proper size bar and joint orientation, so that the contact force will be sufficient to ensure that the bar will not separate from the joint socket during the test and not so large that results in excessive surface wear.

Figure 5. Ballbar calibration test

197

Our first phantom resembles a pelvis coordinate frame, as shown in Figure 6 and a femur bone connected with a precision magnetic ball and socket joint, as shown in Figure 7. Because the magnetic socket of this device is horizontal it is called Horizontal Joint-Operating Room-CAOHS (HJ-OR-CAOHS).
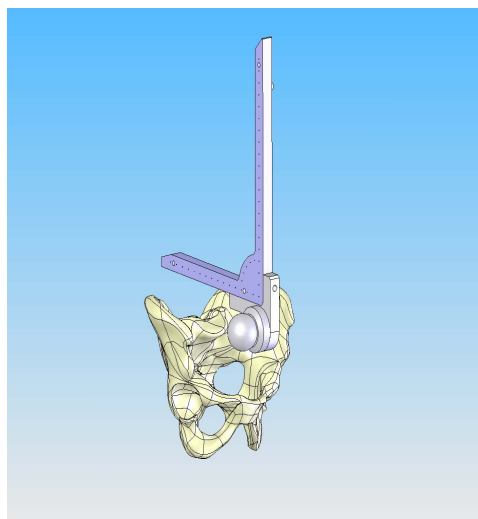

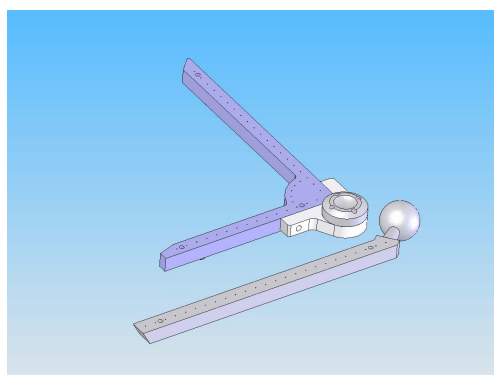Figure 6. The CAOHS phantom coordinate frame superimposed on a pelvis model

Figure 7. The CAOHS phantom coordinate frame and femur bar connected with a magnetic ball and socket joint

The CAOHS phantoms are designed to perform at least three performance tests relevant to hip arthroplasty operations. Such as are the following: 1) measure the CAOS system accuracy of the determination of the location of the coordinates of the center of rotation of the hip joint, represented here by the precision magnetic ball and socket joint, 2) measure the CAOS system accuracy of moving along straight lines at distances comparable to the size of human adult large bones, along two orthogonal directions, 3) measure the CAOS system accuracy of angular moves relevant to orthopaedic hip surgery. If the CAOHS phantoms prove useful for orthopaedic operations, similar devices will be developed for the human knee joint, shoulder joint, etc.

The first HJ-OR-CAOHS phantom was fabricated a few months ago (see Figure 8). It is made of an L shape horizontal XY orthogonal coordinate frame, a joint horizontal mount, the magnetic ball and socket joint and a femur bar. The XY coordinate frame has small target holes (see Figures 13 and 14) at regular intervals of 15 mm, designed to fit the pointed probe tip of the CAOS systems target assemblies. These are plates with four or more active or passive markers, which can be mounted on surgical tools. It also has two larger holes for the mounting of DRB target assemblies. The femur bar also has two larger holes for the mounting of DRB target assemblies, which can be used for the determination of the coordinates of the ball center of rotation. The tips of all the HJ-OR-CAOHS phantom bars are machined to form various angles, which are useful for hip arthroplasty operations (see Figures 11 and 12). An arc at the base of the coordinate frame has been fitted with target holes spaced at regular angular increments, which adds an additional angular calibration and testing capability (see Figure 9). The magnetic ball and socket joint are commercially available and are made of stainless steel material, while the rest of the parts are made of Invar, for better thermal stability inside an operating room.

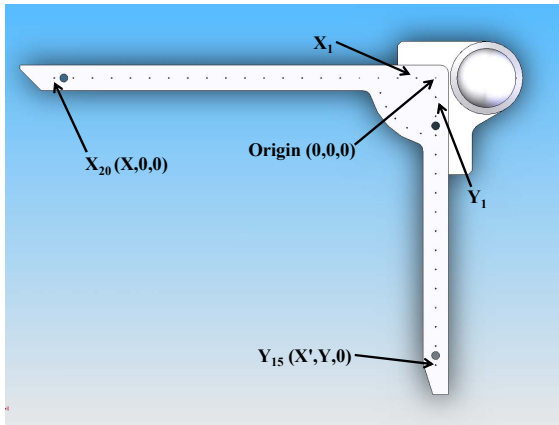Figure 8. The first prototype of the HJ-OR-CAOHS phantom

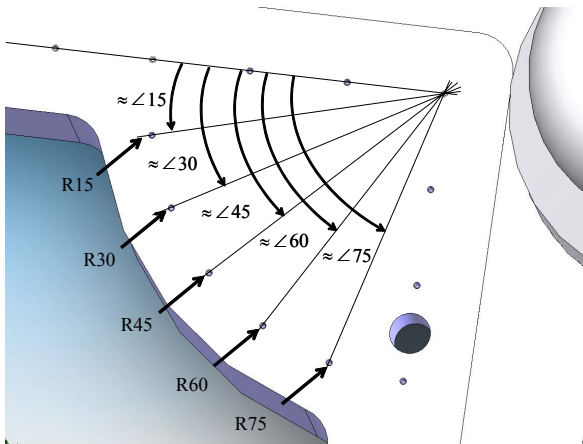Figure 9. The L shape XY coordinate frame with the target holes

Figure 11. The angles between the adjacent planes labeled in the figure can be used for the evaluation of surgical cutting tools

Figure 10. The origin arc with the target holes defining certain angles with respect to the X coordinate axis

Figure 12. The femur bar showing the two angled planes and DRB mount holes

Figure 9 shows the L shape XY coordinate frame with its target holes marked X_1 to X_{20} on the X axis (horizontal in the figure) and Y_1 to Y_{15} on the Y axis (vertical in the figure). The nominal incremental distance between these target points is 15 mm, which gives a nominal X axis length of 300 mm and a nominal Y axis length of 225 mm (see Figure 11). The X axis is longer because it is intended to approximate the length of an adult femur bone. The distance between any two target holes is measured between the tips of the two holes. Although the nominal distance can be calculated assuming a nominal increment of 15 mm, between neighboring holes, the actual distance is determined through careful calibration, which will be described in a future paper.
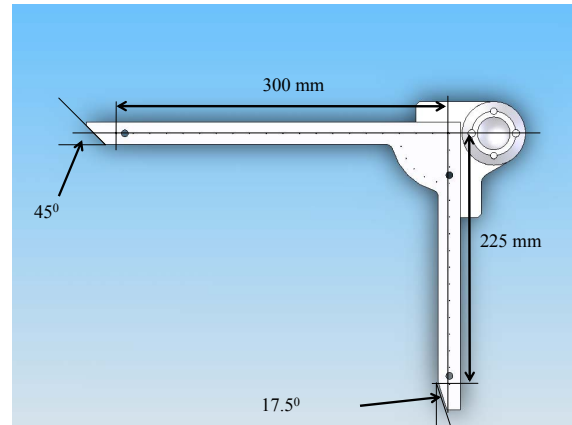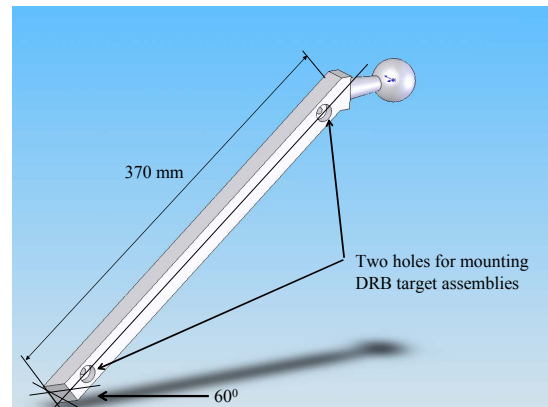
Figure 13 shows the nominal dimensions of the target holes. Special attention was given to the drilling of these holes in order to achieve smooth clean hole walls and tip and a hole axis, which is as close as possible orthogonal to the corresponding coordinate frame XY axis. Several drill bits were used and each one was not used for more than four holes. Every single one of the target holes was examined and photographed under a microscope. One concern was the presence of burrs, which could prevent the tip of the CAOS system target probe from reaching the tip of the target hole. Figure 14 shows a typical hole image, which reveals that the hole tip is really a hemispherical surface and not a sharp tip as Figure 13 implies. It is thus important that during CAOS testing the pointed probe tip of the CAOS systems target assemblies can reach that hemispherical surface and not be

able to move laterally by any significant amount because that motion will introduce measurement errors.
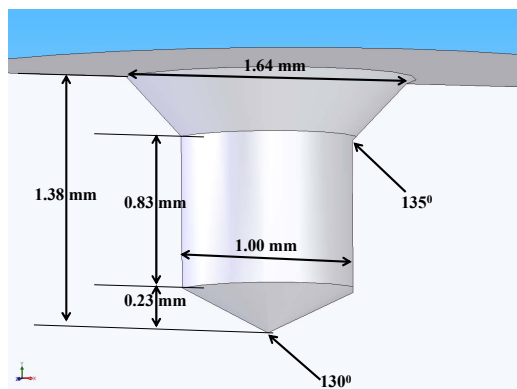

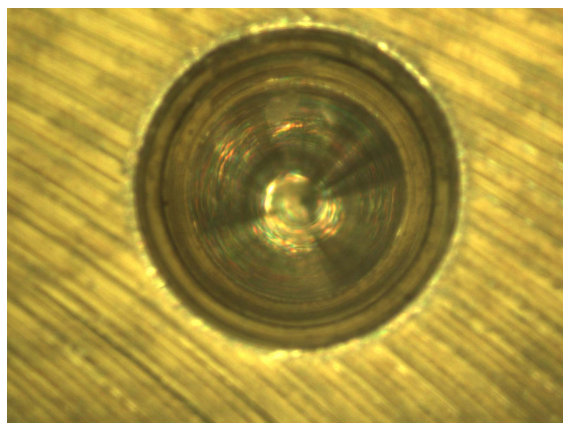Figure 13. Cross section view of the target hole

Figure 14. Microscope images of a target hole

The HJ-OR-CAOHS phantom offers two different options for testing the ability of a CAOS system to measure angles. One may involve the use of the saw blade, spatula or other similar tool and the other the pointed probe tip of the CAOS systems target assemblies. The end planes of all the phantom bars are shaped to form angles that are commonly used during hip orthopaedic operations. From Figure 11 it can be seen that the X axis bar of the phantom coordinate frame terminates at a nominal 45^0 angle, which is considered by many orthopaedic surgeons as the best choice for the hip acetabulum prosthesis inclination angle. The Y axis bar of the phantom coordinate frame terminates at a nominal 17.5^0 angle, which is considered by many orthopaedic surgeons as the best choice for the hip acetabulum prosthesis anteversion angle. The femur bar terminates at a nominal 60^0 angle, which is preferred by many orthopaedic surgeons for the decapitation of the damaged head of the femur bone. The arc around the origin of the coordinate XY frame axes has five target holes at nominal angles of 15^0, 30^0, 45^0, 60^0, 75^0, with respect to the X axis. These are three point angle measurements and allows pointed probe tip measurement tests.

NIST staff have calibrated all the critical features on the HJ-OR-CAOHS using an industrial grade Coordinate Measuring Machine (CMM). These features include the target hole locations and the center of rotation. In all cases the expanded uncertainty U with $k = 2$ in the determination of the three dimensional coordinate is less than 0.08 mm. A future publication will report on the calibration procedures and an additional publication will describe the results of industrial testing. The coordinates of the ball center of rotation are measured with respect to the CMM reference coordinate frame. Using coordinate transformation algorithms similar to those used for the calibration of IR work cells, it is possible to refer these coordinates to the HJ-OR-CAOHS phantom coordinate frame, thus making the use of the phantom independent of the metrology instrument used for its calibration.

A new version of the OR-CAOHS, which has an angled magnetic ball and socket joint similar to that of a human pelvis, is also being designed.

V. CONCLUSIONS

We have described the use of common and inexpensive precision engineering and industrial robot calibration tools for the design of an artifact (phantom), which may be used for measuring the performance of CAOS systems inside operating rooms. This phantom can also be used for the calibration of CAOS systems. Calibration is of course primarily the responsibility of the manufacturer of CAOS systems and it can be performed after fabrication and during servicing operations. We have designed and fabricated a horizontal joint computer assisted orthopaedic hip surgery phantom (artifact). This device appears to be working very well and it was recently calibrated and sent to a medical research group for testing. Calibration and testing results will be reported in future publications.

REFERENCES

[1] Selspot[1] manufactured by SELCOM, Partille, Sweden (presently owned by LMI, Delta, British Columbia, Canada).

[2] Dainis A., Juberts M., "Accurate Remote Measurement of Robot Trajectory Motion," IEEE International Conference on Robotics and Automation, St. Louis, Missouri, pp 92-99, March 1985.

[3] Nolte L.P., Zamorano L., Visarius H., Berlemann U., Langlotz F., Arm E., Schwarzenbach O., "Clinical Evaluation of a System for Precision Enhancement in Spine Surgery," Clinical Biomechanics, Vol. 10, No. 6, pp.293-303, 1995.

[4] Lavallee S., Sautot P., Troccaz J., Cinquin P., Merloz P., "Computer Assisted Spine Surgery: A Technique for Accurate Transpedicular Screw Fixation Using CT Data and a 3-D Optical Localizer," Journal of Image Guided Surgery, Vol. 1, pp. 65-73, 1995.

[5] Nolte L.P., Langlotz F., "Basics of Computer-Assisted Orthopaedic Surgery (CAOS)," in the book "Navigation and Robotics in Total Joint and Spine Surgery," by Stiehl JB, Konermann WH, Haaker RG, Publisher Springer-Verlag, 2004.

[6] Haaker R.G.A., Tiedjen K., Ottersbach A., Rubenthaler F., Stockheim M., Stiehl J.B., "Comparison of Conventional Versus Computer-Navigated Acetabular Component Insertion," J of Arthroplasty, Vol. 22, No. 2, 2007.

[7] Nogler M., Kessler O., Prassl A., *et al.* "Reduced Variability of Acetabular Cup Positioning with Use of an Imageless Navigation System," Clin Orthop , Vol. 426, pp 159-163, 2004.

[8] Thomas B.J., Stiehl J.B., "Basics of Total Hip Replacement Surgery," in the book "Navigation and Robotics in Total Joint and Spine Surgery," by Stiehl JB, Konermann WH, Haaker RG, Publisher Springer-Verlag, 2004.

[9] Bargar W.L., Bauer A., Borner M., "Primary and Revision Total Hip Replacement Using the Robodoc System," Clinical Orthopaedics, Vol. 354, pp. 82-91, 1998.

[10] ATT Metrology Services, Redmond, WA, http://www.attinc.com/target-pg5.htm