

Calibration of a Computer Assisted Orthopedic Hip Surgery Phantom

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ABSTRACT

Orthopedic surgeons have identified a need for calibration artifacts (phantoms) to establish the traceability (to the SI unit of length) of measurements performed with Computer Assisted Orthopedic Surgery (CAOS) systems. These phantoms must be lightweight, easy to transport and simple to use. In collaboration with medical professionals, National Institute of Standards and Technology (NIST) researchers have developed a family of novel CAOS phantoms designed to meet the metrology needs of this critical segment of the US healthcare industry. The phantoms function as a surrogate hip joint and pelvis and can be measured with CAOS systems using the same technique employed to measure a patient's hip joint and pelvis for replacement surgery. The phantoms contain a mechanical ball joint, which functions as a substitute for a patient's hip joint and small holes, referred to as target holes, for receiving the measuring probe of CAOS systems. The location of the mechanical ball joint and the relative positions of the target holes are measured using the CAOS system and the results compared to the known values for these quantities. The results of this comparison are then used to verify the CAOS system performance specifications. In order to determine the known values for the critical dimensions of the phantom, the mechanical ball joint location and target hole positions are measured with a Coordinate Measuring Machine [1] (CMM), which is more accurate than CAOS Systems. This paper will report on the calibration of the NIST prototype phantom using a CMM and simulation tools at NIST.

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computer assisted surgery, computer assisted orthopedic surgery, hip arthroplasty, phantom, calibration.

1. INTRODUCTION

The NIST operating room artifact (known as the phantom)[2][3] is designed to evaluate the measurement performance of three-dimensional coordinate measuring instruments that are used for Computer Assisted Orthopedic Surgery (CAOS). The intent of this report is not to describe the development and use of the phantom. (See [2] and [3].) Instead, this report provides a description of the critical features of the NIST phantom with only enough details about its construction to clearly describe the calibrated dimensions and their general intent. Further, this document will not provide the values of the results of the measurements. Such information is not part of the description of the measurement procedures. Finally, a description of a novel tool for calculating the task specific measurement uncertainty for all of the measurements performed is provided [4].

The phantom is comprised of two independent parts. The base is the primary support structure and is the "L" shaped part depicted on the right-hand side of figure 1 and shown in the photograph of figure 2. The femur bar is removable and connected to the base via a magnetic ball socket; it has kinematic constraints similar as to the human femur bone relative to the pelvis, which is depicted on the left-hand side of figure 1.

The base and femur bar are constructed of INVAR with a coefficient of thermal expansion of $1.30 \mu\text{m} \cdot \text{m}^{-1} \cdot ^\circ\text{C}^{-1}$ and include three types of calibrated features. First, there are small holes (approximately 1 mm in diameter and 1.4 mm in depth) on the base of the phantom, referred to as target holes. Collectively, these target holes function as a three-dimensional point coordinate artifact. The base has target holes aligned along two nominally orthogonal axes and additional target holes aligned along a semicircular path about the intersection of these axes.

(See figure 3.) The three-dimensional coordinates of these target holes are provided as part of the phantom calibration and when referenced to the appropriate coordinate frame (see the next section) these known values can be used to evaluate the performance of CAOS systems in point coordinate measurements.

Second, a stainless steel magnetic kinematic ball nest is bolted to the base; it is designed to firmly hold a highly spherical 38.1 mm diameter stainless steel sphere. The coordinates of the center location of the sphere placed in the kinematic nest, along with its measured diameter, are included in the calibration report. This kinematic ball nest functions as a surrogate hip socket. When fitted with the sphere on the femur bar, CAOS systems can measure the ball center location in a manner consistent with operating room procedures. The calibrated value for the ball center can then be used to evaluate the performance of the CAOS system in determining the location of the center of rotation. This is similar in practice to determining the center of rotation of a patient's hip joint.

Finally, the angles between three sets of planes are also provided. CAOS systems are often configured with a supplemental cutting blade and spatula tools. When these tools



Figure 1. The image on the left is a depiction of a patient pelvis along with a femur bone and an artificial ball joint. Comparing this to the NIST phantom and femur bar on the right side of the figure, it is easy to recognize the motivation for the construction of the measurement artifact.

are present, the sides of the tools will be brought into contact with these surfaces and their angular orientation recorded by CAOS systems. The calibrated value for the angles between each set of planes can be compared to the CAOS measured angles to determine the tool angular positioning performance. In all cases, the measured coordinates provided as part of the calibration report are relative to a common coordinate frame. The details for establishing this common or part-coordinate frame and the method employed to inspect each of the calibrated features are included in the applicable section of this paper.

Calibration of the phantom features was performed using a Coordinate Measuring Machine (CMM) with active part temperature compensation and the task specific measurement uncertainty was evaluated using Pundit/CMM software¹ [3]—which incorporates a measurement uncertainty tool developed at NIST [4]—and following NIST Technical Note 1297, *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*.

2. PART COORDINATE FRAME

Referring to figure 2, the part-coordinate frame origin is located at the center of the bottom plane of the target hole labeled *Origin*. The X-axis is defined as the line that passes through the origin and the bottom center of the target hole labeled X20. The X-Y plane contains the X-axis and the bottom center of target hole Y15. And finally, the Y-axis lies nominally along the direction of the line from the origin through the bottom center of target hole Y15. It's important to note that the coordinate frame as drawn in figure 2 is misleading as the part-coordinate frame's X- and Y-axes lie along the bottom of the target holes and, consequently, the part coordinate frame's X- and Y-axes are inside the part.

3. TARGET HOLE MEASUREMENTS

During calibration, the phantom is positioned with the X- and Y-axes in the X-Y plane of the NIST Resource Engineering Incorporated¹ (REI) CMM. This class of CMM is a standard commercial grade CMM. (Volumetric performance number [6] is approximately 10 μm .) The center of each target hole is designated by its X and Y coordinates. These centers are determined by measuring 4 points distributed along a circular path around the interior of the cylindrical bore that forms the top two thirds of the target hole. The Z coordinates are then obtained by probing vertically, towards the bottom of the target hole, with the probe positioned in the center of the target hole. (Uncertainties associated with the non-perpendicularity of the target hole axis and the X-Y plane have been assessed and are included in the uncertainty statement that is part of the phantom calibration report.)

Unlike the CAOS systems, which use pinpoint probes, CMMs use spherical probes with finite diameters. Consequently, the measured coordinate obtained using a CMM represent the center of the probe. As a consequence, the Z coordinates had to be corrected for the effect of the probe tip radius to be consistent with the coordinates measured by the CAOS systems.

The target holes with names that begin with *R* are labeled from R15 through R75 in figure 3. These target holes are labeled using integer increments of 15. The number following *R* in the name corresponds to the approximate angle in degrees that a vector through the origin and the target hole makes with the X-axis, as shown in figure 3.

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.

4. SPHERE MEASUREMENT (CENTER OF ROTATION)

A sphere with 38.1 mm nominal diameter was measured while positioned in the kinematic ball nest. (See figure 2 below.) The sphere was measured with five points; one on the pole and 4 points distributed approximately 15° above the equator. This measured quantity represents the center of rotation when the femur bar is attached to the phantom base. There is approximately a 3 μm difference in diameter between the size of the sphere attached to the femur bar and the sphere used during calibration. The effects of the difference in size of the two

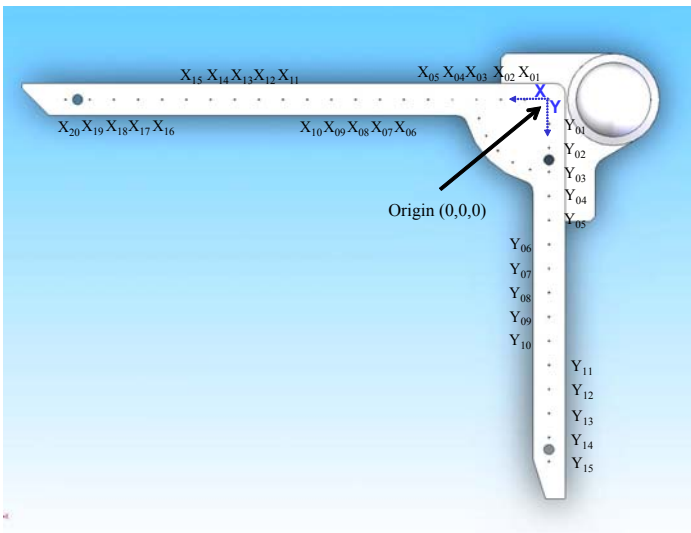
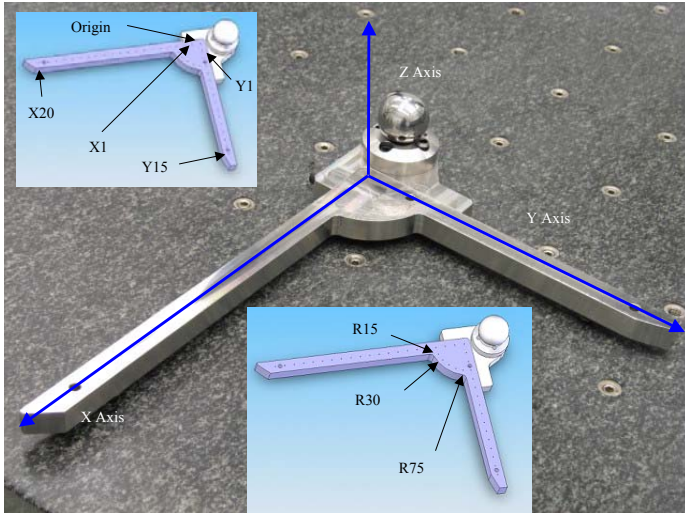


Figure 2. The coordinate of each target hole is defined as the point in its bottom center. The names for the target holes are labeled X1 through X20. They are labeled sequentially from the origin through point X20. The numbering is the same for the Y-Axis, although there are fewer target holes along this axis.

spheres are included in the uncertainty analysis, and the

expanded uncertainty provided in the calibration report reflects the effect of this difference.

5. ANGLE MEASUREMENT

Three sets of planes were measured and the angle between the calculated surface normals is reported for each set of planes. The planes were measured using 5 points: 4 points in each of the

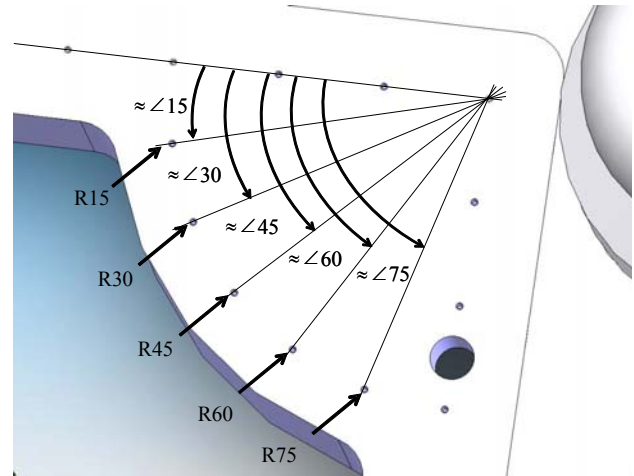


Figure 3. The target holes with names that begin with *R* are labeled from R15 through R75. These target holes are labeled using integer increments of 15. The number following *R* in the name corresponds to the approximate angle in degrees that a vector through the origin and the target hole makes with the X-axis, as shown in figure 2b.

corners of the plane and one point in the approximate center. These planes are shown in figures 4 and 5.

6. MEASUREMENT UNCERTAINTY

Because of the versatility of CMMs, the calculation of measurement uncertainty for the broad array of measurements they can perform is a challenging task. This challenge is a result of the large number of factors that affect the accuracy of CMM measurements. Specifically, CMM hardware errors, environmental effects, form errors in the feature under inspection and the number and distribution of points used to inspect the feature all affect the accuracy of the measurements performed. In response to this challenge, industry has developed some tools to simulate the measurement task while varying the parameters that characterize these factors. To calculate these critical components of uncertainties for the measurements described in this paper, NIST used one such tool, PUNDIT/CMM [4]. This software tool implements a technique called Simulation by Constraints [5] to estimate the components of the measurement uncertainty mentioned above. In the software, all of these effects are modeled and varied and the measurement process simulated.

In particular, the determination of the uncertainty in the X and Y target hole coordinates is complicated by the fact that the cylindrical portion of the target hole is neither perfectly cylindrical nor orthogonal to the X-Y plane. In fact, the angle and shape of each target hole varies slightly due to manufacturing inaccuracy. Clearly, the number and the distribution of points along the surface of the cylindrical portion of the target hole affect the value of calculated coordinates. In order to include the variation of the axis direction and the form error, 4 of the target holes were measured using a large number of points (approximately 26 points total). The data was then

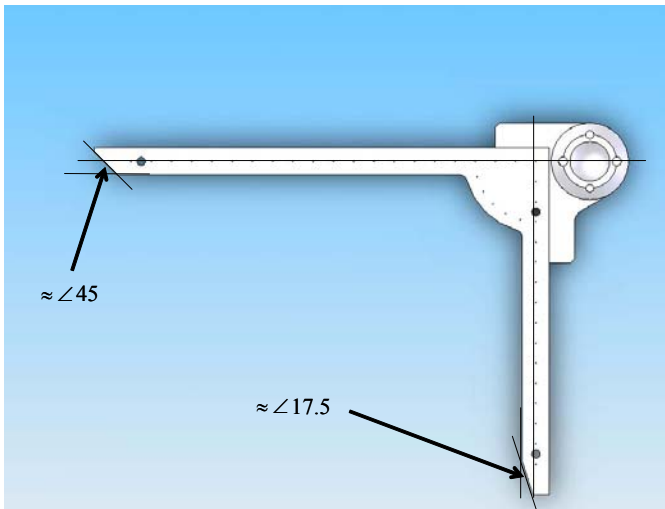


Figure 4. The angle between the adjacent planes labeled in the figure is provided to evaluate the angular measurement performance of CAOS systems when fitted with a supplementary cutting tool.

evaluated and information about the characteristic form error in the cylindrical surface and the variation of the target hole axis direction was entered into the uncertainty software. Further, the bottoms of the target holes are not perfectly flat and smooth. To obtain information for input into the simulation software, a large number of points were measured along the bottom surface of the

target hole. The software then uses this information to vary the form of the surface for each measurement simulation. The

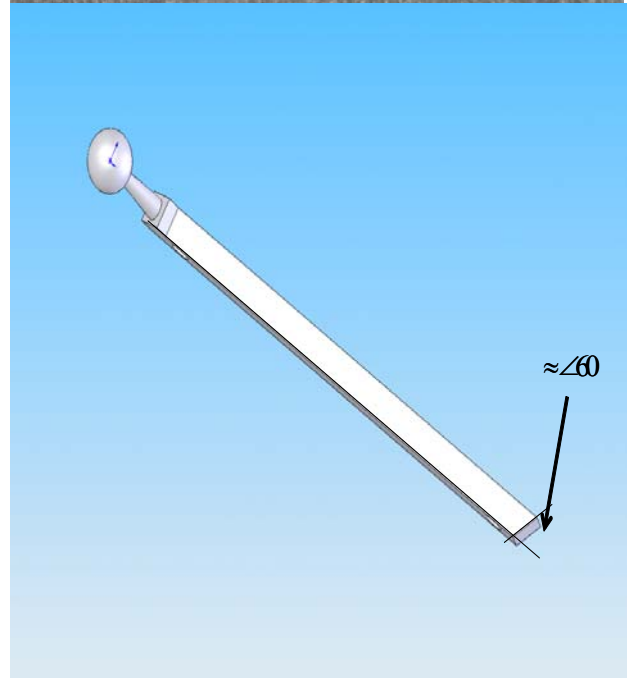


Figure 5. The femur bar shown with the sphere attached. The sphere shown in Figure 3 is removed and replaced with the sphere shown here allowing the femur to be rotated much like a hip joint.

variation in the simulation results characterizes these important components of the measurement uncertainty.

The simulation tool is also used to determine which points should be measured. That is, potential users of the phantom specified the required uncertainties for the calibration before

hand. As typical CAOS point coordinate measurement uncertainty is on the order of 1 mm, it is desirable for the calibration uncertainty to be on the order of 0.1 mm. Consequently, the number and distribution of the points used to calibrate each of the features of the phantom were determined using the simulation software. Specifically, the uncertainty software was used to perform experiments to find more efficient procedures to calibrate parts given a required uncertainty. That is, it would not be an efficient use of measurement and programming time to measure a large number of points on each surface if the required uncertainties do not warrant such effort. By using the simulation tool, sampling points can be increased or decreased and the measurement simulation performed to determine if the required level of accuracy is obtained. In fact, to obtain the required level of accuracy, only measurements of a circular feature on the cylindrical surface of the target hole are required. This greatly simplified the measurement programming and significantly reduces the measurement time.

7. CONCLUSION

We have described the methods, procedures and tool used to calibrate the critical dimensions of the NIST phantom artifact. Field-testing of the prototype phantom artifact has led to proposed refinements in the phantom artifact design. However, the methods and procedures described here may be used to develop a measurement strategy to calibrate future designs of this important artifact.

8. REFERENCES

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