# Robot Position Accuracy Report 

Project Number: 2014RB-006

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## Introduction

In order for us to perform accurate testing, we must establish relationships between the coordinate system of our robot and the world coordinate system. In addition, we need to know that when the robot is instructed to move to a certain position, that it actually went there. The first step is accomplished by using a motion analysis system to capture fixed points, thereby creating a world coordinate system. Then points on the robot may be digitized using the world coordinate system as a frame of reference. From this, the robot can move and know where it is in the world. In other words, given the coordinates of some point located on the robot, the robot can always know where that point is in the world coordinate system given the position command of how the robot is moved. However, errors can occur in which the robot may report that some point " $A$ " on its surface is located at some coordinate " $X$ " in the world, but the motion analysis system may report that that point " $A$ " is really located at some coordinate " $Y$ " in the world. This report covers the details of robot digitization and how certain methods of digitizing may affect the previously mentioned position error.

This position accuracy experiment can be broken into three parts: Defining a world coordinate system, robot digitization, and position accuracy validation. The techniques for each section will be discussed, as well as the final results generated by the position accuracy validation.

## Defining a World Coordinate System

A world coordinate system is created with the motion analysis software by capturing digitized points along two perpendicular axes with a motion position sensor. The third axis is created by taking the cross product of the two digitized axes. In order to more precisely define our world, we increased the distance (a) between our digitized points. In other words, the potential angle uncertainty in angle (c) between our desired axis and digitized axis decreases as the distance between the two digitized points defining the axis increases, given that the points are moved parallel to the desired axis (Fig. 1)

Fig. 1


The original distance between the origin and the $Z$ definition point was 100 mm . The new distance (a) for the z axis definition is 760 mm . The original distance between the origin and the YZ plane definition point was 735 mm . The new distance for the YZ plane definition is 1600 mm . When the motion tracking system is re-registered and aligned the origin and orientation must be redefined. These larger distances increase the robustness of the coordinate system definition and minimize potential errors that can occur from the robot/world relationship using previously collected spatial relationships.

## Robot Digitization

Once the world has been defined, a relationship must be established between the world and the robot. This is done by digitizing a fixed point on the robot as it moves through each of its degrees of freedom (i.e., $x, y, z$, roll, pitch, yaw, stage angle). However, a "by hand" digitizing method in which one person holds the probe and places its tip at the fixed point after each movement has proven to possess uncertainty that can add "noise" to the data. Placement-replacement experiments show that there is inconsistency in producing identical coordinates when digitizing a single point "by hand", and that this method is also operator-dependent. To overcome this problem, the digitizing probe was rigidly fastened to the robot, eliminating placement-replacement errors. Switching to this technique greatly reduced translational and rotational position errors between the robot and motion analysis system.

## Stage Digitization

Previous methods of digitizing the robot's stage called for digitizing fixed points around the stage's estimated center of rotation and fitting a cylinder to the cloud of points. This method generated large errors ( $\sim 2 \mathrm{~mm}$ ) when comparing the coordinates calculated by the robot and the coordinates captured
by the motion analysis system of a fixed point located on the stage after the stage had undergone some angle of rotation. These errors were minimized by adopting the same technique used to improve robot digitization. Instead of digitizing fixed points around an estimated center of rotation, the digitizing probe was rigidly strapped to the stage and points were collected as the stage moved through several angles of rotation, thereby eliminating placement-replacement errors of the digitizing probe as well as ensuring we had collected points around the stage's true axis of rotation. This technique created a much closer agreement in position between the robot and the motion analysis system.

## Position Accuracy Validation

Previously, position accuracy validation was performed by using the digitizing probe to capture the coordinates of a particular point on the robot as it moved about its axes. The accuracy of the system was evaluated by comparing the coordinates registered by the digitizing probe to the coordinates reported by the digitized robot of a common point. Digitizing the designated point by hand, of course, has been found to be unsuitable when position errors over 1 mm are considered to be significant. In order to overcome the inherent unrepeatability of obtaining similar coordinates when digitizing a single point "by hand", we rigidly fastened the digitizing probe to the robot (see Fig. 2) to ensure the probe was not being moved relative to the robot as the robot moved about its axes.

Fig. 2


| Mikrolar Robot |  |  |  |  |  |  |  | "Combined" robot |  |  |  |  |  | tip error |  |  | tip | notes |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $x \quad y$ | $y \quad z$ | 2 | $p$ | w | w | stage | holder | x | $y \quad z$ | z | $p$ | p | w x |  | $y$ | z | euclidean | error |  |
| 80.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | -0.001 | 0.000 | -0.931 | 79.996 | -0.050 | 0.000 | 0.001 | 0.000 | 0.102 | 0.016 | -0.100 | 0.144 |  |  |
| 80.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | -0.001 | 0.000 | -0.931 | 79.996 | -0.050 | 0.000 | 0.001 | 0.000 | 0.112 | 0.014 | -0.126 | 0.169 |  |  |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | -0.001 | 0.000 | -0.003 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.038 | -0.013 | -0.106 | 0.113 |  |  |
| -100.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | -0.001 | 0.000 | 1.156 | -99.993 | 0.062 | 0.000 | 0.001 | 0.000 | 0.013 | -0.074 | 0.022 | 0.078 |  |  |
| 100.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | -0.001 | 0.000 | -1.162 | 99.994 | -0.062 | 0.000 | 0.001 | 0.000 | 0.162 | 0.046 | -0.128 | 0.211 |  |  |
| 0.000 | 100.000 | 0.000 | 0.000 | 0.000 | 0.000 | -0.001 | 0.000 | -99.996 | -1.159 | 0.150 | 0.000 | 0.001 | 0.000 | 0.053 | -0.086 | -0.124 | 0.159 |  |  |
| 0.000 | -100.000 | 0.000 | 0.000 | 0.000 | 0.000 | -0.001 | 0.000 | 99.990 | 1.159 | -0.150 | 0.000 | 0.001 | 0.000 | -0.006 | 0.019 | 0.016 | 0.026 |  |  |
| 0.000 | 0.000 | $-100.000$ | 0.000 | 0.000 | 0.000 | -0.001 | 0.000 | -0.152 | -0.064 | -100.000 | 0.000 | 0.001 | 0.000 | 0.128 | 0.011 | 0.143 | 0.192 |  |  |
| 0.000 | 0.000 | 50.000 | 0.000 | 0.000 | 0.000 | -0.001 | 0.000 | 0.071 | 0.032 | 50.000 | 0.000 | 0.001 | 0.000 | -0.023 | -0.062 | -0.102 | 0.122 |  |  |
| 0.000 | 0.000 | 70.000 | 0.000 | 0.000 | 0.000 | -0.001 | 0.000 | 0.101 | 0.045 | 70.000 | 0.000 | 0.001 | 0.000 | -0.175 | 0.011 | -0.116 | 0.210 |  |  |
| 0.000 | 0.000 | 0.000 | 0.000 | 10.000 | 0.000 | -0.001 | 0.000 | -0.080 | 6.514 | -0.347 | -9.999 | -0.113 | 0.025 | -0.094 | -0.012 | 0.333 | 0.346 |  |  |
| 0.000 | 0.000 | -0.001 | 0.000 | 12.000 | 0.000 | -0.001 | 0.000 | -0.095 | 7.804 | -0.553 | -11.999 | -0.135 | 0.032 | -0.107 | 0.116 | 0.391 | 0.422 |  |  |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 15.000 | -0.001 | 0.000 | 0.331 | 0.051 | -0.001 | 0.023 | 0.008 | 15.000 | 0.133 | -0.010 | -0.183 | 0.227 |  |  |
| 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | -90.000 | -0.001 | 0.000 | -1.327 | 1.270 | 0.001 | -0.049 | -0.121 | -90.000 | 0.312 | -0.256 | -0.072 | 0.410 |  |  |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 90.000 | -0.001 | 0.000 | 1.265 | 1.323 | -0.003 | 0.122 | -0.048 | 90.000 | -0.152 | -0.155 | -0.114 | 0.246 |  |  |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 9.999 | 0.000 | 29.186 | 0.370 | 2.438 | 0.130 | -9.998 | -0.025 | 0.061 | 0.064 | -0.293 | 0.306 |  |  |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 15.000 | 0.000 | 43.511 | 0.549 | 5.555 | 0.199 | -14.998 | -0.047 | 0.005 | 0.067 | -0.291 | 0.298 |  |  |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 45.000 | 0.000 | 119.010 | 1.454 | 48.752 | 0.766 | -44.995 | -0.383 | -0.125 | 0.220 | -0.227 | 0.340 |  |  |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 60.000 | 0.000 | 145.850 | 1.749 | 83.449 | 1.349 | -59.990 | -0.871 | 0.216 | 0.295 | -0.496 | 0.616 | only 1 m | ker visible |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 70.000 | 0.000 | 158.334 | 1.871 | 109.948 | 2.166 | -69.985 | -1.628 N | N | NaN | NaN | NaN | No mar | s visible |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 64.999 | 0.000 | 152.670 | 1.818 | 96.424 | 1.680 | -64.988 | -1.172 | 0.363 | 0.224 | -0.524 | 0.676 | only 1 m | ker visible |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 60.000 | 0.000 | 145.850 | 1.749 | 83.449 | 1.349 | -59.990 | -0.871 | 0.217 | 0.301 | -0.486 | 0.612 | only 1 m | er visible |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 45.000 | 0.000 | 119.010 | 1.454 | 48.752 | 0.766 | -44.995 | -0.383 | -0.133 | 0.227 | -0.237 | 0.354 |  |  |
| 0.000 | 0.000 | 0.000 | 0.000 | 5.000 | 0.000 | 45.000 | 0.000 | 118.922 | 8.982 | 48.527 | -6.297 | -44.868 | 4.615 | -0.103 | -0.018 | -0.079 | 0.131 |  |  |
| 0.000 | 0.000 | 0.000 | 0.000 | 10.000 | 0.000 | 45.000 | 0.000 | 118.834 | 16.463 | 47.648 | -13.276 | -44.309 | 9.525 | 0.101 | 0.188 | -0.312 | 0.378 |  |  |
| 0.000 | 0.000 | 0.000 | 0.000 | 12.000 | 0.000 | 45.000 | 0.000 | 118.799 | 19.429 | 47.113 | -16.022 | -43.968 | 11.441 | 0.070 | 0.244 | -0.268 | 0.369 |  |  |
| 0.000 | 0.000 | -0.001 | 0.000 | -5.000 | 0.000 | 45.000 | 0.000 | 119.096 | -6.066 | 48.318 | 7.806 | -44.686 | -5.359 | -0.229 | 0.231 | -0.224 | 0.395 |  |  |
| 0.000 | 0.000 | -0.002 | 0.000 | -12.001 | 0.000 | 45.000 | 0.000 | 119.214 | -16.470 | 46.614 | 17.432 | -43.541 | -12.078 | -0.334 | 0.218 | -0.193 | 0.443 |  |  |
| 0.002 | 0.000 | 0.000 | 0.000 | -12.000 | -90.000 | 45.000 | 0.000 | -17.756 | -117.848 | 46.884 | 17.400 | -43.671 | -102.056 | 0.178 | 0.103 | 0.149 | 0.254 |  |  |
| 0.000 | 0.000 | -50.000 | 0.000 | -12.000 | -90.000 | 45.000 | 0.000 | -17.830 | -117.882 | -3.116 | 17.400 | -43.671 | -102.056 | 0.391 | 0.109 | 0.099 | 0.417 |  |  |
| 0.000 | 0.001 | -49.999 | 0.000 | -12.000 | -90.000 | 60.000 | 0.000 | -24.728 | -144.732 | 30.883 | 24.157 | -57.720 | -110.470 | -0.201 | 0.145 | 0.471 | 0.532 |  |  |
| 30.002 | 0.000 | -50.001 | 0.000 | -12.000 | -90.000 | 60.000 | 0.000 | -25.077 | -114.732 | 30.862 | 24.158 | -57.719 | -110.471 | 0.598 | 0.164 | -0.018 | 0.620 |  |  |
| -0.001 | 10.000 | -49.999 | 0.000 | -12.000 | -90.000 | 60.000 | 0.000 | -34.727 | -144.849 | 30.898 | 24.157 | -57.719 | -110.470 | -0.165 | 0.179 | 0.486 | 0.544 |  |  |
| 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | -90.000 | 60.000 | 0.000 | 0.493 | -144.407 | 83.758 | 1.254 | -60.113 | -90.789 | -0.192 | 0.154 | 0.330 | 0.412 |  |  |

0.329 RMS error (mm)

## Conclusion

The tests performed using the aforementioned techniques produced close agreement between the robot and the motion analysis system. These tests reveal a maximum position discrepancy of about 0.7 mm , with an RMS error of approximately 0.3 mm . When it is determined that the position accuracy between the robot and motion analysis system needs to be optimal, the robot should be digitized with the probe rigidly strapped to it. Applying this technique to the stage is also necessary to obtain the desired accuracy.

## Future Work

The digitization points for the alignment of the optotrak motion capture system were modified to increase the robustness of the coordinate system definition. Intuitively these will improve the results, but a future revision of this report needs to quantify the variability in 3 areas related to position measurement variables: place-replacement, multi-camera registration, and coordinate system alignment

