Introduction

Motion measurements were performed on the Stäubli RX160 robot per the specifications described in the SLAC statement of work (SOW) PS-391-000-86 on August 12th and 13th. The work was performed at the Stäubli Corporation North American Headquarters in Duncan, South Carolina. The following personal participated in the motion tests:

- Peter CARMAN, Square One System Design
- Roy CRETTOL, Stäubli Corporation
- David FRITZ, SLAC (LCLS)
- Mike GAYDOSH, SLAC (Metrology)
- Lisa MOSIER, Square One System Design
- Robert RULAND, SLAC (Metrology)

Setup

An installed base RX160 robot* was outfitted with the mock detector displayed in Fig. 1. The mock detector was constructed of stainless steel and had approximate dimensions of 200 mm x 200 mm x 150 mm with a mass of 25 kg. Three ball mounted hollow retroreflectors were mounted to the mock detector to be used as reference datums for the laser tracker. The mock detector was fixed to the RX160 wrist with four screws and a pin (see Fig. 2).

The position of the mock detector for the various tests described in this report was measured in two separate manners. For the first day of testing, a Keyence laser displacement sensor and level was used to measure the detector displacement along a single axis and detector roll respectively. This setup in displayed in Fig. 3. A Faro laser tracker, displayed in Fig. 4, was used on the second day to measure the 3-dimensional position of the L, M and R tooling balls mounted on the mock detector.

Position Repeatability Test

Five points, labeled 0 through 4, were programmed into the robot control system to perform the position repeatability test. The placement of the programmed points was chosen to gravity load the robot joints in numerous directions and to exceed the 1.4 meter distance specified in the SOW. Images of the programmed points are displayed in Figs. 5-9. A Cartesian coordinate system was defined at the 0 position such that the Y axis was aligned with gravity (vertical), the X axis along the L to R Ball direction and the Z axis normal to the mock detector face.

Three measurement sets were acquired on Day 1 with the Keyence sensor to independently measure the X, Y and Z repeatability of the robot. A single data set was acquired with the laser tracker on the second day. For both measurement sets, the 0 position of the mock detector was zeroed at the beginning of the data set acquisition and was not re-initialized within a data set. The robot was then commanded to move from position 0 to position 3 and then back to position 0 where the absolute location was then measured. The path taken to return the mock detector from position 3 to position 0 was varied by either taking the direct route or by traveling to the other points as an intermediate step.

Fig. 10 displays the raw data of the Keyence measurements. Data acquired from the laser tracker is plotted in Figs. 11 and 12. A statistical analysis was performed to calculate the standard deviation and mean position

*The robot that was used in the test was not calibrated.

for both data sets and the results are displayed in Table 1. In summary the Keyence measurements and laser tracker measurements, with the exception of the M ball measurements, yielded a positional precision of $\approx 30\,\mu$m and positioning accuracy of $\approx 20\,\mu$m. There is currently no explanation for the deviation of the M ball measurements.

Datum	σX	σY	σZ	$\bar{X}$	$\bar{Y}$	$\bar{Z}$
Keyence	29 μm	21 μm	14 μm	-22 μm	-1 μm	-16 μm
L Ball	37 μm	16 μm	18 μm	-26 μm	-6 μm	-19 μm
M Ball	66 μm	27 μm	36 μm	-92 μm	-45 μm	-66 μm
R Ball	29 μm	17 μm	16 μm	9 μm	-9 μm	8 μm

Table 1: Standard deviation and mean values of the position distribution for the position repeatability test measured with the Keyence displacement sensor and the laser tracker.

Stability Test

The stability test was performed by monitoring the static mock detector location at position 0 with the Keyence gauge. Measurements were continuously acquired for 30 minutes with a sampling rate of 1 Hz. Each axis was measured independently in separate acquisitions. The measurements are displayed in Fig. 13. The deviation from starting position never exceeded 6 μm. At this level of deviation it is difficult to evaluate the cause of drift since the temperature stability of the test facility was not known.

The Y and Z stability tests were repeated with higher sampling rates as the power to the robot motors was cycled. The purpose of these tests was to simulate the X-ray hutch entrance or egress of a experimenter. It is expected that an electrical signal that senses the hutch personnel protection state will be used to control power to the robot motors. The test results are plotted in Fig. 14. Position bumps, more prevalent in the Y direction, were evident upon motor power up. However, the position returned to the nominal value after a few seconds.

Path and Motion Center Test

The path and motion center test was performed with the laser tracker placed in proximity to the robot arm base ($\approx$ 1.25 m). The origin of the laser tracker was estimated and the robot was commanded to move to various points about that origin at a 0.5 m radius. The actual point of rotation was measured with the laser tracker and the offset from the tracker origin was used as input to the robot control software to adjust the point of rotation. After two iterations the point of rotation was measured to be (171 μm, 329 μm, 149 μm). The offset value could be improved with the following improvements:

1. Calibration of the robot.
2. Better knowledge of the tooling point location.
3. Larger solid angle range of the points measured by the laser tracker to improve the accuracy that the spherical motion origin can be determined.

Rotation Precision/Repeatability Test

The detector roll angle was measured during the position repeatability test for both the Keyence gauge tests, using the level, and the laser tracker test. For the laser tracker measurements, the detector roll was computed from the difference in Y measurements of the L and R tooling balls, and knowledge of the L and R separation.

The readings from the level are displayed in Fig. 15. There was a jump in the detector roll between data point 21 and 22 of the X-axis test. This was attributed to slop in the fasteners attaching the mock detector to the robot wrist, which was evident when some force was manually applied to the mock detector. A jump was not seen in the other data sets. The detector roll calculated from the laser tracker position stability test is plotted in Fig. 16. Neglecting the aberration observed in the Keyence X-axis test, the detector roll repeated to within 0.03^o.

The detector roll was also measured while the robot was commanded to move the detector to 10 different points on a 1 m sphere with various azimuth ($\pm 40^o$, $\pm 20^o$, 0^o) and elevation angles (0^o, 20^o). The results are plotted in Fig. 17. There appeared to be a systematic error in the measurement since a clear trend was evident in both data sets measured at the two elevations. The probable cause is error in the definition of the XZ plane when the robot coordinate system was defined. If this plane was sloped with respect to gravity a systematic error would occur. Additionally, calibration error of the robot could also lead to a systematic error since absolute positioning accuracy is important for this test[†].

Miscellaneous Topics

- The robot and laser tracker coordinate systems were correlated upon installation of the tracker. This was accomplished by moving the robot to 3 locations and measuring the position with the tracker. This provided enough information to solve the transformation matrix between the two coordinate systems. However, the tracker measured robot position was off by $\approx$ 1 mm when the robot was commanded to move to a 4th point. The likely cause of this error is lack of knowledge of the programmed tooling point and absolute positioning errors of the robot. It was assumed that the tooling point was at the joint 6 (wrist) center of rotation, displaced by a $\approx$ 150 mm offset which was measured with a scale. This is where the M ball was supposed to be centered. However, there is certainly error in the measurement of the offset on the order of 1 mm. Additionally, the M ball was displaced by 0.25 mm from the center of rotation. This was measured by tracking the M ball as joint 6 was rotated. The other major contribution to the error, absolute positioning accuracy, could be significantly enhanced if the robot was calibrated.
- Cabling to the detector must be routed outside of the robot. There are some cables and pneumatic lines built into the robot arm but these are not appropriate for water, data or control lines to the detector.

[†] The detector was not leveled at each point on the sphere and thus the robot was not appropriately trained. Thus, the absolute positioning accuracy of the robot contributes to the measurements.

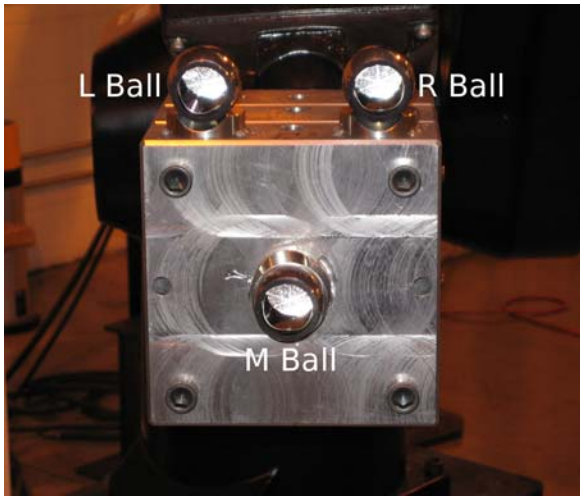
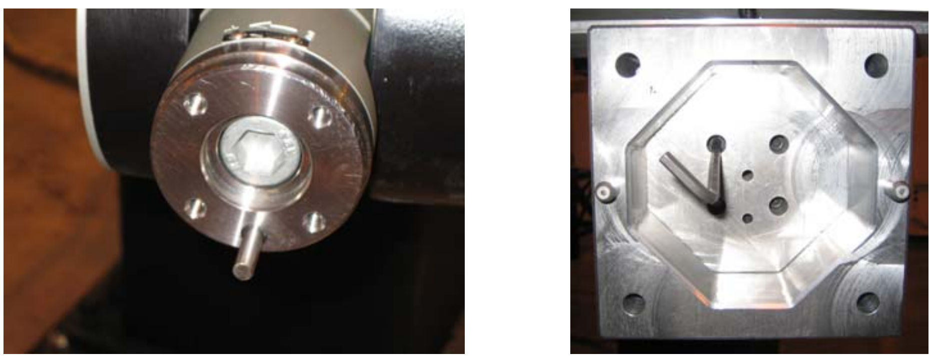
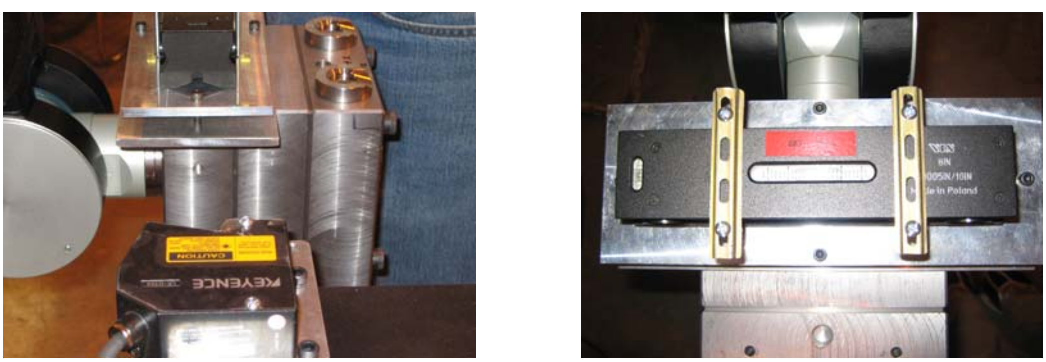


Figure 1: Picture of the mock detector and tooling ball datums.



(a) (b)

Figure 2: Image of the RX160 wrist and the mock detector mounting hardware.



(a) (b)

Figure 3: Image of the (a) keyence displacement sensor measuring along the X axis and (b) level used to measure the mock detector roll.

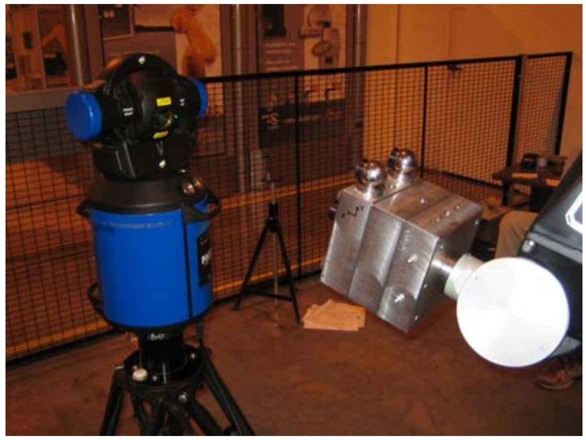


Figure 4: Image of the laser tracker setup.

(a) (b)

Figure 5: Detector position 0 front (a) and side (b) view.

(a) (b)

Figure 6: Detector position 1 front (a) and side (b) view.

(a) (b)

Figure 7: Detector position 2 front (a) and side (b) view.

(a) (b)

Figure 8: Detector position 3 front (a) and side (b) view.

(a) (b)

Figure 9: Detector position 4 front (a) and side (b) view.

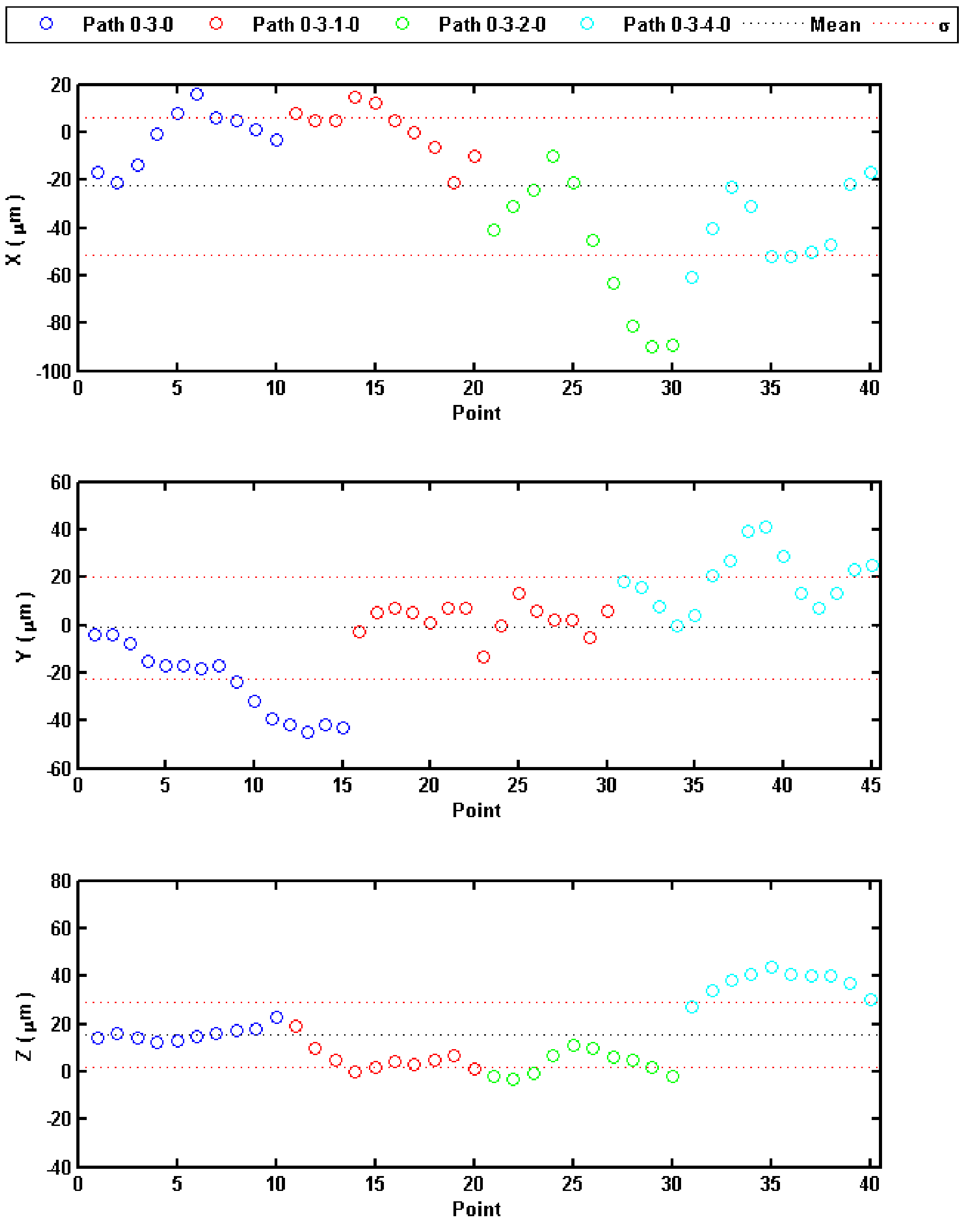


Figure 10: Position of the mock detector datums in measured with the keyence laser gauge along the X, Y and Z axis. The black dotted line represents the mean value and the red dotted lines represent one standard deviation from the mean. The color of the points represent various commanded paths.

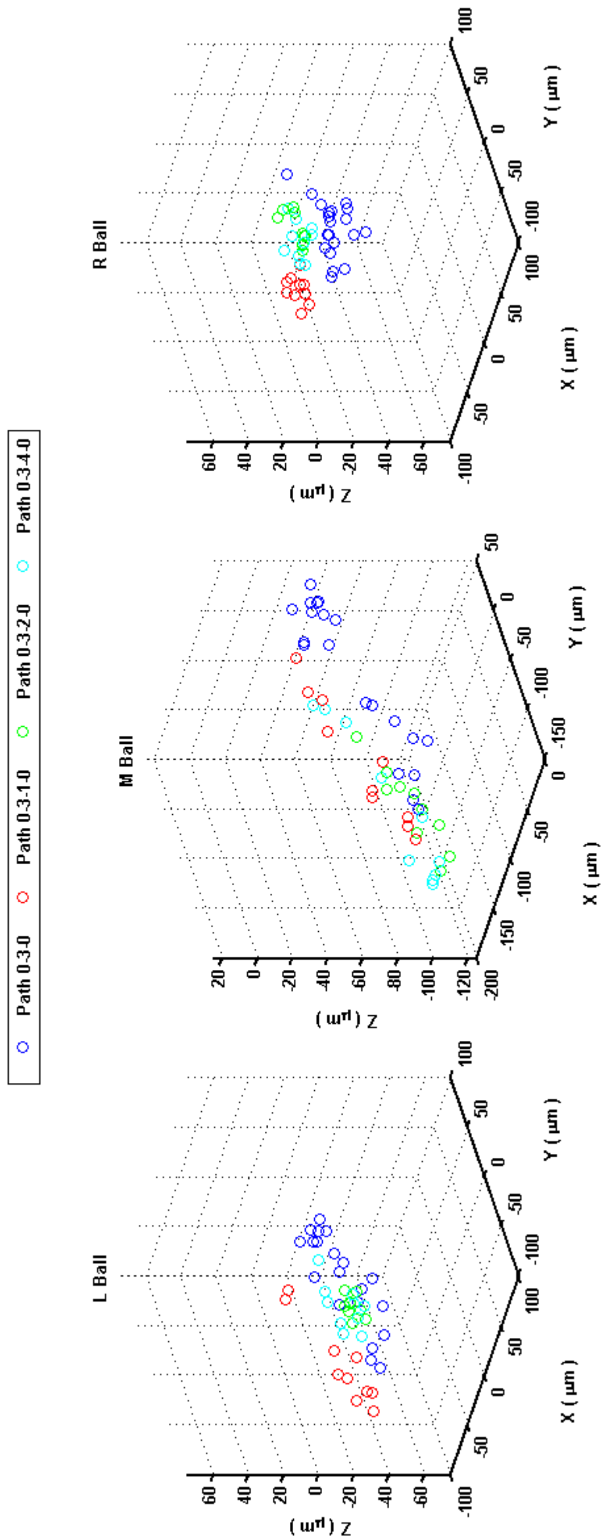


Figure 11: Position of the mock detector datums measured with the laser tracker for 50 measurements. The color of the points represent various commanded paths.

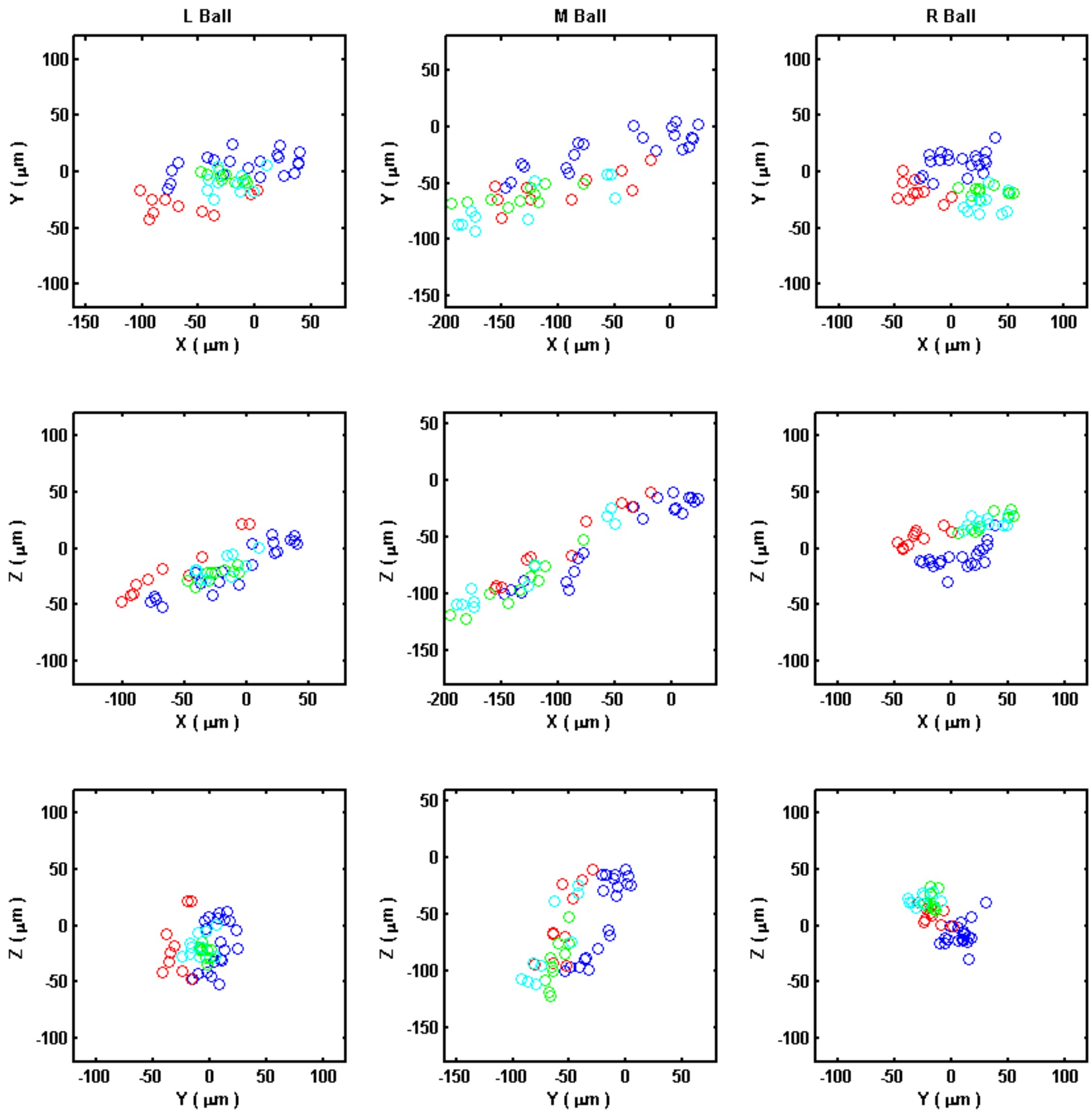


Figure 12: Position of the mock detector datums in XY, XZ and YZ coordinate plane measured with the laser tracker. The color code is identical to that of Fig. 11.

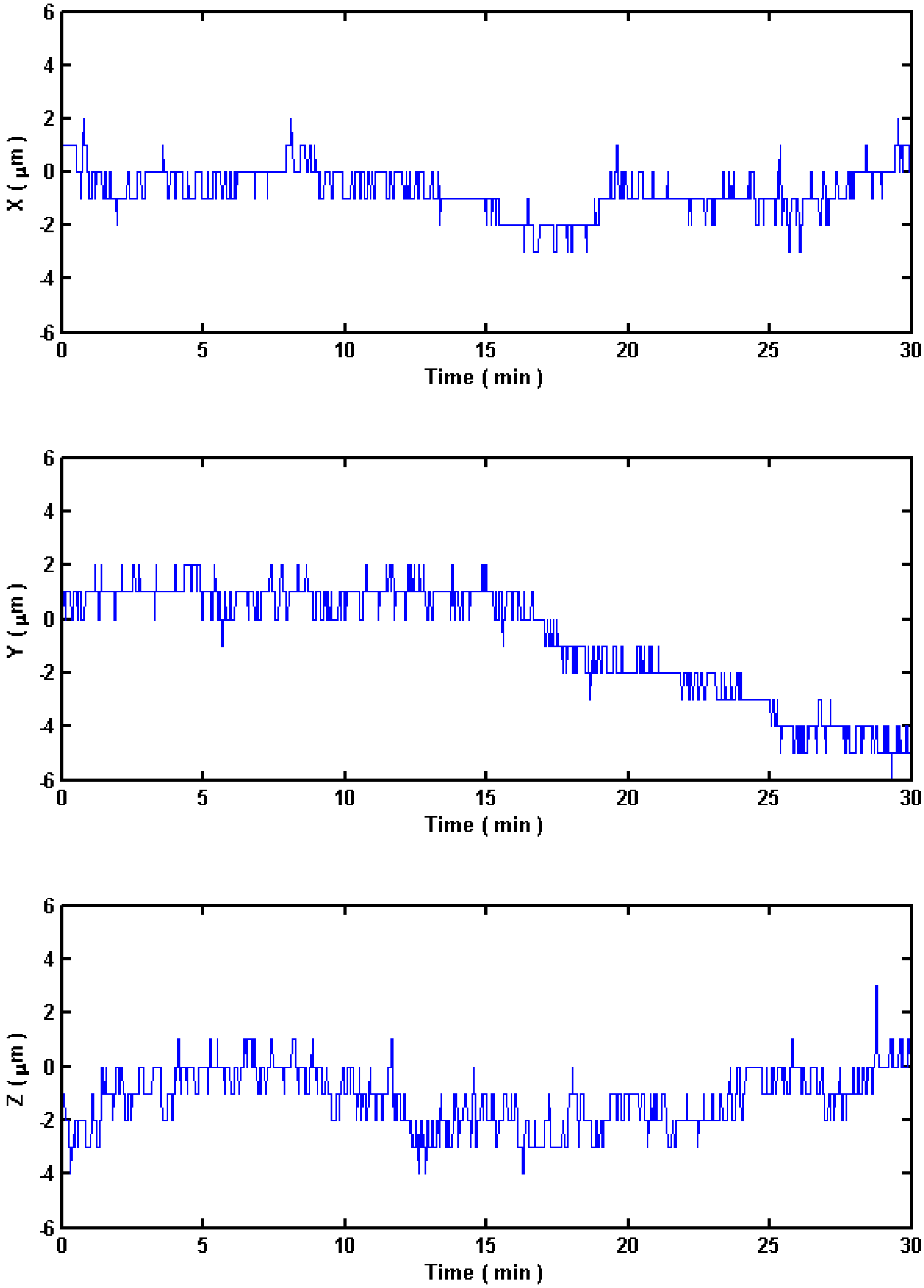
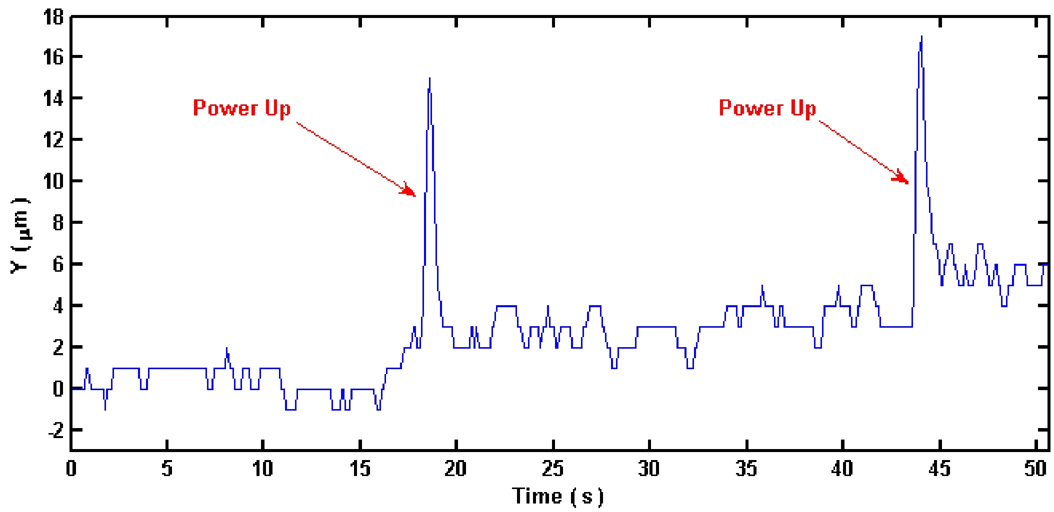


Figure 13: X, Y and Z position of the mock detector as a function of time. The measurements were acquired during separate acquisitions with the keyence gauge.



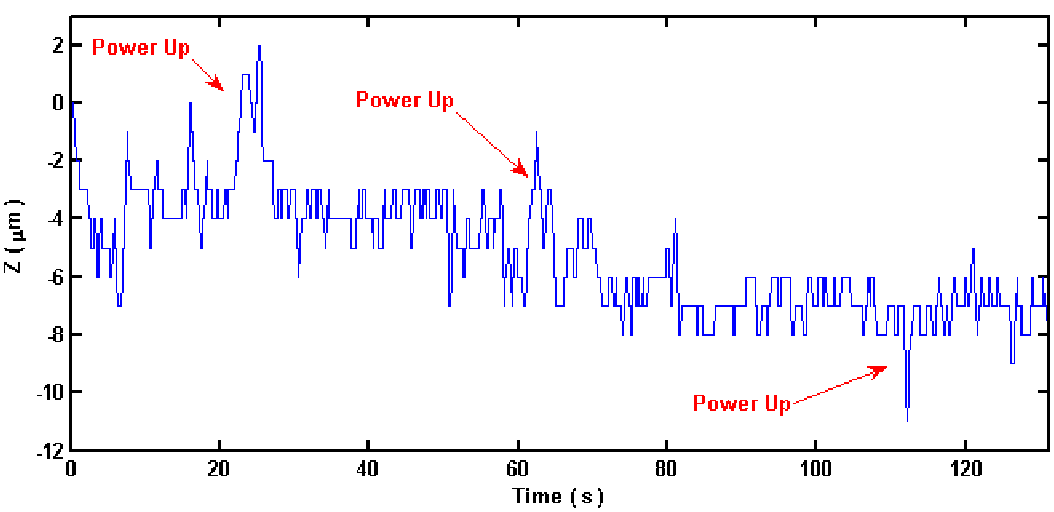


Figure 14: Y and Z position of the mock detector as a function of time. The power to the robot motors was turned off at the marked times. The measurements were acquired with the keyence gauge.

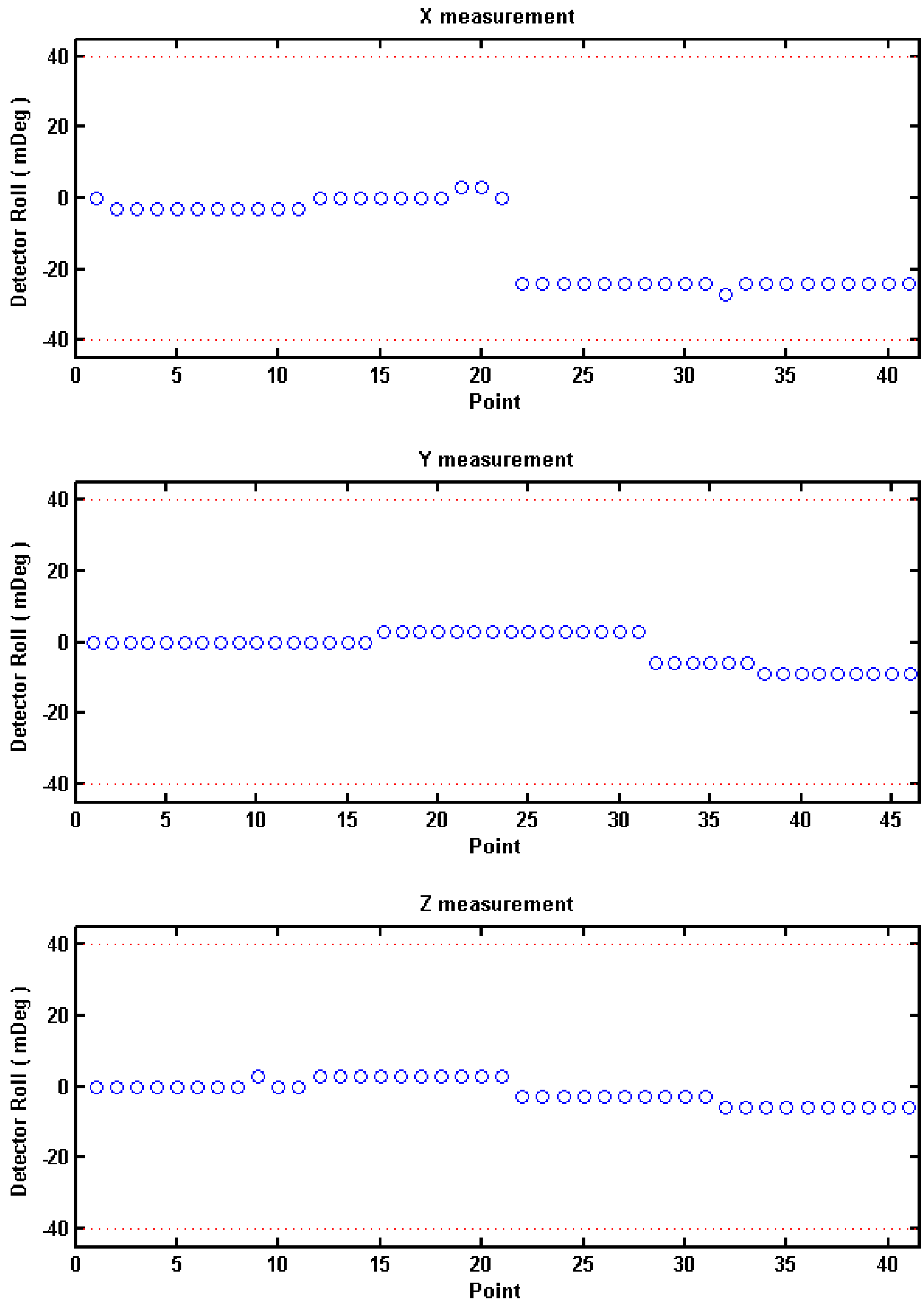


Figure 15: Mock detector roll repeatability measured from readings of the level during the X, Y and Z keyence gauge tests respectively.

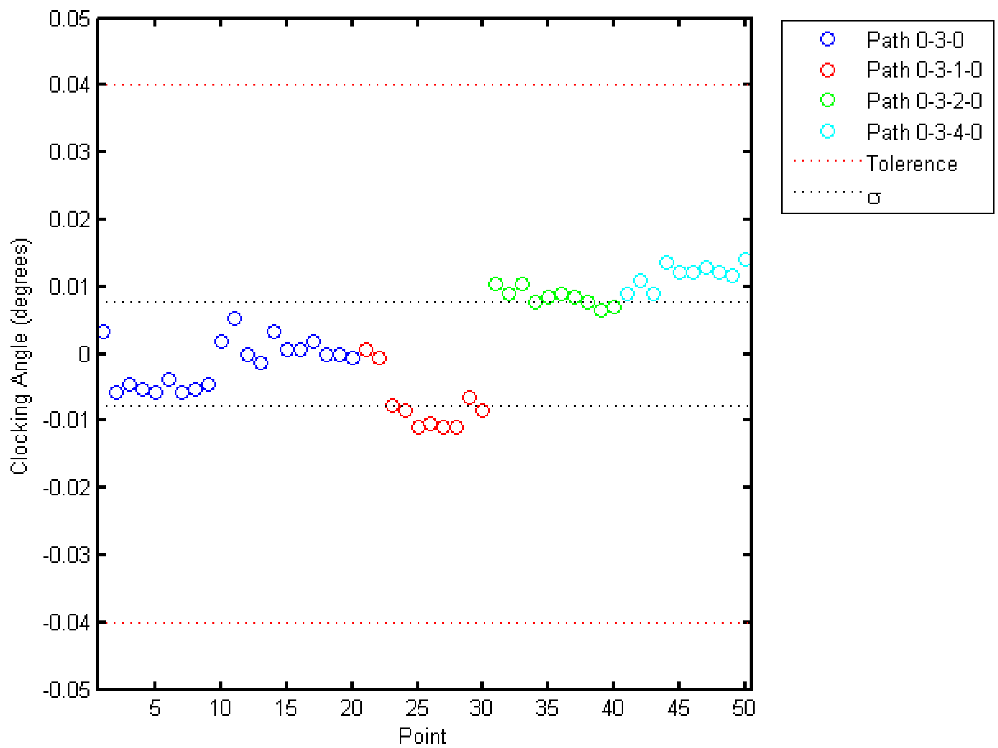


Figure 16: Mock detector roll repeatability calculated from the same laser tracker data set for the position repeatability test.

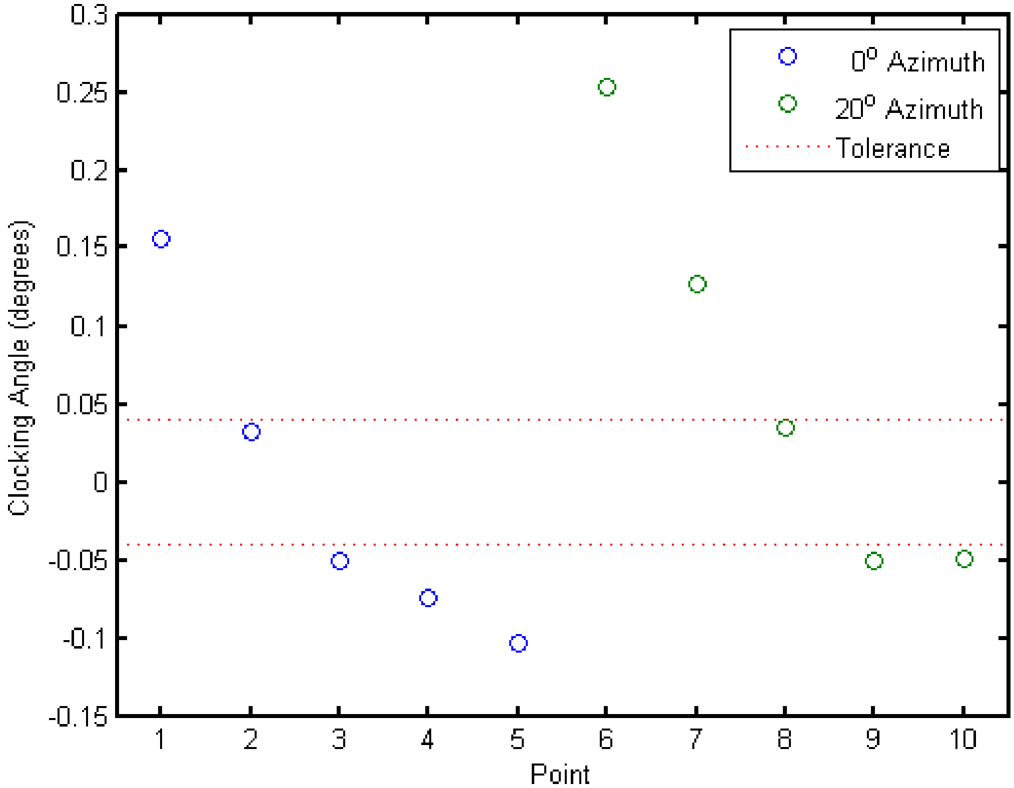


Figure 17: Mock detector roll measured at 10 azimuth and elevation locations. The red dashed line represents the tolerance requirement for the XPP detector mover. The deviation from the allowable tolerance is likely a systematic error due to the programmed definition of the detector motion coordinate system and calibration of the robot.