PERFORMANCE EVALUATION OF A LASER TRACKER HAND HELD TOUCH PROBE

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INTRODUCTION

Hand held touch probes and laser scanners are increasing the scope and applicability of laser trackers. While methods to evaluate the performance of laser trackers in conjunction with spherically mounted retroreflectors (SMRs) are well established, methods for evaluating the performance of hand held probes [1-2] are still under discussion within ISO 10360-10. We discuss the performance of a hand held touch probe in this paper. Single point articulation tests (SPATs) are commonly employed both to calibrate and to test these devices. We have modeled a hand held touch probe and subsequently performed simulations to understand the influence of different error parameters on measured coordinates in two different configurations of SPATs. The overall objective is to develop detailed uncertainty budgets for measurements made using the hand held touch probe. We present preliminary simulation and experimental results here as a first step towards realizing that objective.

THE HAND HELD TOUCH PROBE

There are several designs of hand held touch probes in the market. A schematic of the hand held touch probe under evaluation is shown in Fig. 1. The laser tracker measures the position of the retroreflector located in the hand held touch probe. An orifice at the apex *o* of the retroreflector allows a portion of the laser beam to travel further onto a charge-coupled device (CCD). The position of the laser spot on the CCD determines the pitch angle β (rotation about the y axis of the hand held touch probe) and yaw angle γ (rotation about the z axis). Roll angle α (rotation about the *x* axis) is determined by a gravity sensor. The link lengths *a* (along the *x* axis), *b* (along the *y* axis, not shown in the figure because it is nominally zero in this configuration), and *c* (along the *z* axis) are determined through a calibration procedure performed prior to measurement. Using the three measured angles and three link lengths, the coordinates of the stylus tip *P* can be determined through a geometric transformation. The hand held touch probe also has a separate yaw joint. While we use this yaw joint to orient the retroreflector towards the tracker between the different SPATs, we have not exercised the yaw joint during a SPAT; we therefore do not consider this in our model. Simulations and experiments were performed using the horizontal stylus only.

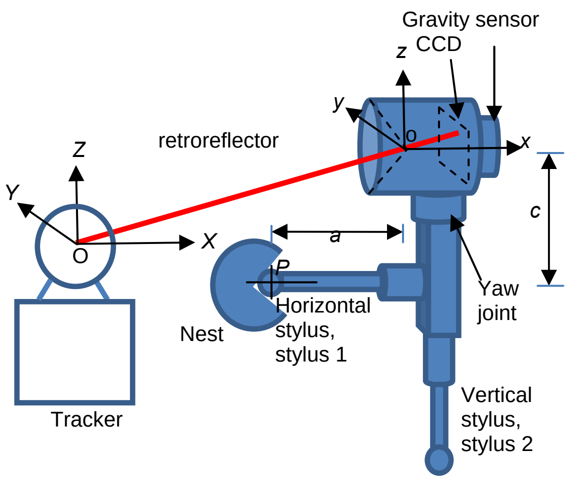

FIGURE 1. Schematic of the hand held touch probe

COORDINATE SYSTEMS

We define two coordinate systems, one on the tracker (*XYZ*) and another on the hand held touch probe (*xyz*). The origin of the coordinate system on the hand held touch probe is located at the apex of the retroreflector. The *x* axis is normal to the plane of the CCD while the *z* axis is parallel to the long handle of the hand held touch probe as shown in Fig. 1. Let the position of the retroreflector as recorded by the tracker in spherical coordinates be (*R*, *H*, *V*). In order to determine the coordinates of the stylus tip *P* in the laser tracker coordinate system, we employ the following sequence of translations and rotations.

Let the retroreflector of the hand held touch probe first be located at (*R*, 0, 0) as shown in Fig. 2(a). Let the orientation of the hand held touch probe be such that roll, pitch, and yaw angles are zero at this position. The stylus tip coordinate is known in the tracker frame at this position and is given by (*R*-*a*, -*b*, -*c*). The hand held touch probe is then rotated by an angle *V* about the *Y* axis and then by an angle *H* about the *Z* axis to the position shown in Fig. 2(b). The hand held touch probe is then rotated about *its x* axis by the roll angle (Fig. 2(c)) and subsequently about *its y* axis by the pitch angle (Fig. 2(d)) and then about *its z* axis by the yaw angle (not shown in Fig. 2). The resulting coordinate for the stylus tip is the desired coordinate in the laser tracker coordinate system.

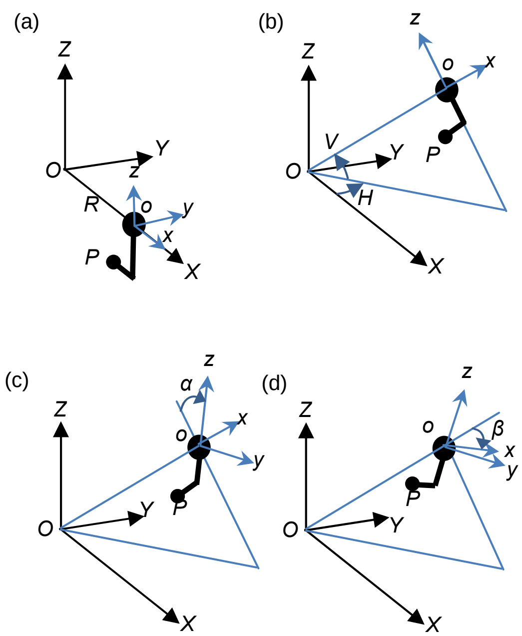

FIGURE 2. Transformations to calculate stylus tip coordinate in laser tracker frame (a) retroreflector located at (R, 0, 0) with hand held touch probe oriented such that there is no roll, pitch, or yaw, (b) hand held touch probe rotated about Y axis by angle V and then about the Z axis by angle H, (c) hand held touch probe rotated about its x axis by the roll angle, (d) hand held touch probe rotated about its y axis by the pitch angle

Single point articulation tests

Two configurations of SPATs are considered in this study; they are shown in Fig. 3. In each case, with the stylus tip located in the nest so that the center of the stylus tip remains in the same position during articulation, the hand held touch probe is rotated about each of the three axes to the extent possible, which is ±30° for the pitch and yaw axes and ±60° for the roll axis. While the hand held touch probe itself is capable of 360° along the roll axis, physical limitations in the test setup only allowed for ±60° in that axis. The nominal values for link lengths *a*, *b*, and *c* are 85 mm, 0, and 85 mm respectively for SPAT #1, similar to the horizontal configuration shown in Fig. 1 and in Fig. 3(a), and 85 mm, 40 mm, and 85 mm respectively for SPAT #2 as shown in Fig. 3(b). The nest was located about 2 m from the laser tracker.

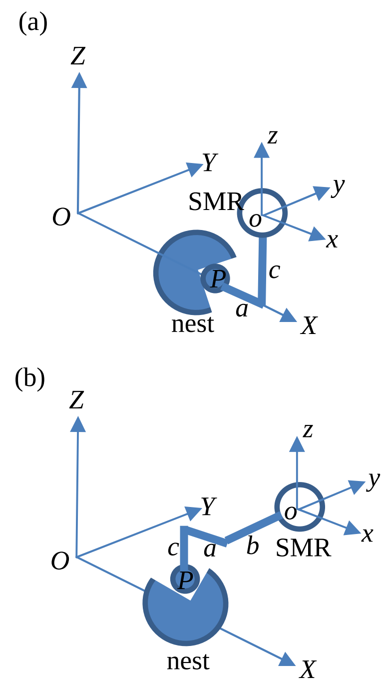

FIGURE 3. Two configurations of SPATs shown (a) SPAT #1 (a = 85 mm, b = 0, c = 85 mm) and (b) SPAT #2 (a = 85 mm, b = 40 mm, c = 85 mm)

Errors in the link lengths and in the measured angles produce errors in the measured coordinates. In order to determine reasonable values for the parameters to be used as input to the simulations, two different experiments were performed. First, the manufacturer suggested calibration procedure was performed several times to determine the one standard deviation repeatability in the link lengths. This procedure involves performing a SPAT while exercising the yaw joint between the different orientations of the hand held touch probe. The manufacturer's software considers the different stylus tip coordinates obtained during the SPAT and the laser tracker's determination of the nest coordinate obtained using an SMR to evaluate the link lengths. Multiple such calibrations resulted in link length repeatability on the order of 10 µm. Although it is possible there are other sources of systematic error that will result in a larger uncertainty in the link lengths, the one standard deviation repeatability of 10 µm is considered as the standard uncertainty in each of the three link lengths *a*, *b*, and *c*, and propagated to the stylus tip in the simulations.

In order to estimate the uncertainty in the roll, pitch, and yaw angles, the hand held touch probe was mounted on a precision air bearing rotary table and the yaw angle of the hand held touch probe was compared against the encoder readings of the rotary table. That experiment indicated a yaw angle error on the order of 1 mrad, which is considered as the uncertainty in each of the three angles, and propagated to the stylus tip in the simulations. It should be noted that the roll angle is a coarser measurement in comparison to pitch and yaw; at this time, we have not quantified the errors associated with the roll angle and therefore simply use the same value as obtained for yaw.

Results and discussion

As mentioned in the previous section, the purpose of the simulations is to understand the influence of errors in each of the six input parameters on the stylus tip coordinate for the two different SPATs. A SPAT can be performed in either the absolute mode or in the relative mode. In the absolute mode, the coordinates of the stylus tip for the various orientations in a SPAT are compared to the coordinate as measured using an SMR mounted on the nest. In the relative mode, the coordinates of the stylus tip for the various orientations in a SPAT are compared against each other.

The stylus tip size in our hand held touch probe was 6 mm in diameter. The SPAT is typically performed using a manufacturer provided nest that has a conical seat in a 1.5 in spherical shell. When the stylus tip is located in the conical seat, the center of the tip is ideally also the center of the spherical shell, and the coordinate of that point can be determined using a 1.5 in SMR. In some situations, it may not be physically possible to measure the coordinate of the nest using an SMR and therefore relative SPATs are sometimes performed.

TABLE 1. Simulation results for SPAT #1 analyzed in absolute mode and in relative mode. All units in millimeters.

	SPAT #1 in absolute mode									SPAT #1 in relative mode								
	Roll test			Pitch test			Yaw test			Roll test			Pitch test			Yaw test		
	X	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
a	0.01	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00
b	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00
c	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00
α	0.00	0.08	0.07	0.00	0.11	0.00	0.00	0.08	0.04	0.00	0.02	0.07	0.00	0.05	0.00	0.00	0.00	0.04
β	0.08	0.07	0.09	0.12	0.00	0.12	0.08	0.00	0.09	0.00	0.07	0.03	0.05	0.00	0.05	0.00	0.00	0.01
γ	0.00	0.08	0.07	0.00	0.08	0.00	0.04	0.08	0.00	0.00	0.03	0.07	0.00	0.00	0.00	0.04	0.01	0.00

TABLE 2. Simulation results for SPAT #2 analyzed in absolute mode and in relative mode. All units in millimeters.

	SPAT #2 in absolute mode									SPAT #2 in relative mode								
	Roll test			Pitch test			Yaw test			Roll test			Pitch test			Yaw test		
	X	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
a	0.01	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00
b	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00
c	0.00	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00
α	0.00	0.10	0.10	0.00	0.12	0.04	0.00	0.09	0.08	0.00	0.06	0.09	0.00	0.05	0.00	0.00	0.00	0.05
β	0.09	0.07	0.08	0.12	0.00	0.12	0.09	0.00	0.09	0.00	0.07	0.03	0.05	0.00	0.05	0.00	0.00	0.03
γ	0.04	0.09	0.07	0.04	0.09	0.02	0.08	0.09	0.00	0.00	0.03	0.07	0.00	0.00	0.02	0.05	0.03	0.00

The results of the simulations for the two SPATs are shown in Tables 1 and 2. Each of the SPATs are comprised of three tests – a roll test, a pitch test, and a yaw test. Each of these three tests involves probing the nest by rotating the hand held touch probe along one of the three axes. The tables show the *maximum absolute error* in stylus tip along the *X*, *Y*, and *Z* axis for each of these three simulated tests. Each row in the table corresponds to stylus tip error in the presence of an error in one of the six input parameters (a 10 µm error in *a*, *b*, or *c*, or a 1 mrad error in α, β, or γ). The data are analyzed in absolute mode and again in relative mode.

Tables 1 & 2 show that unit errors in the link length reflect as unit errors in one or more of the coordinates; that is, there is no amplification of the errors as expected. Angular errors, however, depend on the Abbe offset and can produce large point coordinate errors. A pitch of 1 mrad, for example, produces a 0.12 mm error along *X* and *Z* for both SPAT configurations in absolute mode for the hand held touch probe under consideration. Those errors drop to 0.05 mm in relative mode, indicating that the relative mode of analysis may attenuate the effect of certain error sources.

There are additional interesting observations that can be made from these tables. A roll test is not necessarily the most sensitive test to detect an error in the roll angle α. In fact, the *Y* coordinate in a pitch test is more sensitive to error in the roll angle for the hand held touch probe under consideration. While a pitch test is sensitive to pitch angle errors, yaw angle errors can be captured in any of roll, pitch, or yaw tests. In addition, it can be seen that Tables 1 and 2 are nearly identical indicating that the *Y* offset of 40 mm in SPAT #2 did not produce a noticeable amplification of angular errors in comparison to SPAT #1.

Table 3 shows the experimentally obtained maximum absolute errors along the three axes for the roll, pitch, and yaw test for the two configurations of SPATs. The experiments were repeated three times; the absolute maximum errors from all three repeats are shown in the table. The data for these tests were analyzed in relative mode because the nest used to acquire data was a three-pronged seat for a 6 mm tip that could not seat an SMR. The experimentally observed errors are fairly small, with the largest error on the order of 0.06 mm. It can be seen that the results obtained from simulations (right half of Tables 1 and 2 that show SPAT results based on relative mode of analysis) are also on the order of about 0.07 mm, indicating that the values of input parameters used in the simulations are reasonable. However, as mentioned earlier, we do note that it is possible that the relative mode of analysis has suppressed the effect of certain error sources and therefore the hand held probe may possess error sources that have not been revealed. We plan on performing these tests again in absolute mode in the future.

TABLE 3. Experimentally obtained SPAT errors in millimeters. Data analyzed in relative mode.

	SPAT #1		
	X	Y	Z
Roll test	0.03	0.05	0.02
Pitch test	0.04	0.03	0.03
Yaw test	0.04	0.06	0.06
	SPAT #2		
	X	Y	Z
Roll test	0.03	0.03	0.02
Pitch test	0.04	0.03	0.02
Yaw test	0.03	0.06	0.02

CONCLUSIONS

SPATs are commonly employed to calibrate and evaluate the performance of hand held touch probe accessories of laser trackers. We describe a model based approach to understand the influence of different parameters on stylus tip errors for different configurations of SPATs. As future work, we plan on refining the model and determining more suitable values for input parameters of the simulation, such as better estimates for roll angle errors. We also plan on performing absolute SPATs and length tests along sensitive directions. Characterizing error sources is critical towards developing test procedures that are sensitive to the different error sources.

REFERENCES

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