DYNAMIC MONITORING OF DEFORMING STRUCTURES : GPS VERSUS ROBOTIC TACHEOMETRY SYSTEMS

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Abstract

The Global Positioning System has been the leading technology for monitoring the movements of points at high data rates (i.e. 1 Hz). Areas of application include the monitoring of operating cranes, bridge and building vibration studies, and the dynamic alignment of structures during construction. In recent years, robotic tacheometry ("total station") systems have been developed that can track moving points and make observations of angles and distances at rates up to 1 Hz. This paper compares the accuracy and utility of robotic tacheometry systems to that of GPS.

Several issues are uncovered that currently limit the practical use of robotic tacheometry systems in kinematic positioning. The two main problems are a) low EDMI accuracy, which is directly correlated to station velocity along the line-of-sight, b) uneven sampling over time and the lack of observation time-tagging. However, it is also noted that robotic tacheometry systems have the advantage in stop-and-go applications, where they are capable of millimetre level accuracy, compared to centimetre level results when using GPS.

1. Introduction

There exist many situations in which the three-dimensional co-ordinates of a moving object are required to a high-level of accuracy and at a high data rate. Typical applications include studies of bridges and buildings under load, monitoring cranes in operation for deflections and aligning large machinery during construction. In such applications, simultaneous positioning of several points at the sub-centimetre level may be required at data rates of 1 Hz or more.

Over the last decade, the Global Positioning System (GPS) has emerged as the technology of choice in such monitoring applications. In particular, GPS has the advantages of high data acquisition rate (typically up to 10 Hz) and autonomous operation. Also, using differential techniques and the appropriate equipment, it can furnish position estimates in real-time with centimetre-level accuracy. However, the disadvantage of GPS is that it requires a line-of-sight from the monitoring receivers to the transmitting satellites and thus performs poorly in urban and forested areas, and not at all indoors. Thus, there are many application areas where GPS is not an option, such as monitoring the travel of indoor cranes

In recent years, robotic tacheometeric systems (RTS) have been developed which can track a moving target and make automatic measurements of angles and distances to the target in motion. These instruments can make measurements at data rates up to 1 Hz and can operate autonomously once "lock" to the target has been manually set by an operator. As a result, a study was conducted to gauge the suitability of RTS for monitoring of moving objects, with a view to its application in indoor tracking applications. This paper presents a comparison of the performance of RTS and GPS in tracking an object travelling in a known trajectory and underlines some of the difficulties encountered in applying RTS to dynamic monitoring.

2.0 "Stop-and-Go" Accuracy of RTS versus GPS

The first experiment performed was to gauge the "stop-and-go" accuracy of an RTS to that of GPS. The RTS used was a Leica TCA 2003 equipped with a 360^o prism which allows tracking of the target in any orientation. The GPS receivers used were two Trimble 4700 receivers. One acted as the base receiver and the other as a remote, thus allowing differential-mode operation. All GPS data collected was processed by GravNav^{TM}, which is capable of resolving carrier-phase ambiguities on-the-fly.

The prism and remote receiver were mounted at either ends of a 1.5m bar, which was in turn mounted on a table such that it rotated horizontally about a central axle. This constrained the two target points to a circular trajectory in a fixed plane as the bar was spun. The base station GPS receiver was set up a few metres away and its co-ordinates were determined in a separate GPS survey. The setup is shown in figure 2.

Figure 1. Experimental Setup

"Stop-and-go" refers to a measurement scheme whereby a moving point is tracked as it moves, but measurements of interest are only made when the point is stationary for a certain length of time (i.e. a few seconds). A typical example of this is the case of an operating crane, where one wishes to study the respective deflections of the structure under load and with load removed but one is unconcerned about the position of the crane when it is actually moving.

To simulate such a scenario, the targeted bar was rotated to eight equally spaced rotation angles and left stationary for 10 seconds at each position. This resulted in eight static position estimates from GPS and RTS which could then be separately used to determine the parameters of a best fit circle. The deviations of the position estimates from the best-fit circle yielded an estimate of the positioning accuracy of the particular system used.

Two standoff distances were used for the TCA, 7.2 metres and 77.7 metres, thus allowing a comparison of the accuracy of the tacheometer at close and medium range distances. As well, the experiment was conducted using each of the two tracking measuring modes available on the TCA, regular and rapid, to investigate the effects of these modes on the measurement accuracy.

For both the GPS and the TCA, data was collected at 1 Hz and a sample of ten data points were averaged to represent each static portion. An estimate of the *repeatability* of the two measurement systems is then possible by examining the scatter of the individual epoch estimates about their mean. Table 1 shows the average repeatability for the GPS data and the four TCA data sets. Note that the TCA angular repeatabilities are also shown in distance units for purposes of comparison.

As expected, the repeatability of the distance measurements decreases as the standoff distance increases, but surprisingly, the rapid track mode of measurement shows slightly better repeatabilities than the standard track mode. However, the technical specifications for the TCA state a distance measurement accuracy of 3 mm and 5 mm for the regular and rapid modes, respectively. As a result, one can conclude that repeated distance measurements must be highly correlated to one another, thus resulting in high repeatability, but lower overall accuracy. In the case of angular measurements, a similar problem exists since although the specified accuracy of the instrument is 0.5”, horizontally and vertically, the use of the 360^o prism degrades the accuracy to the 5 mm level (Leica, 1998). This is clearly much greater than the observed repeatability.

Finally, note that the repeatability of the GPS is at the few millimetre level. On baselines of short length, the dominant error source is multipath, which can induce position errors of up to several centimetres. In addition, multipath is highly correlated over a period of minutes and as a result, the repeatabilities reported here are not indicative of the true accuracy of the GPS data, which is at the centimetre level (Radovanovic et al, 1999).

Table 1. Average Repeatabilities (1σ) of TCA and GPS measurements.

	TCA (standoff distance / mode)					**GPS**
	Near / Reg	*Near / Rap*	*Far / Reg*	*Far / Rap*		
Horizontal (“ : mm)	0.8 : 0.03	0.9 : 0.04	0.9 : 0.34	1.1 : :0.37	**North (mm)**	1.5
Vertical (“ : mm)	1.2 : 0.04	1.1 : 0.04	1.0 : 0.34	1.2 : 0.41	**East (mm)**	1.2
Distance (mm)	0.6	0.4	0.7	0.5	**Height (mm)**	1.8

As discussed above, the repeatability of the measurements is not indicative of the true accuracy of the position estimates. To estimate and compare the accuracy of the TCA and GPS, the averaged static position estimates for the 4 TCA sets and 1 GPS set of eight points each were used to determine the parameters of a best-fit circle. This resulted in five solved parameters – the three dimensional position of the centre of the circle, the circle radius and the inclination of the circle in two directions. For all data sets, the solved parameters were identical to within their apostori variance factors.

Once the parameters of the best-fit circle had been solved, the standard deviations of the residuals were calculated. These represent the deviations of the static position estimates form the best-fit circle. The average standard deviations for each data set are shown in table 2. Note that these are the standard deviations for the *averaged* static positions and not a representation of the epoch-to-epoch accuracy, which would be worse.

In all cases, the standard deviations of the TCA-determined positions are lower than that achievable with GPS. As well, the vertical standard deviations are greater in all tests. In the case of GPS, this is a well-known phenomena due to poor the positioning geometry of the receiver with respect to the overhead satellites (Hofmann-Wellenhoff et al, 1997). In the case of the TCA results, the authors believe that this is a result of imperfections in the table surface, which mean that the true trajectory of the target is not in a fixed plane. While this greatly affects the vertical results, such deviations would not affect the horizontal positions greatly. Thus, the horizontal standard deviations will be considered representative of positioning accuracies achievable by the TCA.

Table 2. Average Standard Deviations of “Stop-and-Go” Positions using 10 second Averaging Interval and 1 Hz Data Rate.

	TCA (standoff distance / mode)				**GPS**
	Near / Reg	*Near / Rapid*	*Far / Reg*	*Far / Rapid*	
North (mm)	1.4	1.0	0.2	0.5	1.9
East (mm)	1.4	0.8	0.5	0.6	1.7
Height (mm)	1.8	1.9	2.1	1.6	5.5
Total (mm)	2.7	2.3	2.2	1.8	6.1

Two surprising results of this test are that the accuracy of the TCA actually improves as the standoff distance increases, and that the rapid mode results show improved accuracy at short range. One can account for the improved accuracy at longer range by considering that the minimum recommended standoff distance for automatic measurement is 20 metres. Thus the TCA has difficulty correctly measuring the angle to the target at short distances. This is further aggravated by the use of the 360^{o} prism, which degrades the angular measurement significantly. Of course, as the standoff distance grows beyond some limit, the distance measurement errors will begin to predominate. However, why the rapid tracking mode is more accurate at short distances remains to be investigated further.

3.0 Kinematic Accuracy of RTS versus GPS

A true dynamic monitoring system must be able to determine the position of a target in motion. To test the capabilities of the TCA in kinematic mode, the authors manually rotated the targeted bar, attempting to keep a fairly constant rate of rotation. Once again, the two modes of the TCA were tested and GPS data was collected throughout the test at 10 Hz. The standoff distance of the TCA was kept short, at 7.2 metres. This allowed for large transverse angular velocities at the instrument, which tested the tracking capabilities of the TCA.

The data collected was used to calculate epoch-by-epoch target positions. Furthermore, by using the solved parameters of the best-fit circle solved during the previous experiment, the deviations of these epoch-by-epoch positions from the known circular path could be calculated for both modes of the TCA and the GPS. Table 3 shows the standard deviation of these errors for both measuring systems. Note that the values for the TCA have been broken down into angular and distance components, and that the angular components are additionally shown in distance units.

In kinematic mode, the GPS results are comparable in accuracy to those of the stop-and-go, bearing in mind that the stop-and-go accuracies are the result of averaging a set of epoch-by-epoch position estimates. However, the degradation in the positioning accuracy of the TCA is quite startling. The horizontal and vertical angular accuracies are quite similar to those observed in the stop-and-go experiment, but the distance accuracy is extremely poor.

Table 3. Comparison of Kinematic Accuracies (1σ) for TCA and GPS Epoch-to-Epoch Measurements

	TCA			**GPS**
	Regular	*Rapid*		
Horizontal (" : mm)	32 : 1.11	23 : 0.80	**North (mm)**	4.5
Vertical (" : mm)	107 : 3.73	89 : 3.11	**East (mm)**	3.0
Distance (mm)	84	29	**Height (mm)**	7.0

Figure 2 shows a plot of the distance errors for both measurement modes in relation to the points on the circular trajectory at which they were observed. In regular tracking mode, the largest distance error is 30 centimetres, whereas in the rapid tracking case, the largest error is 9 centimetres. Furthermore, a systematic pattern is immediately apparent. Since the north axis coincides with the line of sight from the instrument and the centre of the circular trajectory, one can deduce that the greatest distance errors occur when the target is moving directly towards the instrument and minimum when the target is moving perpendicular to the line of sight. This phenomenon has been observed by other authors, such as Becker (2000).

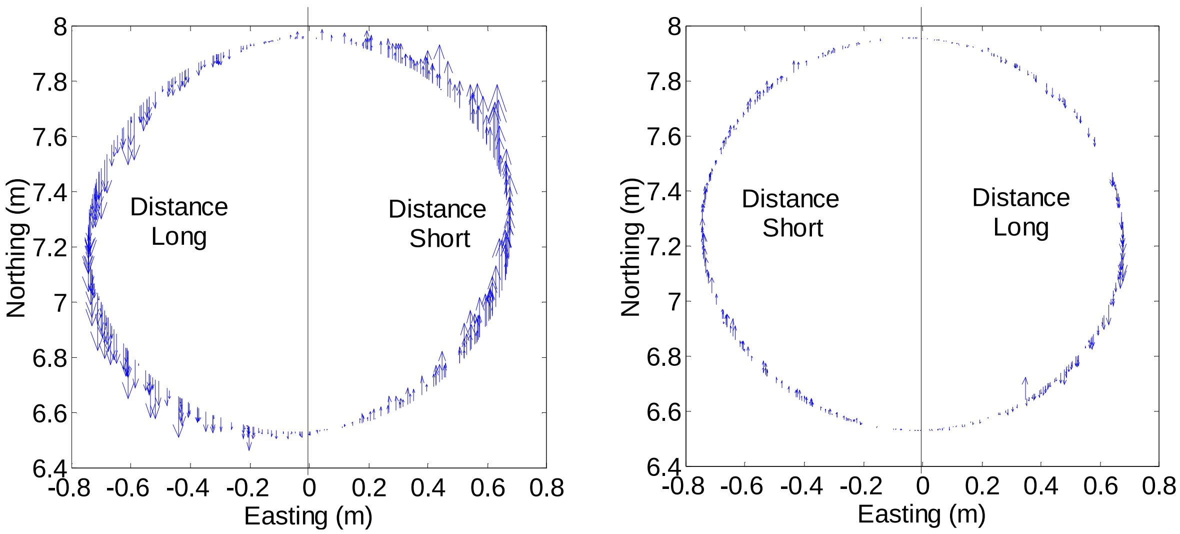

Figure 2. Distance Errors at Observed Points on Circle. Rotation is counter-clockwise.

The distance measurement problem in kinematic mode is illustrated in figure 3. The electronic distance measuring instrument (EDMI) on the TCA operates with a certain *integration time*. However, the angular measurement components do not. As a result, for a given measurement, the angles measured to the point are correct (within the measurement accuracy), but the distances recorded correspond to some epoch in the near past. Of course, this error is then most severe when the velocity of target *along the instrument-target line of sight* is greatest. Specifically, the following relations can be written :

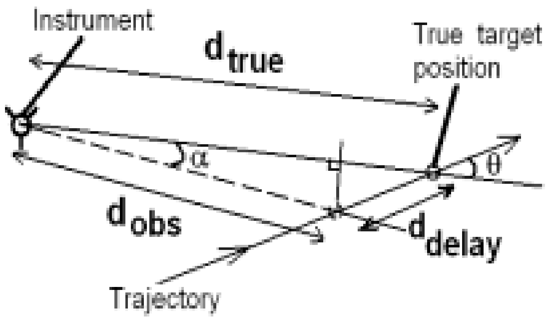

Figure 3. Illustration of Ranging Error.

$$\alpha = \operatorname{asin}\left(\frac{d_{delay} \cdot \sin\theta}{d_{obs}}\right)$$

$$\begin{aligned} err &= d_{true} - d_{obs} \\ &= d_{obs}(\cos\alpha - 1) + d_{delay} \cdot \cos\theta \end{aligned} \quad (1)$$

where

d_{obs},d_{true} … observed and true distances to target point

d_{delay} … target travel during integration period where

$$d_{delay} = v \cdot \Delta t$$

v … velocity of target

Δt … timing constant

θ … angle between target trajectory and line-of-sight

Since the target point is constrained to a known circular trajectory, the angle θ between the target direction of motion and the target-instrument line of sight can be calculated given the position of the target at any time. Since the position errors are smaller than 30 centimetres, the effect of using the observed positions to calculate θ in the following analysis is negligible.

Unfortunately, measurement samples from the TCA are not time tagged, and a study by Ueno and Santerre (2000) has revealed that the sampling rate of the instrument in not constant at 1 Hz, but actually varies around 0.7 Hz. As a result, it is impossible to determine accurate target velocities using the information from the TCA. For this reason, a velocity profile versus angular displacement for the two tests (regular and rapid tracking modes) was derived using the 10 Hz GPS data. Figure 4 shows the angular velocities as a function of angular displacement. The rotation speeds vary from 10 deg/s up to 80 deg/s and are quite variable over even small spans of time. By calculating the angular rotation of the targeted bar using a given epoch of TCA data, the velocity of the target can be determined via interpolation. Note that the target velocities in linear units thus range from 0.12m/s to 1.0 m/s. Also, a total of 106 total rotations were observed.

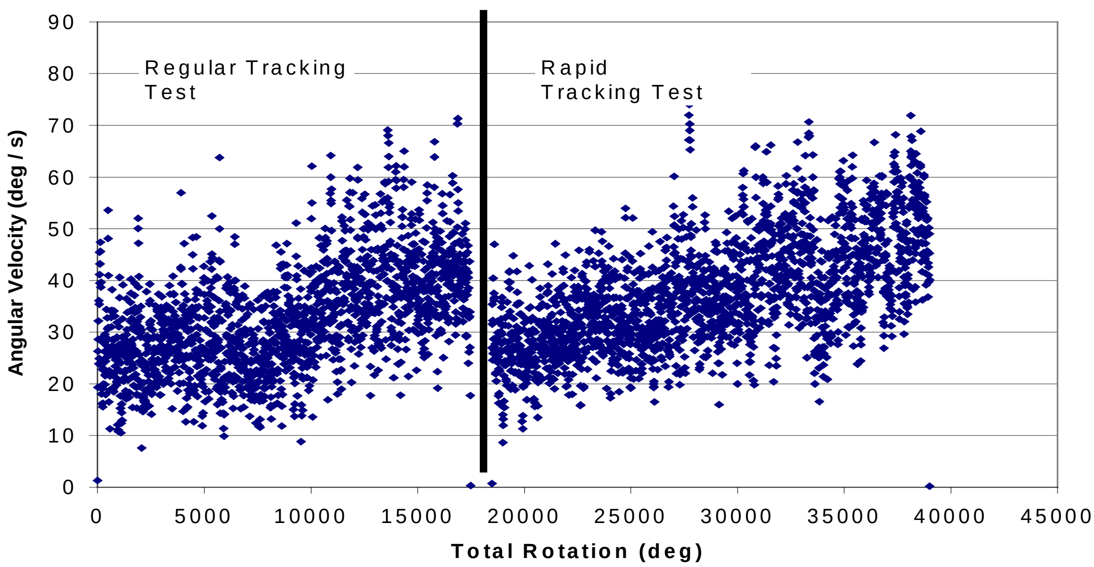

Figure 4. Angular Velocities of Targeted Bar Versus Rotation Angle.

If one assumes that d_{delta} is small in relation to the observed distance, then we can assume that the effect of α in equation (1) is negligible. As a result, the distance error is directly proportional to the target velocity projected along the line of sight. This of course assumes that the target moves in a straight line over the integration time, which we will assume valid for our purposes. Figures 5 and 6 show the results of plotting the distance error for a given data sample against its calculated line-of-sight velocity. The linear relationship between line of sight velocity and distance error is evident, implying the existence of a timing constant. Fitting a line throughout the data for each case yields the value of this constant – 0.28 s for regular tracking and 0.08 for rapid tracking. These values agree very closely with those determined by Stemfhuber (2000).

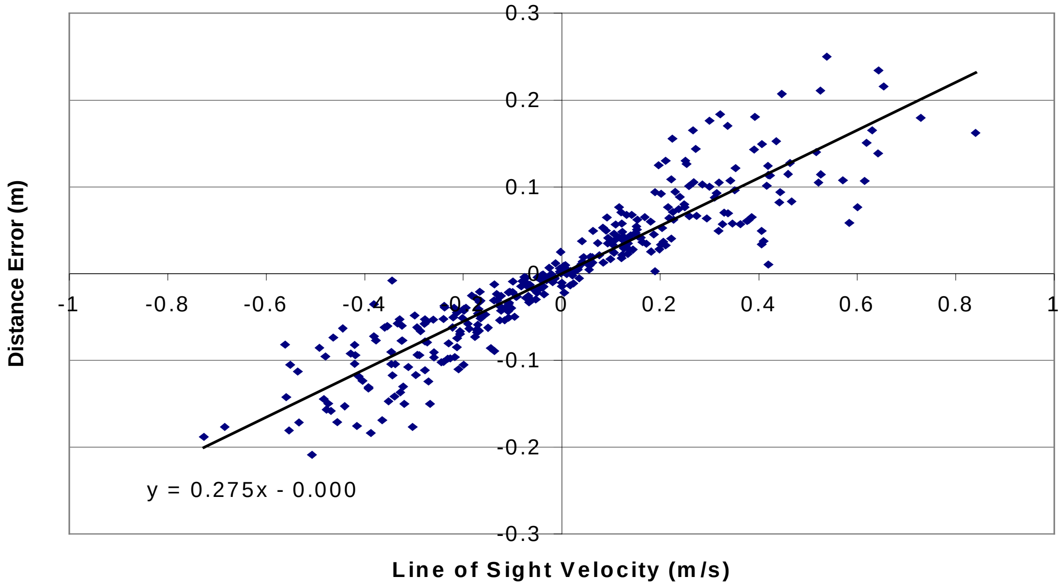

Figure 5. Target Line of Sight Velocity versus Distance Error – Regular Tracking.

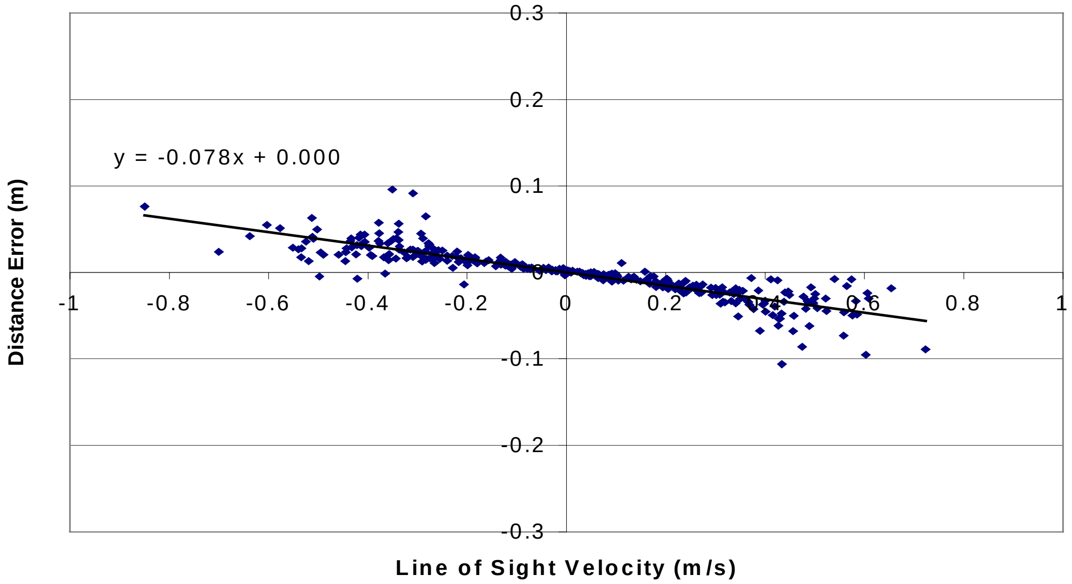

Figure 6. Target Line of Sight Velocity versus Distance Error – Rapid Tracking.

However, the sign of this constant is opposite for the two tracking modes. The case of the regular tracking mode makes physical sense, as it indicates that when a target is moving *away* from the tacheometer, the distances measured are too *short* (see figure 2 for confirmation of this). This means there is a certain latency in the distance measurements and the recorded distances correspond to epochs when the target was closer to the tacheometer. Indeed, the TCA technical specifications (Leica, 1998) state that the “time per measurement” for the regular tracking mode is 0.3 seconds, which is close to the timing constant derived of 0.28 seconds. However, if this is simply coincidence is not known. The “time per measurement” for the rapid tracking mode is stated as 0.15 seconds, but this not near the derived timing constant of 0.08 seconds. As a result, the authors must conclude that, while the ranging error is clearly linearly dependant on the line of sight velocity, the physical meaning of the timing constant remains unknown. I

Nonetheless, the timing constants derived can be used to improve the positioning accuracy of the TCA. Given two points measured at a known sampling rate, the ranging error to both should be similar assuming that the velocities over the measurement period is constant. As a result, this error will cancel when determining the velocity and direction of travel of the target using the observed data. Using this velocity, and the angle between the target trajectory and the line of sight, a correction to the ranges measured can be derived with knowledge of the timing constant.

Unfortunately, the time period between data samples is not constant nor computable simply from data provided by the TCA. To estimate the sampling rate (nominally set to 1 Hz), the authors used the following procedure. First, the angular displacement between two data samples was calculated using the TCA data, as well as the total rotation angle of the bar. Next, using the GPS-derived velocity profile previously shown in figure 4, the average velocity between the two samples was calculated. The division of the observed angular displacement by the average velocity then yields an estimate of the sampling interval. The sampling interval calculated for each epoch is shown in figure 7. The average sampling interval is 1.8 seconds, with a standard deviation of 0.3 seconds. In addition, there is no apparent correlation between the sampling interval and the target dynamics or the measurement mode.

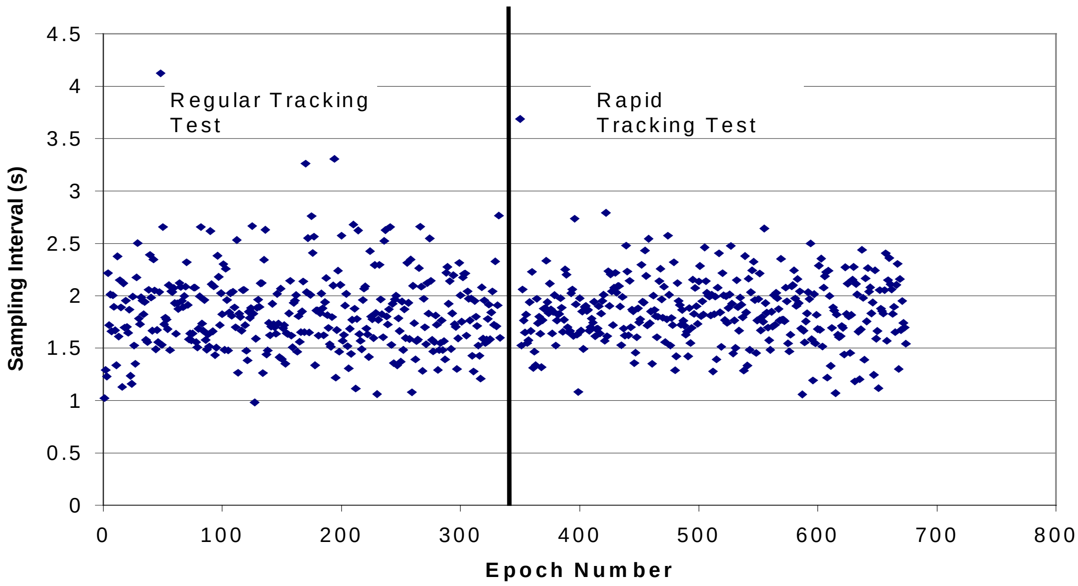

Figure 7. Observed TCA Sampling Intervals.

The final test was to assume a nominal sampling interval of 1.8 seconds and apply the above mentioned correction technique. Table 3 presents the standard deviations of the corrected distance measurements and the standard deviations of the original distance measurements for comparison. An improvement of greater than 50 % occurs for both measuring modes. The authors believe that the remaining errors stem from the assumption of a constant sampling interval and the fact that over 1.8 seconds, the targeted bar can rotate by up to 100 degrees. This of course means that the assumption of a straight-line trajectory between data point is of course invalid. An improvement in the correction method may be to predict a non-linear trajectory using several points, perhaps involving spline extrapolation.

Table 3. Distance Error Standard Deviations Before and After Correction

	Positioning Mode	
	Regular	**Rapid**
Uncorrected (mm)	84	29
Corrected (mm)	38	14
Percentage Improvement (%)	55	48

4.0 Conclusions and Future Work

The performance of a robotic tacheometric system has been compared to that of GPS under two kinematic operating modes – stop-and-go and true kinematic. In stop-and-go mode, the RTS was shown to be superior to GPS, achieving horizontal accuracies of 0.5 mm at a standoff distance of 77 metres, as opposed to an accuracy of 2 mm horizontally in the case of GPS. Thus for applications where the stop-and-go strategy is appropriate, an RTS may be a more precise option, assuming that the target dynamics are such that the RTS can track it without losing lock. However, there remains work to be done in determining why the rapid tracking mode yields higher accuracy positions than the regular tracking mode, a result that is counterintuitive.

In general, it is more desirable to be able to monitor a moving point throughout its trajectory. Unfortunately, it is under this scheme that several major deficiencies in the RTS used became apparent. First and foremost, it has been shown that the distances measured by the RTS suffer from an error that is linearly dependent on the velocity of the target along the line of sight. In the test performed here, where line-of-sight velocities were limited to a maximum of 0.8 m/s, the resulting error is as great as 22 centimetres. Although a scheme was developed to correct this error based on velocities derived from the collected data and using the fast tracking measurement mode, the remaining distance errors remain at the centimetre-level. This is still approximately twice the error level achievable with epoch-by-epoch GPS. Until this problem is solved, the utility of RTS in precision monitoring of moving objects will be limited.

A second limitation of the RTS used is that its sampling interval is equal to that set by the user and more importantly, is not constant over time. As shown in this paper, the sampling interval for this test was approximately 1.8s, but varied with a standard deviation of 0.3s. In general, it is very difficult to make use of kinematically collected data if the temporal characteristics of the observation process are unknown. In addition, note that it is not crucial that the sampling interval be exactly constant, but rather that the exact time at which each measurement was made is known. Thus, a simple solution to this problem would be to time tag the data as it was collected. This perhaps could be implemented by transferring the data to a computer as it was collected by the RTS, and time tagging the results using the computer's internal clock. Of course, the latency in the system and the computer clock offset to UTC would have to be determined if a direct comparison or combination with GPS data were to occur.

In conclusion, the authors believe that the solution of the time tagging problem is most crucial in developing an RTS-based monitoring system. Once this is done, and assuming higher data rates become possible, robust velocity profiles of a moving target can be calculated, and then used to correct the velocity-dependent distance errors. If one wished, the corrected distances could then be used to calculate improved velocities, and the entire correction process repeated. The goal would be to arrive at sub-centimetre level accuracy from epoch-to-epoch. If this level is achieved, then RTS can become a viable option to GPS in many outdoor applications, and will become an indispensable tool in monitoring moving structures indoors.

5.0 References

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