HIGH-PRECISION TOTAL STATION—IMU INTEGRATED POSITION AND ATTITUDE DETERMINATION

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ABSTRACT: This paper introduces a high precision system which combines the laser tracking and IMU to substitute the GNSS navigation systems when there is no GNSS signal. The cooperative prism work with Laser Tracking play a key role which as important as GNSS. Through it, we can procure real time position result, however, there exist delay time between the sampling time and the true time. At the same time, the sensor calibration, one precondition for sensor orientation with prism and IMU must be performed. Based on tradition inertial navigation modelling, we analyze the composing of error exist in this system, add the delay time as a new estate variable, establish a new estate equation whose simpler but fit the local reference frame more suitable. For the purpose of reckoning integration, we choose the method of standard Kalman as the filter to implement the sensor correction of the inertial data. In addition to acquiring RMS values of centimeter, simultaneity, in virtue of ZUPT or other methods, we also can obtain the bias drift of gyro. Importantly, a combination of Laser Tracking/IMU can making the stability improved greatly. Ultimately, we have conducted a series of tests and showed the good precision potential of position and orientation.

1. INTRODUCTION

Navigation and positioning technology becomes essential to numerous automated systems nowadays. Positioning precision and system reliability impacts its capacity and potential applications directly. GNSS and GNSS/IMU is widely spread. However satellite navigation depends more on GPS. In special circumstances, such as less or no satellite signal district (e.g. high building zone tunnel/underground space/indoors/under canopy) and unreachable zone (e.g. dams or bridges), the system is difficult to apply.

Figure 1 TS/IMU navigation systems

Based on this, this paper researches a local autonomous synthetical positional navigation system which can be used in special circumstance and needs no satellite information. Through laser tracking positioning/inertial combination navigation, it can achieved high accuracy positioning and attitude determination.

Figure 2. System composition

System is composed of IMU/Total Station/Time Synchronizer/Odometer/Data acquisition and processing unit, and introduction of GPS receiver to be position reference system. System block diagram shown in Figure 2:

Figure 3. DGPS/IMU navigation systems
According to the deployment of the relationship between sensor units, TS/IMU combination navigation system can be divided into observation station and mobile station. Among them, Total Station, time synchronizer and computer storage are placed at fixed given control points as part of observation station. IMU/total reflection prism and odometer are deployed on mobile carrier which is used to measure the speed / angular velocity /acceleration.

During actual working, Total Station tracks reflection prism real time, and gives the location of the prism distance, direction, pitch angle and other information. Meanwhile, inertial data (include angular velocity and acceleration) and incremental pitch angle and other information. Meanwhile, inertial data (include angular velocity and acceleration) and incremental pitch angle and other information. With the premise of observation data meeting high precision, we can use least-squares fitting of cubic spline interpolation method of data processing to get discrete points of space-based trajectory. The cause of dynamic measurement capacity is complex. Besides normal correction of atmospheric effects, earth curvature correction, prism constant, tilt error, the error of dynamic measurement also includes time delay, angle measurement and distance measurement error, measurement noise and random hopping.

Because of the absence of gross errors can be removed redundant observation conditions, gross errors can be removed only through the mathematical methods. With the premise of observation data meeting the precision, we can use least-squares fitting of cubic spline interpolation method of data processing to get discrete points of space-based trajectory. The cause of dynamic measurement capacity is complex. Besides normal correction of atmospheric effects, earth curvature correction, prism constant, tilt error, the error of dynamic measurement also includes time delay, angle measurement and distance measurement error, measurement noise and random hopping.

Due to different causes of static and dynamic time-delay, data processing should be separate. Static time-delay is stable, so it only requires least squares to estimate time delay; when dynamic, it can only estimate average time-delay value.

2.2 Total Station dynamic positioning precision

Under static, the precision of total station is good, and the method is mature. But it can’t measure the dynamic capacity. The cause of dynamic measurement capacity is complex. Besides normal correction of atmospheric effects, earth curvature correction, prism constant, tilt error, the error of dynamic measurement also includes time delay, angle measurement and distance measurement error, measurement noise and random hopping.

Because of the absence of gross errors can be removed redundant observation conditions, gross errors can be removed only through the mathematical methods. With the premise of observation data meeting the precision, we can use least-squares fitting of cubic spline interpolation method of data processing to get discrete points of space-based trajectory. Due to different causes of static and dynamic time-delay, data processing should be separate. Static time-delay is stable, so it uses least squares to estimate time delay; when dynamic, it can only estimate average time-delay value.

Figure 4. Work flow

2. SENSOR ERROR ANALYSIS

To achieve high precision combination navigation positioning, the most important is to be acknowledge of sensor error modeling and the interaction of error source, apart from researching the frame of filter. For system-level error, it should be calibrated and compensated from system view to reduce the acquisition of sensor unit precision. TS/IMU combine navigation is composed from error source below:

### 2.1 IMU error transmission equation

The error equation of Strapdown inertial navigation system has two forms: $\psi$ angle error and $\phi$ angle error. $\psi$ angle error equation is below:

$$
\begin{bmatrix}
\delta \hat{\psi}_x \\
\delta \hat{\psi}_y \\
\delta \hat{\psi}_z \\
\hat{\phi}_x \\
\hat{\phi}_y \\
\hat{\phi}_z \\
\hat{\phi}_w \\
\end{bmatrix} = 
\begin{bmatrix}
0 & 2\Omega \sin L & 0 & g & 0 & 0 & 0 & 0 & 0 \\
-\Omega \sin L & 0 & 0 & 0 & -g & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -\Omega \cos L & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \Omega \sin L & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \Omega \cos L & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \Omega \sin L & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \Omega \cos L & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
\delta \hat{\psi}_x \\
\delta \hat{\psi}_y \\
\delta \hat{\psi}_z \\
\hat{\phi}_x \\
\hat{\phi}_y \\
\hat{\phi}_z \\
\hat{\phi}_w \\
\end{bmatrix}
$$

where,$\ \ \ \ \ V_N, V_E$ is equivalent to the North and East to the accelerometer error;

$e_N, e_E, e_D$ are equivalent to the North, East to the sky values to the gyro drift

$$
\begin{align*}
V_N &= C_{11} \delta \hat{\psi}_x + C_{12} \delta \hat{\psi}_y \\
V_E &= C_{21} \delta \hat{\psi}_x + C_{22} \delta \hat{\psi}_y \\
e_N &= C_{11} e_X + C_{12} e_Y + C_{13} e_Z \\
e_E &= C_{21} e_X + C_{22} e_Y + C_{23} e_Z \\
e_D &= C_{31} e_X + C_{32} e_Y + C_{33} e_Z
\end{align*}
$$

To the IMU of the system, accelerometer bias $\mathbf{v}_a, \mathbf{v}_e$ is about 100 $\mu$ g. Gyro random drift $e_x, e_y, e_z$ is about 0.1°/h.

Figure 5. Flat distant of prism and GPS centre

From the data on the map, it shows time-delay phenomenon. The level of straight line at static and dynamic fluctuations in paragraph exists hopping of 0.2 meter. During time-delay
correction, error reduces evidently.

Figure 6. Flat distant of prism and GPS centre after time delay correction

After time-delay correction, horizontal distance between prism and GPS receiver phase center can be induced.

For high-precision dynamic measurements, error modeling of Total Station is as below:

\[
\begin{align*}
\Delta x_k &= x_0 - [L(1 + k) + \Delta L] \cos (\alpha + \Delta \alpha) \sin (\beta + \Delta \beta) \\
\Delta y_k &= y_0 + [L(1 + k) + \Delta L] \cos (\alpha + \Delta \alpha) \cos (\beta + \Delta \beta) \\
\Delta z_k &= z_0 + [L(1 + k) + \Delta L] \sin (\alpha + \Delta \alpha) \\
\Delta \alpha &= \Delta \alpha_1 + \Delta \alpha_2 \\
\Delta \beta &= \Delta \beta_1 + \Delta \beta_2
\end{align*}
\]

\(k\) is scaling factor ranging, \(\Delta L\) is dynamic error caused by time-delay

\(\Delta \alpha\) is pitch angle measurement error, it is composed of \(\Delta \alpha_1, \Delta \alpha_2\), \(\Delta \alpha_1\), photoelectric encoder errors which exists in both static and dynamic mode. \(\Delta \alpha_2\), is pitch angle error of dynamic measurement which is caused by time-delay

\(\Delta \beta\) is an error of course angle measurement. It is composed of \(\Delta \beta_1, \Delta \beta_2\). \(\Delta \beta_1\), is Photoelectric encoder error which exists in both static and dynamic mode. \(\Delta \beta_2\), is course angle measurement error which is caused by time-delay.

2.3 Odometry error

Strapdown inertial navigation system supply increment mileage through odometer, and achieves dead reckoning-based navigation and positioning of the solution. Initial position of movement is \((x_0, y_0, z_0)\). By data acquisition, \(\Delta l_i\) is increment of odometer, \(\phi_i\) is course angle, \(\theta_i\) is angle of elevation, it can reckon the punctual position \((x_k, y_k, z_k)\):

\[
\begin{align*}
x_k &= x_0 - \sum_{i=1}^{4} \Delta l_i \cos \theta_i \sin \phi_i \\
y_k &= y_0 + \sum_{i=1}^{4} \Delta l_i \cos \theta_i \cos \phi_i \\
z_k &= z_0 + \sum_{i=1}^{4} \Delta l_i \sin \theta_i
\end{align*}
\]

Odometer measures the relative ground speed and location changes of the tire, and coefficient is relatively fixed that is calibrated before using. However the tire pressure and road friction coefficient may induce slight changes of odometer coefficient. Considering the acquisition of high precision navigation system and high precision of IMU in short time, we use IMU positioning to calibrate it. Normally we use forgetting factor recursive least squares method to ensure that the odometer of the fast convergence coefficient. When coordinates of two control points is given, real time calibration of odometer coefficient is done by control points or other auxiliary information.

2.4 System error

System error of time synchronization is composed of sampling delay of Total Station and IMU, error of time synchronization between time base of total station and IMU. Total station is the main error in time synchronization, which is as far as 0.1-0.2 sec. The remaining error is just microseconds that can be omit.

Time delay of total station includes two main parts: one is the time from beginning to the end measurement; other is the delay that from input to output happened in the computer. Time of dynamic standard position which supplied from computer is from the first character of dynamic data character string inputting to the computer. If time of dynamic standard position is delay, the corresponding result will be before the actual one. If the location of the dynamic standard deviation in accordance with a certain amount of time to back up, the average of measurement error turn to the least. Due to the speed of carrier influencing the capacity of total station, time delay is slightly different in measurement. Dynamic tracking of total station is about 100ms-10ms at different condition. After correction of time delay, result has marked improvement.

Time delay model of total station: \(r = r_b + r_r + r_o\).

\(r_b\) is regarded as fixed time delay, it meets the condition of \(r_b = 0\).

\(r_r\) is slow-varying drift, which can be described in first-order Markov process \(r_r = -\frac{r_r}{\tau} + \omega\).

\(r_o\) is fast-varying drift, it meets the condition of \(E[r_o(t)r_o(\tau)] = q\delta(t - \tau)\).

When actual using, it acts a leading role of delay model, is about 100ms, it value is from 50 to 100ms.
2.5 Lever Arm compensation effect

Lever arm effect is an acceleration component interference that is occurred by un-overlapping of installation location and carrier swing center. When carrier is swinging and IMU is not in the center, accelerometer error exists. For accelerometers and gyroscopes, as the concept of measuring the output signal of the strapdown inertial navigation system, larger principle error exists at initial alignment, therefore it must be compensated or cleared up. Before using laser or IMU to combination exists at initial alignment, therefore it must be compensated or the strapdown inertial navigation system, larger principle error gyroscopes, as the concept of measuring the output signal of the carrier swing center. When carrier is swinging and IMU is not normalized.

In the final experiment, three-dimensional relative position of prism and GPS should be measured accurately. Through attitude solution, prism’s position conversed to GPS position and compared to actual value.

3.1 The equation of state

Such as the type described, the system for the state vector is

\[ X_{\text{INS}} = [\delta L, \delta L, \delta H, \delta H, \delta \phi_U, \phi_U, \tau] \]

\[ X_{\text{GPS}} = [\delta L, \delta L, \delta H, \delta H, \delta \phi_U, \phi_U, \tau] \]

For more description of the state vector and state vector of the corrective process can be found in the literature 2, 3

3.2 Measurement equation

\[ Z_{\text{INS}} = \begin{bmatrix} L_{\text{INS}} - L_{\text{TS}} \\ \lambda_{\text{INS}} - \lambda_{\text{TS}} \\ h_{\text{INS}} - h_{\text{TS}} \end{bmatrix}, \quad Z_{\text{GPS}} = \begin{bmatrix} L_{\text{GPS}} - L_{\text{INS}} \\ \lambda_{\text{GPS}} - \lambda_{\text{INS}} \\ h_{\text{GPS}} - h_{\text{INS}} \end{bmatrix} \]

\[ Z = [Z_{\text{INS}}, Z_{\text{GPS}}] = [H_{\text{TS}}, H_{\text{GPS}}] \begin{bmatrix} X_{\text{TS}}, X_{\text{GPS}} \end{bmatrix} + [V_{\text{TS}}, V_{\text{GPS}}] \]

\[ H_{\text{TS}} = [I_{10 \times 10}, 0_{10 \times 10}], \quad H_{\text{GPS}} = [I_{10 \times 10}] \]

3.3 Kalman Filter

State prediction step \( \hat{X}_{k-1} = \phi_{k-1 \rightarrow k} \hat{X}_{k-1} \)

Step in the forecast mean square error

\[ P_{k-1} = \phi_{k-1 \rightarrow k} P_{k-1} \phi_{k-1 \rightarrow k}^T + \Gamma_{k-1} \Omega \Gamma_{k-1}^T \]

Kalman gain matrix \( K_k = P_{k-1} H_k^T (H_k P_{k-1} H_k^T + R_k)^{-1} \)

State estimation:

\[ \hat{X}_k = \hat{X}_{k-1} + K_k (Z - H_k \hat{X}_{k-1}) \]

Mean square error estimation \( P_k = (I - K_k H_k) P_{k-1} \)

3.4 SKF

Fixed-interval smoothing the fundamental idea uses time interval\([0, \ldots, M]\]

value \( \tilde{Z}_M = [Z_k^T Z_{k+1}^T \ldots Z_{M}^T] \quad X_k(k = 1, 2, \ldots, M) \) to estimate the state \( X_k(k = 1, 2, \ldots, M) \)

\[ \begin{bmatrix} X_{k+1} \\ X_{k+1}^T \\ X_{k+1}^T \\ X_{k+1}^T \end{bmatrix} = \begin{bmatrix} \phi_{k+1/k} & 0 & 0 & 0 \\ I & 0 & 0 & 0 \\ 0 & I & 0 & 0 \\ M & M & M & M \end{bmatrix} \begin{bmatrix} X_k \\ X_k^T \\ X_k^T \end{bmatrix} + \begin{bmatrix} X_{k+1} \\ X_{k+1}^T \\ X_{k+1}^T \end{bmatrix} W_k \]

\[ Z_k = [H_k, 0, \ldots, 0, 0] X_k^T + V_k \]

\[ M \]

The corresponding state estimation, the mean square error of estimation and prediction of gain matrix is

\[ \begin{bmatrix} \hat{X}_{k+1/k}^1 \\ \hat{X}_{k+1/k}^2 \\ \hat{X}_{k+1/k}^3 \\ \hat{X}_{k+1/k}^4 \end{bmatrix} K \begin{bmatrix} \hat{X}_{k+1/k}^1 \\ \hat{X}_{k+1/k}^2 \\ \hat{X}_{k+1/k}^3 \\ \hat{X}_{k+1/k}^4 \end{bmatrix} \]

Figure 7. Procession of attitude and position

Figure 8. Schematic
\[
\begin{bmatrix}
P_{k+1}^{\text{DF}} \\
\vdots \\
P_{k+1}^{\text{DF}} \\
M \\
\vdots \\
P_{k+1}^{\text{OF}} \\
\end{bmatrix} \propto \begin{bmatrix}
P_{k+1}^{\text{DF}} \\
\vdots \\
P_{k+1}^{\text{DF}} \\
M \\
\vdots \\
P_{k+1}^{\text{OF}} \\
\end{bmatrix}
\]

\[
K_k^{(1)} K_k^{(2)} K_k^{(3)}
\]

\[
P_{k+1}^{\text{(i+1)}} = P_{k+1}^{\text{i}} (\theta_{k+1} - K_k^T H_k)^T
\]

\[
X_k^{x+1} = X_k^{x-1} + K_k^{(i+1)} Z_k
\]

\[
K_k^{(i+1)} = P_{k+1}^{\text{i-1}} H_k^T (H_k P_{k+1}^{\text{i-1}} H_k^T + R_k)^{-1}
\]

About fixed-interval smoother filter, more information has described in the literature 8.

4. PRECISION TEST

Choose a long straight-line and gentle slope road as long as 0.8km with open around. Control point is at a side of the road, and then we set up total station; select another side to set up baseline control point. The position of two control point is measured by GPS. To connecting with time synchronizer, the measurement data can be calibrated accurately. Put 360 degree total reflecting prism and GPS receiver fixed at the top of mobile measurement carrier. The horizontal distance between the two is about 0.440 centimeter.

Open IMU and GPS receiver, total station measures information about baseline and calculate the azimuth. Aim total station at center of prism, Open Automatic tracking. Mobile measurement carrier moves, total station will automatic rotate lens to maintain the fixing state.

Figure 9 Position and attitude reference system

4.1 Absolute precision

Compare the horizontal distance between phase center of GPS receiver and prism to validate the precision of tracking total station.

Tracking gram of GPS receiver and total reflecting prism is as
Figure 12 Absolute position error after time compensating

Figure 13. Attitude error of two systems(KF)

Figure 14. Attitude error of two systems(SKF)

From the comparison of figure 14/15, using SKF can improve the speed of Algorithm convergence and precision of error estimation.

4.2 Compared precision

It is worth noting that the absolute precision validation can not show the TS/IMU the actual precision in local orientation. In dynamic condition, GPS dynamic position precision is about 2 centimeter. It brings GPS error evitable when using method mentioned before to validate the precision. Moreover, bias of baseline can not be ignored in absolute precision validation. Consequently, the principle error and error of reference system should be reduced only when validating the TS/IMU precision in local orientation.

In actual working, users pay more attention on precision in local orientation than on accuracy. Thus, to acquire the precision, we put two total station on fixed points, and observe the same object in unified time system. In this way, the error of reference system can be avoided and the bias of baseline is diminished by simply means of linear fitting.

From transmission standard deviation formula

$$S_N = \sqrt{\left(\frac{\partial}{\partial T} S_A\right)^2 + \left(\frac{\partial}{\partial T} S_B\right)^2 + \left(\frac{\partial}{\partial T} S_C\right)^2 + \Lambda^2 + \left(\frac{\partial}{\partial T} S_H\right)^2}$$

One experiment is consistent with precision $S = \frac{S_N}{\sqrt{2}}$, S is the error of single equipment, $S_N$ is compared precision of two systems.

4.3 Attitude error

Due to unattached two systems, random delay of time can be considered absolutely irrelevant. Thus, it leads to distortion of result when measurement model inaccurate and filtering according to linear filter. To the same carrier, the attitude, speed and position at certain time is assured and exclusive. Result of two systems express the precision of system. From comparative analysis, using SKF is better than the KF filter to processing not only in convergence speed and also in accuracy.

4.4 Speed error

Figure 15. Attitude tracking of two TS/IMU(KF)
As the same, test result shows that SKF method is better than KF, through state estimation to the same object speed in two dependent system. Table 2 is speed and accuracy result.

<table>
<thead>
<tr>
<th>Std-Velocity(SN)</th>
<th>Up (m/s)</th>
<th>East (m/s)</th>
<th>North (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKF</td>
<td>0.0025</td>
<td>0.0053</td>
<td>0.0095</td>
</tr>
<tr>
<td>KF</td>
<td>0.0085</td>
<td>0.0156</td>
<td>0.0330</td>
</tr>
</tbody>
</table>

\[
S = \frac{S_N}{\sqrt{2}}
\]

<table>
<thead>
<tr>
<th></th>
<th>Up (m/s)</th>
<th>East (m/s)</th>
<th>North (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKF</td>
<td>0.0018</td>
<td>0.0037</td>
<td>0.0067</td>
</tr>
<tr>
<td>KF</td>
<td>0.0060</td>
<td>0.0110</td>
<td>0.0233</td>
</tr>
</tbody>
</table>

Max-Error

<table>
<thead>
<tr>
<th></th>
<th>Up (m/s)</th>
<th>East (m/s)</th>
<th>North (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKF</td>
<td>0.0298</td>
<td>0.0273</td>
<td>0.0386</td>
</tr>
<tr>
<td>KF</td>
<td>0.0898</td>
<td>0.0880</td>
<td>0.1191</td>
</tr>
</tbody>
</table>

Table 2. Velocity precision

4.5 Position error

In virtue of baseline error leading to systematic bias of two system result, it shows error grows with measurement distant in error curve, as graph 20/21. Linear fitting to do with measurement result according to 24. Error result shows in graph 22/23 and table 3 after removing baseline bias.

\[
Y = K_2X^2 + K_1X + K_0
\]
4.6 Time delay estimation

Estimated residuals of random time delay shows as below: it express the estimation capacity of different filter to nonlinear system. Result in graph24 and table 3 shows SKF estimation of random time delay is also better than KF.

Figure 21. Estimated time of delay at random

<table>
<thead>
<tr>
<th>Type of filter</th>
<th>Estimated time of delay(second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS1/IMU</td>
<td>0.00996</td>
</tr>
<tr>
<td>TS2/IMU</td>
<td>0.01107</td>
</tr>
<tr>
<td>SKF</td>
<td>0.01671</td>
</tr>
<tr>
<td>KF</td>
<td>0.02162</td>
</tr>
</tbody>
</table>

Table 4. Estimated time of delay

5. CONCLUSION

The method of processing TS combined with IMU that makes use of IMU navigation data to smoothly process TS position information. It filters out drift of position data, enhances TS dynamic and position precision. Meanwhile it assures capability of combined navigation position. The result shows, TS/IMU can achieve the precision of 1-2cm. Thus, it should be pointed out that the work load which use SKF method is much higher than that use KF filter. It is determined by the proportion of smooth interval and time constant of filter. So it debugging when system needs, normally about double or triple. Too much smooth interval is not evident to improve the estimating mean squared error. Meanwhile, SKF method belongs to liner filter in virtue. Accordingly, we should do more research on nonlinearity method to improve precision and robust.

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