Tightly Coupled RTK/MIMU using Single Frequency BDS/GPS/QZSS Receiver for Automatic Driving Vehicle

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Abstract—**Autonomous driving is a main research focus in automobile industries. Recently, Google, along with several automobile manufacturers has rapid progress in this field, leading them to test it on public roads. Precise positioning technology is one of the keys in this advance technology. It is relatively easy to obtain its precise position (i.e., 10 centimeters) using real time kinematic (RTK) in open sky area. Considering the vehicle will be operated in all kinds of environment, the positioning system should be able to provide robust localization information in harsh environment. Most of the driving environment is blocked by trees or high buildings, it is especially difficult to get a "fixed" solution for RTK algorithm in such environments. Sometimes, it is also difficult to get position information by single point positioning (SPP) because less than four satellite are visible. This paper describes a tightly-couple integrated positioning system using MEMS IMU and low-cost single frequency GNSS receiver for vehicle driving in urban area. The design objective is to realize accuracy and robust position in various streets environment.**

In Tokyo, the observation conditions of GPS and BDS is perfect. At the same time, Japan has their own regional navigation system called QZSS, which is designed to stay high elevation for Japanese region. Thus, BDS/GPS/QZSS system is selected in this paper. In fact, there are several frequency bands in each navigation system. BDS have B1,B2,B3 bands, GPS have L1,L2,L5 bands, and QZSS is similar to GPS. Accordingly, there are several kinds of GNSS receivers, single frequency, dual frequency or triple frequency receivers. The advantage of the dual frequency receiver is to eliminate the effect of ionosphere. However, it is more expensive than single receiver. Meanwhile, with the rapid development of the integration circuit technology, the channel capability of satellite navigation receiver increases quickly, resulting in the price of multi-constellation system receiver is close to the price of single system receiver. In order to increase the number of the visible satellite in harsh environment, this paper applies a BDS/GPS/QZSS receiver to provide the raw observations. But it is still a problem for vehicle to drive in tunnel because none of the satellites are visible.

Inertial navigation system (INS) consists of three axis accelerometers and three axis gyroscopes, which is generally called inertial measurement unit (IMU).After initialization, INS is applied to provide continuously navigation service while the GNSS solution is not available. However, if there is no correction, it will gradually diverge because of error accumulation. Comparing with GNSS solution, IMU is short-term high accuracy but error accumulating. In the market, there are three levels of IMU. Navigation grade IMU is the most precise but the most expensive equipment. At the same time, the volume and power consumption is huge for automobile applications. Tactical level one is the second precise equipment. It is still high-cost for autonomous driving market. The consumer grade IMU is usually made by MEMS technology. The power consumption and the price of MEMS are reasonable. Although MEMS IMU (MIMU) is still low precision now, the accuracy is gradually increasing recently and its price, volume and power consumption have undefeated features for consumer market, this paper select MEMS IMU as the test equipment.

Finally, this paper apply coupled information to correct the error of MIMU and to detect & recovery multipath and cycle slip, These raw measurement can be preprocessed before RTK algorithm, by decreasing the

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environment influence to the pseudo range and carrier phase, the fix ratio or the accuracy of the float solution can be improved. The technology mentioned in this paper can be used to develop a low-cost precision position system for automatic driving vehicle.

Keywords—RTK, IMU, Multipath, cycle slip

I. INTRODUCTION

This section provides an overview of the GNSS positioning technology that is currently being used in Aided Inertial Navigation Systems for Automatic Driving Vehicle. RTK technology is the main solution to get an accuracy position. However, it is easily influenced by kinds of harsh environment. Inertial technology provides a solution to GPS unavailability. They are self-contained and independent from GPS and are therefore unaffected by satellite blockages and signal interference. So, RTK/INS couple system can been used to establish a robust position system.

II. POSITIONING VIA RTK GNSS

GPS technology has created many possibilities for new navigation applications. In the automatic driving vehicle field, it has been a robust solution to navigate their way through unknown territory. If RTK is used, GNSS can be used for safety and control applications.

In the RTK algorithm, Kalman filtering is used to estimate not only the position/velocity of the rover station but also the single-differenced(SD) float ambiguity with a full utilization of the historical measurements. Three axis position and velocity and the SD ambiguities are selected as the system states in the Kalman filter. It can be expressed as follows:

$$\vec{X}=[x_r,y_r,z_r,v_x,v_y,v_z,N_{1,r}^{GPS},N_{2,r}^{GPS}\cdots,N_{1,r}^{BDS},N_{2,r}^{BDS}]^T \text{.............(1)}$$

The advantage to select SD ambiguities instead of double difference (DD) is to avoid the handover of the “reference satellite,” which is very common in the street. The measurement is expressed as follow:

$$\vec{Z}=[\rho_{rb}^{M1GPS},\cdots,d_{rb}^{M1GPS},\cdots,\phi_{rb}^{M1GPS},\rho_{rb}^{M1BDS},\cdots,d_{rb}^{M1BD},\cdots,\phi_{rb}^{M1BDS}]^T \text{..(2)}$$

where ρ denotes pseudorange, ϕ denotes carrierphase and d denotes Doppler shift. ρ_{rb}^{M1GPS} denotes the DD pseudorange of GPS satellite, ρ_{rb}^{M1BDS} is the DD pseudorange of BDS satellite. Because the time system of QZSS satellite is synchronous with GPS, it can be regarded as a common GPS satellite. The observation matrix H is expressed as follow:

$$\vec{X}=H=\frac{\partial\vec{Z}}{\partial\vec{X}}=\begin{bmatrix}H_x^\rho & 0 & 0\\ 0 & H_x^\rho & 0\\ H_x^\rho & 0 & D\end{bmatrix}\; H_x^\rho=\begin{bmatrix}(e_M-e_1)^T\\ (e_M-e_2)^T\\ \vdots\\ (e_M-e_i)^T\end{bmatrix} \text{..................(3)}$$

where e_M denotes the line of sight (LOS) vector of the reference satellite and e_i denotes the LOS vector of the *j*-th satellite. The system propagation matrix F matrix is expressed as follow:

$$F=\begin{bmatrix}1 & & & 1 & & & & \\ & 1 & & & 1 & & 0 & \\ & & 1 & & & 1 & & \\ & & & 1 & & & & \\ & 0 & & & 1 & & 0 & \\ & & & & & 1 & & \\ & & & & & & \ddots & \\ & 0 & & & 0 & & & \ddots \\ & & & & & & & & 1\end{bmatrix} \text{.............(4)}$$

The SD float ambiguity can be converted into a DD one using the corresponding convert matrix, which is expressed as follow:

$$G=\begin{bmatrix}I_{6\times6} & \\ & D\end{bmatrix},\; D=\begin{bmatrix}1 & -1 & & \\ \vdots & & \ddots & \\ 1 & & & -1\end{bmatrix} \text{..............................(5)}$$

Then LAMBDA method is used to search the best integer ambiguities. By equations(1) to (5), this implemented RTK algorithm works well in open sky area. However, it is very difficult to provide a fix position result when the vehicle driving across streets.

Common RTK algorithm is easily affected in street environment. Take the influence of the tall building as example, when the vehicle drive across the tall building which is located at the east of the street, the positioning result jumps to the west of the ground truth. After the vehicle leaves the influence area, the position result immediately recovery to normal level. By analyzing the raw measurement in this area, one multipath which is about 4 meters and obvious cycle slip can be found.

III. TIGHTLY COUPLE WITH RTK/IMU

This paper innovatively introduces the multipath detection algorithm, cycle slip detection and recovery algorithm to combine RTK and IMU to improve system performance. Fig.1 shows the flowchart of the proposed tightly couple RTK/IMU integration. RTK/IMU couple filter is the core of this algorithm.The1) multipath detection and recovery and 2) cycle slip detection and recovery are the key points.

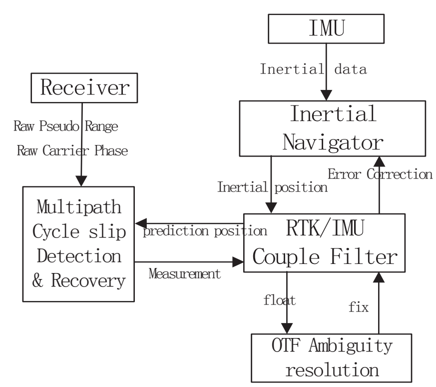

Fig. 1. Flowchart of the proposed tightly couple RTK/IMU integration

This RTK/IMU couple filter, which is also a Kalman filter, is used to correct the IMU error. The system states are expressed as:

$$\vec{X}=\begin{bmatrix}\delta\psi_{eb}^{e}\\ \delta\upsilon_{eb}^{e}\\ \delta\gamma_{eb}^{e}\\ b_a\\ b_g\end{bmatrix}\qquad(6)$$

where $\delta\psi_{eb}^{e}$ is three axis orientation error, $\delta\upsilon_{eb}^{e}$ is three axis velocity error, $\delta\gamma_{eb}^{e}$ is three axis position error, b_a is three axis bias of accelerometer, and b_g is the three axis bias of gyroscope.The measurement is expressed as follow:

$$\vec{Z}=\begin{bmatrix}\rho_{rb,GNSS}^{M1}-\rho_{rb,IMU}^{M1}\\ \vdots\\ \rho_{rb,GNSS}^{Mn}-\rho_{rb,IMU}^{Mn}\\ \dot{\rho}_{rb,GNSS}^{M1}-\dot{\rho}_{rb,IMU}^{M1}\\ \vdots\\ \dot{\rho}_{rb,GNSS}^{Mn}-\dot{\rho}_{rb,IMU}^{Mn}\end{bmatrix}\qquad(7)$$

where $\rho_{rb,GNSS}^{Mn}$ is the n-th DD pseudorange from GNSS, $\rho_{rb,IMU}^{Mn}$ is the n-th DD pseudorange from IMU, $\dot{\rho}_{rb,GNSS}^{Mn}$ is the n-th DD pseudorange rate from GNSS, $\dot{\rho}_{rb,IMU}^{Mn}$ is the n-th DD pseudorange rate from IMU. $\rho_{rb,IMU}^{Mn}$ and $\dot{\rho}_{rb,IMU}^{Mn}$ are calculated by the double difference from the position and velocity from the IMU data.

The pseudorange from IMU can be expressed as follow:

$$\rho=d+\delta\tau^{s}-\delta\tau^{u}+I+T\qquad(8)$$

$$d=\sqrt{\left(x_{r,IMU}-x_s\right)^2+\left(y_{r,IMU}-y_s\right)^2+\left(z_{r,IMU}-z_s\right)^2}\qquad(9)$$

where d is the distance from receiver to the satellite, $x_{r,IMU}$, $y_{r,IMU}$, $z_{r,IMU}$ are three axis position of the user receiver which can be calculated by IMU, x_s, y_s, z_s are the three axis position of the satellite which can be got from the broadcast ephemeris. $\delta\tau^{s}$ is the clock bias of the satellite, and $\delta\tau^{u}$ is the clock bias of the user receiver, I and T are error correction of ionosphere and troposphere.

The pseudorange rate from IMU can be expressed as follow:

$$\dot{\rho}_{IMU}=\upsilon_{IMU}-\upsilon_s+\delta\dot{\tau}^{s}-\delta\dot{\tau}^{u}\qquad(10)$$

where υ_{IMU} denotes the velocity from IMU, υ_s is the velocity of satellite from the broadcast ephemeris, $\delta\dot{\tau}^{s}$ is the clock drift of the satellite, and $\delta\dot{\tau}^{u}$ is the clock drift of the user receiver.

The DD pseudorange $\rho_{rb,IMU}^{Mn}$ can be expressed as follow:

$$\rho_{rb,IMU}^{Mn}=\left(\rho_{b}^{M}-\rho_{r,IMU}^{M}\right)-\left(\rho_{b}^{n}-\rho_{r,IMU}^{n}\right)\qquad(11)$$

where the superscript M means the master satellite, the superscript n means the n-th satellite, the subscript b means the base station and the subscript r means the rover station. $\rho_{r,IMU}^{M}$ is the pseudorange of the master satellite from IMU, $\rho_{r,IMU}^{n}$ is the pseudorange of the n-th satellite from IMU,

The DD pseudorange rate $\dot{\rho}_{rb,GNSS}^{Mn}$ can be expressed as follow:

$$\dot{\rho}_{rb,IMU}^{Mn}=\left(\dot{\rho}_{b}^{M}-\dot{\rho}_{r,IMU}^{M}\right)-\left(\dot{\rho}_{b}^{n}-\dot{\rho}_{r,IMU}^{n}\right)\qquad(12)$$

The observation matrix is expressed as follow:

$$H=\frac{\partial\vec{Z}}{\partial\vec{X}}=\begin{bmatrix}0_{1,3} & 0_{1,3} & e_1-e_M & 0_{1,3} & 0_{1,3}\\ 0_{1,3} & 0_{1,3} & e_2-e_M & 0_{1,3} & 0_{1,3}\\ \vdots & \vdots & \vdots & \vdots & \vdots\\ 0_{1,3} & 0_{1,3} & e_n-e_M & 0_{1,3} & 0_{1,3}\\ 0_{1,3} & e_1-e_M & 0_{1,3} & 0_{1,3} & 0_{1,3}\\ 0_{1,3} & e_2-e_M & 0_{1,3} & 0_{1,3} & 0_{1,3}\\ \vdots & \vdots & \vdots & \vdots & \vdots\\ 0_{1,3} & e_n-e_M & 0_{1,3} & 0_{1,3} & 0_{1,3}\end{bmatrix}\qquad(13)$$

where e_n is the LOS vector of the n-th satellite, e_M is the LOS vector of the master satellite.

Q matrix is for the noise covariance of the prediction process in the Kalman filter, the parameter of Q matrix should be employed by the IMU grade. Equation (14) is the typical one for the MEMS IMU.

$$Q=\begin{bmatrix}10^{-4}I_3 &&&&\\ & 0.04I_3 &&&\\ && 0_3 &&\\ &&& 4\times10^{-11}I_3 &\\ &&&& 10^{-5}I_3\end{bmatrix}\qquad(14)$$

R matrix is for the noise covariance of measurement. In this algorithm, the measurement is DD pseudorange and DD pseudorange rate, kinds of error has been eliminated by the DD process and the noise level is mainly decided by the CNR. This paper introduce a noise mode to establish the relation between the noise level and CNR as follow:

$$R=\begin{bmatrix}R_{\rho,1} &&&&&\\ & \ddots &&&&\\ && R_{\rho,n} &&&\\ &&& \frac{R_{\rho,1}}{100} &&\\ &&&& \ddots &\\ &&&&& \frac{R_{\rho,n}}{100}\end{bmatrix}\qquad(15)$$

$$R_{\rho,i}=10\sqrt{11000\times10^{\frac{CNR}{-10}}}\qquad(16)$$

Similarly, *P* matrix should be employed by the IMU grade. The initial *P* matrix is for the initial covariance matrix for these system states. It is initialized as follow:

$$P=\begin{bmatrix}2^{\circ 2}I_3 &&&&\\ & 0.1^2I_3 &&&\\ && 3^2I_3 &&\\ &&& 0.01G^2I_3 &\\ &&&& 200^{\circ}/h\ ^2I_3\end{bmatrix}\qquad(17)$$

This paper describes the tightly couple RTK/IMU algorithm as shown equations (6) to (17). The equations are used to correct IMU error and to ensure that the MEMS IMU will not diverge. Afterwards, IMU will provide an initial position in each epoch to detect multipath and cycle slip.

IV. Multipath and Cycle Slip

Multipath can be detected by IMU position. It is important to note that ρ can be obtained from GNSS receiver and can be estimated using IMU message at the same time. If there is no multipath presence in the pseudorange, the GNSS pseudorange measurement should be close to the pseudorange estimated from IMU, the difference between the pseudorange from

GNSS and the pseudorange from IMU is the residual of atmosphere correction mode and noise from code tracking loop. This can be expressed as follow:

$$\rho_k^{GNSS}-\rho_k^{IMU}=\varepsilon_{I,k}+\varepsilon_{T,k}+\varepsilon_{L,k} \quad (18)$$

where ρ_k^{GNSS} denotes the pseudorange from GNSS at the k-th epoch, ρ_k^{IMU} denotes the pseudorange from IMU, $\varepsilon_{I,k}$ is the residual error of ionosphere correction, $\varepsilon_{T,k}$ is the residual error of the troposphere correction, $\varepsilon_{L,k}$ denotes the white noise from the code tracking loop which is typical below 0.5m. $\varepsilon_{I,k}$is about tens of meters in extreme situation because of the broadcast ephemeris is not accuracy enough. The precise ephemeris can avoid this problem, but it is not available real time. Although the error of the broadcast ephemeris is existent, it will not change quickly among the adjacent epoch. So it will be eliminated by the difference between epochs. The multipath detection method can be shown as follow:

$$\left|(\rho_k^{GNSS}-\rho_{k-1}^{GNSS})-(\rho_k^{IMU}-\rho_{k-1}^{IMU})\right|>\delta_\rho \quad (19)$$

where ρ_k^{GNSS}, ρ_{k-1}^{GNSS} are the pseudorange from GNSS at the epoch k or k-1, ρ_k^{IMU},ρ_{k-1}^{IMU} are the pseudorange from IMU at the epoch k or k-1. Considering that the noise level of the code tracking loop, the value of thresholdδ_ρ is 1 meter. By equation(17), the multipath will be detected if it occurs. The detected multipath biased measurement will not be used in the RTK algorithm if there are enough satellites. If the number of measurements is low, leading that the information of the biased satellite is essential, its pseudorange will be calculated again by IMU data from equation (17), multipath problem can be decreased.

The other influence factor from the environment is cycle slip, cycle slip detection & recovery is also key point for the algorithm in this paper. If there is no cycle slip, the pseudorange difference between epochs should be close to the carrierphase difference between epochs, this can be expressed as follow

$$\rho_k^{GNSS}-\rho_{k-1}^{GNSS}=\varepsilon_L+\varepsilon_M+\phi_k-\phi_{k-1} \quad (20)$$

where ϕ_k , ϕ_{k-1} are the carrierphase measurement at epoch k or k-1. $\varepsilon_L$denotes the code tracking noise, ε_M is the error by multipath, the cycle length of carrierphase is about 0.2 meter, but the level of the code tracking noise and the multipath is above 0.5m. Only in extreme perfect situation, equation (18) can be used to detect cycle slip, however, it will fail to detect cycle slip in general.

The advantage of IMU is its short-term stability, it means that the difference position between is precise enough, and it is immune to the harsh environment. cycle slip detection & recovery method can be expressed as follow:

$$\varepsilon_\phi=\left|(\phi_k-\phi_{k-1})-(\rho_k^{IMU}-\rho_{k-1}^{IMU})\right|>\delta_\phi \quad (21)$$

where ϕ_k , ϕ_{k-1} are the carrierphase measurement at epoch k or k-1, ρ_k^{IMU},ρ_{k-1}^{IMU} are the pseudorange from IMU at the epoch k or k-1. $\varepsilon_\phi$denotes the residual error of carrierphase. The value of thresholdδ_ϕ should have several level, 0.2m, 1m. whenε_ϕ is bigger than 1m, it means that bit cycle slip has absolutely happens, the SD float ambiguity should be set again in the RTK kalman filter. if ε_ϕ is bigger than 0.2m, half cycle or small cycle slip may have happen, it should provide a warning information to the RTK implement to verify the carrirephase again. Once cycle slip is detected, the carrierphase will be given up or reset, the process method depends on the necessity of this measurement in the RTK implement.

From equations (18) to (21), this paper describes the detailed method of using the IMU data to avoid multipath and cycle slip problem in street environment. By these methods, the robust of the RTK algorithm in harsh environment will be improved obviously.

V. Experiment Setup

The test platform is consisted of two GPS/BDS/QZSS single frequency receivers and a low-cost MEMS IMU. Two receivers are implemented as base and rover stations, respectively. The rover is placed on the top of the test vehicle and the base station is placed on the roof of the research building of institute of industrial science. Test route is near the emperor square. The distance between the base station and the rover is about 7 Km.

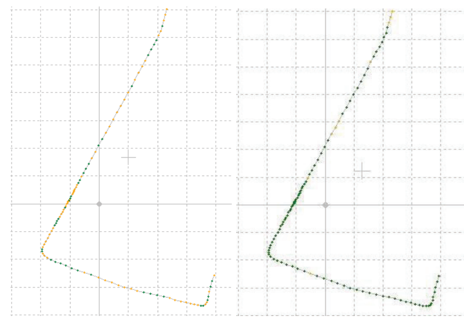

Fig. 2. result with RTK & RTK/INS tightly couple

Fig.2 shows the result with RTK or RTK/INS solution in the emperor square. In this figure, the blue point means that the ambiguities is "fixed" and the yellow point means that the ambiguities is "float". It is obvious that the RTK solution is easily influenced by kinds of street environment, however, the robustness of position is enhanced by RTK/INS tightly couple algorithm.

VI. Conclusion

This paper has described one solution of inertial-GPS integration for the purpose of obtaining inertially aided RTK. A RTK Algorithm is introduced. By the pure RTK solution, sometimes the ambiguity can been "fixed", however, it is easily influenced by street environment which is very common for automatic driving vehicle.

In a tightly coupled integration, the receiver is used as a source of observables. The integer ambiguity search function is combined with the integration Kalman filter, so that, the integer ambiguity search is by construction inertially aided. This form of integration demonstrated a perfect performance in street environment.

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