

USING LAND-VEHICLE STEERING CONSTRAINT TO IMPROVE THE HEADING ESTIMATION OF MEMS GPS/INS GEOREFERENCING SYSTEMS

Xiaoji Niu^{a,*}, Hongping Zhang^a, Kai-Wei Chiang^b, Naser El-Sheimy^c

^a GNSS Centre, Wuhan University, P.R.China – xjniu@whu.edu.cn; hpzhang@whu.edu.cn

^b Department of Geomatics, National Cheng-Kung University, Taiwan - kwchiang@mail.ncku.edu.tw

^c Department of Geomatics Engineering, University of Calgary, 2500 University Dr NW, Calgary, Alberta, T2N1N4 Canada - elsheimy@ucalgary.ca

Commission I, WG I/5 (or ICWG V/1)

KEY WORDS: GPS/INS, MEMS IMU, Land Vehicle Constraint, Direct-Georeference, Mobile-Mapping

ABSTRACT:

The integrated navigation systems of Global Positioning Systems (GPS) and Inertial Navigation Systems (INS) are used to provide direct-georeferencing for Mobile Mapping Systems (MMS). MEMS (Micro Electro-Mechanical Systems) inertial sensors have been developed to the stage that the GPS/INS integration systems based on low-cost MEMS IMU (Inertial Measurement Unit) are considered to be used as a cheap direct-georeferencing for mobile mapping, especially for the close-range vehicular photogrammetry systems. However, the limited performance of the MEMS sensors, especially the instability of the MEMS gyros, will give degraded orientation (e.g. heading) information, especially when the vehicle stops or creeps in traffic jams.

This paper presents a method to mitigate such heading degradation under zero or low speed challenging conditions by using the steering constraint of the land vehicle, which stands for the fact that most of the land vehicles will have bounded turning rate under certain speed because of their minimum steering radii. When the speed is low or zero, the steering constraint becomes tight and therefore can suppress the heading drift of the MEMS GPS/INS. Real field test results are given in the paper to show the contribution of the steering constraint to the heading accuracy, using some typical low-speed and static cases as detail examples. With appropriate parameter adjustment and quality control mechanism of the steering constraint, the results show clear improvement to the heading estimation for zero/low speed scenarios; and have no major side-effect to the other scenarios, e.g. high speed case and real vehicles turns. The steering constraint is an effective method to mitigate the heading degradation in zero/low speed condition for the MEMS GPS/INS georeferencing systems.

1. INTRODUCTION

Simultaneous developments in GPS and INS have lead to integrated GPS/INS systems that can provide direct-georeferencing for image-based mapping systems (Li, 2005). Such systems directly provide the position and attitude of cameras, necessary for subsequent mapping from the imagery, rather than it indirectly being determined from object-space control points. This has led to improvements in both the efficiency and cost-effectiveness of spatial data acquisition. Current implementations of the navigation sensors are based on high priced, restricted handling, navigation or tactical grade IMU. These constraints limit the applicability of MMS.

With the development of MEMS inertial sensors, GPS/INS integration systems based on low-cost MEMS IMU are considered to be used as a cheap direct-georeferencing for mobile mapping, especially for the close-range vehicular photogrammetry systems (Niu, 2006; El-Sheimy, 2007). For such low-cost georeferencing module, the position solution mainly relies on GPS; and the MEMS IMU focuses on providing attitude estimation through the GPS/INS integration. However, the limited performance of the MEMS sensors, especially the instability of the MEMS gyros, will give degraded attitude when the vehicle is lack of dynamics, e.g. when moves with constant speed or when the vehicle stops. The heading degradation might be from more than one degree to several degrees (Niu, 2006). The so called non-holonomic constraint of the land-vehicle can improve the heading accuracy

significantly when the vehicle moves with enough speed (Niu, 2007; Sukkarieh, 2000). But when the speed gets low or even zero, the non-holonomic update can barely contribute. So there is a blind zone for the heading update of the GPS/INS systems when the vehicle moves with little maneuver and with low/zero speed. In this blind zone, the heading has to fully count on the MEMS heading gyro, which normally causes angle drift of 0.01-0.05 deg/s (i.e. 0.6-3.0 deg/min).

Shin proposed a method to constrain the heading drift when the vehicle stops, which is called Zero Integrate Heading Rate (ZIHR) measurement (Shin, 2005). It regards the heading change between two epochs (e.g. with interval of 1 sec) should be zero when the vehicle stops. This algorithm can mitigate the heading drift effectively through updating the gyro bias. But it cannot cover the heading drift when the vehicle moves with very low speed, e.g. when the car is creeping in traffic jam.

Here we propose a method that can cover both the static case and the low speed case. It makes use of the steering constraint of the land vehicles. Most of the vehicles have their minimum steering radii; therefore will have bounded turning rate under given speed. When the speed is low, the possible steering rate becomes small; when the vehicle stops, the steering rate is limited to zero (i.e. ZIHR). Table 1 summarizes the measurements and constraints that can correct the heading drift from the INS under different driving conditions. It is clear that

* Xiaoji Niu. GNSS Centre, Wuhan University, 129 Luoyu Road, Wuhan, 430079, P.R.China. xjniu@whu.edu.cn

the steering constraint is the unique method to suppress the heading drift under low speed scenario.

	High dynamic (i.e. with maneuver)	Low dynamic (i.e. no maneuver)		
		High/mid speed	Low speed	Zero speed
GPS position and velocity				
Non-holonomic constraint				
Zero rate update (ZIHR)				
Steering Constraint				

Table 1. Heading updates of INS in different driving conditions

2. METHOD AND ALGORITHM

2.1 Direct Constraint

A simple way of using the steering constraint of the land vehicles is to apply the minimum steering radius to constrain the amplitude of the heading rate based on the vehicle speed, as shown in Equation (1)

$$\omega = \frac{v}{\rho} < \frac{v}{\rho_{\min}} \quad (1)$$

where ω = turning rate
 v = vehicle speed
 ρ = turning radius of vehicle
 ρ_{\min} = minimum turning radius of vehicle

Such implementation is straight-forward and is always true. But the given boundary will be too wide to be useful. For example, assume the vehicle moves as low as pedestrian, 1.5 m/s, giving the minimum turning radius of 4.0 m, we have the turning rate should be less than 21.4 deg/s according to Equation (1). This threshold is as large as the normal vehicle turning rate; therefore won't help to constrain the heading drift much. We have to implement the steering constraint in another way that is more efficient.

2.2 Pseudo Measurement Method

The steering constraint can be translated to the following logic. The vehicle's turning rate has some positive relation to the vehicle's speed in a statistic manner, i.e. the vehicle has less possibility to turn with high rate when it moves slowly. To implement this logic, we construct a pseudo heading change measurement saying that the heading change is always zero between two epochs; and the corresponding variance of this pseudo measurement is set based on the vehicle's speed. The lower the speed, the more likely the pseudo measurement tends to be true; and vice versa. When the speed becomes zero, the pseudo measurement becomes strictly true and degenerates to the ZIHR measurement.

The zero heading change assumption is essentially the zero heading rate assumption, i.e.

$$\dot{\psi} = 0 + n_{SC} \quad (2)$$

where ψ = the vehicle heading
 n_{SC} = the equivalent noise to reflect the uncertainty of the zero heading rate assumption (the subscript "SC" stands for steering constraint), whose variance is

$$Var(n_{SC}) = \left(\alpha \cdot \frac{1}{3} \cdot \frac{v}{\rho_{\min}} \right)^2 \quad (3)$$

where α = adjustment coefficient
 v = vehicle speed
 ρ_{\min} = minimum turning radius of vehicle

Here the uncertainty of the zero heading rate assumption is actually modelled as a zero mean Gaussian noise; and the maximum possible turning rate according to the minimum turning radius is set as the three sigma of the Gaussian distribution (i.e. where the 1/3 comes from in the equation). The adjustment coefficient α is used for tuning the strength of the steering constraint. The coefficient should not be too large (e.g. close to 1.0) that make the constraint too loose; it can not be too small either that will suppress the real heading change.

The vehicle's heading rate in Equation (2) can be approximated as the angular rate along the z axis in IMU frame based on the following assumptions that fit MEMS sensors and the land vehicle driving condition: a) the MEMS IMU is aligned with the vehicle; b) the earth rotation rate can be ignored; c) the roll and pitch of the vehicle are small. Combined with the error model of MEMS gyro, we have

$$\omega_{ib}^{b(z)} = \hat{\omega}_{ib}^{b(z)} - b_{gz} - n_{gz} \approx \dot{\psi} = 0 + n_{SC} \quad (4)$$

i.e.

$$\hat{\omega}_{ib}^{b(z)} = b_{gz} - n_{gz} + n_{SC} \quad (5)$$

where $\omega_{ib}^{b(z)}$ = angular rate along the z axis in IMU frame
 $\hat{\omega}_{ib}^{b(z)}$ = heading gyro output
 b_{gz} = bias of the heading gyro
 n_{gz} = noise of the heading gyro

According to Equation (5), the zero turning rate assumption is eventually converted to a measurement equation to update the gyro bias. The noises of this measurement include two parts, the white noise of the gyro sensor and the artificial noise that reflect the uncertainty of the zero turning rate assumption. These two noises can be regarded as independent to each other and merged as one noise with sum of their variances. Equation (5) can be further integrated in the interval between two epochs to get the zero heading change measurement equation, which can make full use of the information between the two epochs

and mitigate the impacts such as the gyro noise and the vehicle bumps.

It is easy to imagine that the zero heading rate (or the zero heading change) measurement equation will be met well when driving straight; but it will be broken when making turns, especially when making turns with low speed. Preliminary results also show that it is hard to come up with a compromised adjustment coefficient (α) to fulfil both the straight road driving and the intersection turning. Therefore, a quality control mechanism has to be introduced to deal with the vehicle turning cases. Here a standard innovation based quality control is applied to the zero heading change measurement update in the GPS/INS Kalman filter. Any measurement with innovation outside the computed $\pm 3\sigma$ will be rejected. Such quality control policy works well in the real tests.

2.3 Algorithm Implementation

The above algorithm in section 2.2, i.e. the idea of the zero heading change measurement was implemented base on a software platform called AINSTM toolbox, developed in the Mobile Multi-Sensor Systems (MMSS) Group at the University of Calgary. It is an Aided Inertial Navigation System MATLAB[®] Toolbox for integrating GNSS and INS data (Shin and El-Sheimy, 2004). AINSTM uses an extended Kalman Filter (EKF) to optimally combine GNSS positions and velocities with inertial data. Data from other aiding sensors, such as odometers or heading sensors can also be used, or non-holonomic constraints can be applied. In addition to forward filtering, the toolbox can perform backward smoothing using the Rauch-Tung-Striebel (RTS) smoother. The smoothing solution can be basically regarded as the optimal weighted average of the forward filtering and backward filtering. It essentially makes full use of the information of the whole dataset to estimate the position and attitude at each time epoch (Shin, 2005). Therefore its accuracy is significantly better than the forward Kalman filtering. Smoothing is very appropriate for post-processing missions, including mobile mapping. (El-Sheimy, 2007)

The proposed zero heading change measurement was inserted in the sequential measurement updates of the Kalman filtering algorithm in AINSTM. The adjustment coefficient (α) and the innovation-based quality control were tuned to the point that the steering constraint update can constrain the heading drift effectively when the vehicle stops or moves straight with low speed; and gives little impact to the real heading turns, i.e. has little side-effect to the heading estimation in general.

3. TEST RESULTS AND DISCUSSIONS

3.1 Test Conditions

The datasets to verify the effect of the steering constraint were selected carefully. Two Calgary downtown datasets and one university campus dataset, which have consecutive stops and slow creeps because of the traffic and intersections, were chosen to check the contribution of the steering constraint. The downtown test trajectories are shown in Figure 1. There are serious GPS signal blockages and multi-path interferences in the downtown core area. The campus test trajectory is shown in Figure 2. It includes different kinds of turns and has medium GPS signal blockages.

The objective testing system is a GPS/INS integrated navigation system using a MEMS IMU composed of the MEMS inertial sensors from Analog Devices Inc. (ADI) and GPS receiver from NovAtel (Analog Devices Inc., 2003; Niu, 2005). Double-difference carrier phase derived GPS positions and velocities were used as the GNSS update, because they are available for post processing in the mobile mapping system without much additional cost. To help to maintain the position accuracy during GPS signal outages and degradations, the non-holonomic constraint and the odometer signal of the vehicle are applied in the data processing (Niu, 2007). Both the forward filtering and the backward smoothing processes are performed to the datasets.

In the tests, the reference for the position, velocity and attitude comes from the smoothed best estimates (SBET) of a high-grade DGPS/INS system (POS AV) from Applanix Corp., which uses a tactical-grade IMU (1.0 deg/h). The attitude accuracy of the reference solution is known to be 0.02° for roll and pitch, and 0.05° for heading, when there are continuous GPS updates. It is qualified to be used as the true attitude for the MEMS system that has heading error from half a degree to a few degrees.



Figure 1. Trajectories of downtown tests



Figure 2. Trajectories of campus test

3.2 Typical Results

Two typical cases are given to show the contributions of the steering constraint. Since the heading drifts during low/zero speed periods can be somehow hidden in the backward smoothing results, here we present the forward filtering results to show the difference more clearly.

Figure 3 is the result of a portion of one downtown test that suffered heavy traffic in the areas with intensive skyscrapers. The upper subplot is the heading error of the MEMS GPS/INS system (using the tactical grade IMU as the truth); the lower subplot gives the bias estimation of the heading gyro just for reference. Here please note that the heading error is somewhat biased from zero for about +0.6 deg, as shown by the black dash-dot line on the plot. This is because the MEMS IMU is not perfect aligned with the tactical grade IMU. Therefore, when we calculate the heading error of the MEMS system, it should be the variation from the dash-dot line at +0.6 deg.

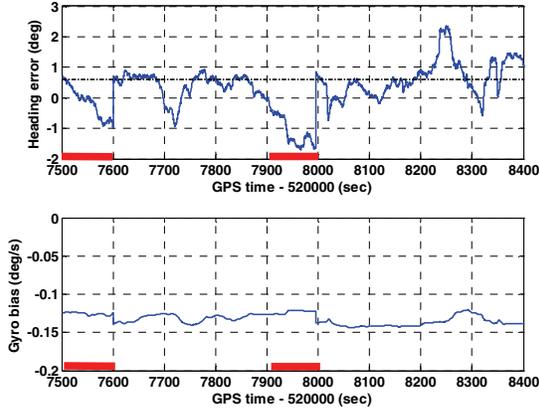


Figure 3. Heading estimation without using steering constraint

The heading error plot shows several clear heading degradations at some points. Two of them happened when the vehicle moved slowly or stopped, as highlighted by the red bars. For the first one (from 7500s to 7600s), the vehicle was stopped by the traffic and with only a small straight movement in the middle of the period; the GPS signal was blocked completely. The heading drifts to the negative side for about 1.5 deg because there was no update information to constraint it. For the second heading degradation, the vehicle was creeping and halting on a straight street where GPS had either no fixing or only a few wrong position fixings. The heading drifted to the negative side for about 2.0 deg because of the misleading by the wrong GPS points and the lack of heading update information in low speed.

Figure 4 shows the driving conditions of the vehicle by the vehicle speed and turning rate (i.e. heading gyro output). Figure 5 shows the serious GPS outages and the wrong GPS fixing during the second GPS degradation case.

The steering constraint algorithm, i.e. the zero heading change update, was applied to the dataset. The result is shown in Figure 6. Compare to Figure 3, the heading drift reduces from 1.5 deg to 0.8 deg for the first case; and from 2.0 deg to 1.6 deg for the second case respectively. Compare the gyro bias estimation in the lower subplot, it was kept updated by the steering constraint; while the one in Figure 3 tended to stay as it is. This is the root cause of the heading improvement by the steering constraint, as discussed in the algorithm section. The second case also shows that the steering constraint can not only mitigate the heading drift from the IMU, but also mitigate the heading disturbance by the poor GPS.

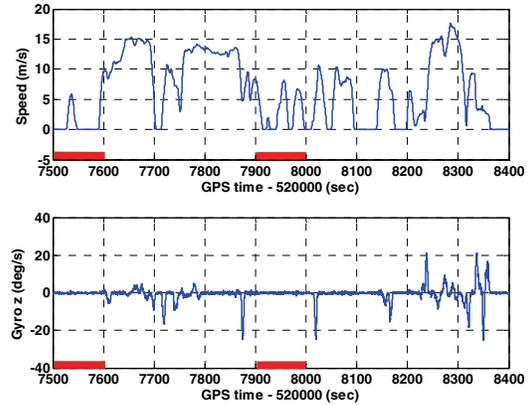


Figure 4. Driving conditions of downtown test

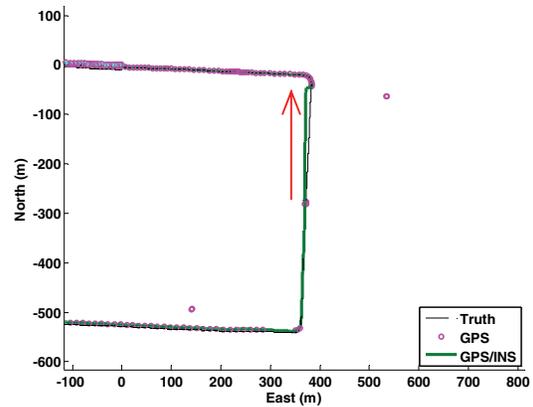


Figure 5. Poor GPS condition during the 2nd heading degradation case

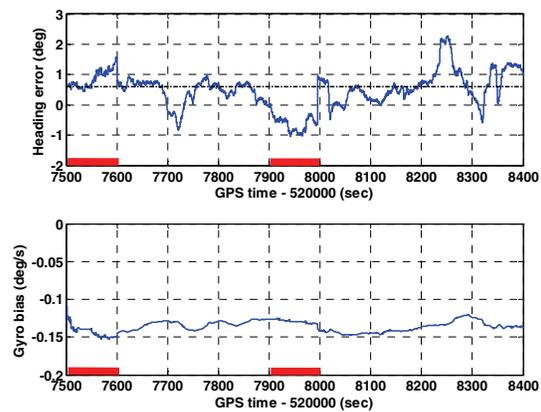


Figure 6. Heading estimation with using steering constraint

It is worth mentioning that there are other heading drift cases in Figure 3 and Figure 6, such as 7690s – 7740s, 8230s – 8265s. But they happened under normal driving speed and with heading turns (as shown in Figure 4), which can't be improved by the steering constraint in principle.

The rest parts of heading error shown in Figure 3 and Figure 6 are almost the same, which means the steering constraint doesn't affect the heading accuracy when vehicle turns or moves with high/mid speed. In other word, the steering constraint doesn't prohibit the real heading change, even when the vehicle moves in very low speed. A convincing example is the end part of the dataset (8340s – 8370s) when the vehicle made consecutive turns under very low speed in a parking lot. Such no side-effect advantage mainly comes from the innovation-based quality control mechanism in the zero heading change update equation of the Kalman filter.

Other downtown and campus datasets show the similar results as the examples given above. Here it should be note that the steering constraint method can only improve the heading accuracy in specific scenarios; and those scenarios only occupy a very small portion of the normal road test data. Therefore it can not improve the general performance of the MEMS GPS/INS systems. Table 2 is the summary of the navigation errors (backward smoothing result) in the campus test, which can be regard as a representative of the MEMS system performance under the mid level GPS signal blockage.

	Pos_error (m)		Att_error (deg)	
	x/y	z	x/y	z
RMS	0.33	0.50	0.11	0.28
Max	1.27	2.08	0.55	1.65

Table 2. Statistic error of MEMS GPS/INS system

4. CONCLUSIONS

The results and analysis have shown that the proposed steering constraint method can effectively mitigate the heading drift issue of the MEMS GPS/INS systems when the vehicle moves with low speed or stops, especially when GPS is blocked or degraded. Meanwhile, it has little side-effect to any real heading turns of the vehicle.

With the improvement to the heading estimation by the steering constraint method, the orientation information provided by the MEMS GPS/INS system becomes more robust and consistent. Its performance is one more step close to meet the requirements of the direct georeferencing, especially for the close-range vehicular photogrammetry systems which require lower levels of georeferencing.

REFERENCES

Analog Devices Inc., 2003. Datasheet of $\pm 150^\circ/s$ Single Chip Yaw Rate Gyro with Signal Conditioning: ADXRS150. Product datasheet. <http://www.analog.com/MEMS>.

El-Sheimy, N. and Niu X., 2007. The Promise of MEMS to the Navigation Community. *Inside GNSS*, March 2007.

Li, J., and Chapman, M., 2005. Introduction to MMS. Special Issue, Journal of The American Society for Photogrammetry and Remote Sensing, 71(4), April 2005.

Nassar, S., Syed, Z., Niu, X. and El-Sheimy, N., 2006. Improving MEMS IMU/GPS Systems for Accurate Land-Based Navigation Applications. In: *The Institute of Navigation National Technical Meeting (ION NTM 2006)*, Monterey, California, USA, January 18-20, pp. 523-529.

Niu, X. and El-Sheimy, N., 2005. Development of a Low-cost MEMS IMU/GPS Navigation System for Land Vehicles Using Auxiliary Velocity Updates in the Body Frame. In: *The US Institute of Navigation Satellite Division Technical Meeting*, Long Beach, California, Sep 13-16, 2005, pp. 2003-2012.

Niu, X., Hassan, T., Ellum C., and El-Sheimy, N., 2006. Directly Georeferencing Terrestrial Imagery using MEMS-based INS/GNSS Integrated Systems. In: *XXIII FIG (International Federation of Surveyors) Congress*, Munich, Germany, 8-13 October 2006.

Niu, X., Nassar, S. and El-Sheimy, N., 2007. An Accurate Land-Vehicle MEMS IMU/GPS Navigation System Using 3D Auxiliary Velocity Updates. *Navigation*, Journal of the Institute of Navigation, USA. 54(3), Fall 2007, pp. 177-188

Shin, E. H. and El-Sheimy, N., 2004. Aided Inertial Navigation System (AINSTTM) Toolbox for MatLab[®] Software, INS/GPS integration software. Mobile Multi-Sensors System (MMSS) research group, the University of Calgary http://mms.geomatics.ucalgary.ca/Research/Tech%20transfer/1NS_toolbox.htm

Shin, E. H., 2005. Estimation Techniques for Low-Cost Inertial Navigation. PhD Thesis, MMSS Research Group, Department of Geomatics Engineering, University of Calgary, Calgary, AB, Canada, UCGE Report No. 20219.

Sukkarieh, S. (2000). Low Cost, High Integrity, Aided Inertial Navigation Systems for Autonomous Land Vehicles. PhD Thesis, Australian Centre for Field Robotics, Department of Mechanical and Mechatronic Engineering, The University of Sydney, Sydney, Australia.

ACKNOWLEDGEMENTS

This study was partially supported by research grants from the Natural Science and Engineering Research Council of Canada (NSERC) and the Canadian Geomatics for Informed Decisions (GEOIDE) Network Centers of Excellence (NCE) awarded to Dr. Naser El-Sheimy.

Dr. Eun-Hwan Shin is acknowledged as the primary author of the AINSTTM toolbox used for the data processing. Dr. Chris Goodall, Dr. Zainab Syed, Dr. Sameh Nassar, and Dr. Yong Yang are acknowledged for conducting the field test together.