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# Cycle slip detection and fixing by MEMS IMU/GPS integration for mobile environment RTK-GPS

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RTK-GPS (realtime kinematic GPS) is one of the most precise positioning technology, with which users can obtain cm-level accuracy of the position in realtime by processing carrier-phase measurements of GPS signals. RTK-GPS has been already utilized for many applications like surveying, construction, agriculture and transportation. Recently, some researchers have tried to apply RTK-GPS to precise navigation of a mobile vehicle. On the condition under the clear sky, RTK-GPS provides fair performance even in the mobile environment. The performances includes availability of solutions, accuracy, TTF (time to fix), and reliability of integer ambiguity resolutions. However, in urban area like in a downtown street, RTK-GPS shows poor performance. One reason of the performance degradation on such condition is cycle slips. Cycle slips are defined as the discontinuities in the measured carrier-phase caused by loss-of-lock of signal tracking in GPS receivers. A sudden jump of the carrier-phase measurement forces the integer ambiguity discontinuity. The Main sources of the cycle slips are obstructions of GPS signals due to buildings, trees or bridges. So the cycle slips much more occur in mobile environment than in static conditions. In the most of the RTK-GPS receivers, once a cycle slip detected, the estimated integer ambiguity is reset to the initial state. This reinitialization process often takes a few minutes, so the precise solution is not provided in the period. With frequent cycle slips, the availability of the RTK-GPS solutions becomes very low. Additionally, it is not easy to recognize a small cycle slip in the mobile environment. The miss-detection of the cycle slip much degrades the RTK-GPS accuracy. Reliable cycle slip detection is more important on this situation. One of the major technical issues for the mobile environment RTK-GPS is to overcome the cycle slips.

For mobile vehicle navigation with GPS, a low-cost MEMS (micro-electro-mechanical systems) IMU (inertial measurement unit) is sometimes integrated to improve the performance. In such GPS/IMU integrated system, the IMU is used to obtain user positions and velocities during the GPS signal outages. For mobile environment RTK-GPS, this IMU integration is also effective to improve the navigation conditions. In this study, we employed tightly coupled GPS/IMU integration in order to detect and repair the cycle slips for RTK-GPS. As for the tightly coupled GPS/IMU integration, the user position, velocity and attitude are estimated by EKF (extended Kalman Filter) by using both of GPS and IMU measurements. The sensor biases of the gyros and accelerometers of the IMU are also incorporated in the filter, because sensor biases of a MEMS IMU are relatively large and time-varied. In addition to these unknown states, the double-differenced integer ambiguities are estimated in the case of RTK-GPS. The

estimated float ambiguities by EKF are resolved into integer value by a usual integer ambiguity resolution way for RTK-GPS.

In this study, in the measurement update of EKF, pre-fit residual of the double-differenced carrier-phase measurement, that is the difference between the predicted and observed state, is compared to the pre-defined threshold for the cycle slip detection. The measurement with larger residual than the threshold is marked as a candidate of the phase discontinuity by a cycle slip. After all the checks, the algorithm enters to the cycle slip repair process. The mount of the each cycle slip has usually the integer value of cycle. So the cycle slip amount as the unknown parameters, the integer vector search process runs to obtain the best estimated integer vector to minimize the least square residuals according to the covariance matrix of the predicted receiver position. To reduce computational cost to solve this ILS (integer least square) problem, the well known efficient strategy LAMBDA is employed to search proper integer vector in this study. Once best solution of the integer vector obtained, it is validated by simple ratio-test with the best and the second best solutions of ILS. If this discrimination test is passed, the states of the carrier phase integer ambiguities are updated by adding the integer vector to repair the cycle slips. If the test failed, the integer ambiguities are reinitialized and restart estimation process from guess estimation values. This proposed cycle slip detection and repair process can be applied to usual RTK-GPS algorithm without the IMU. However, it is hard to provide good performance without an IMU because of the low accuracy of the predicted user position.

We made some field tests to demonstrate and evaluate proposed GPS/IMU integration scheme to detect and repair cycle slip for mobile environment RTK-GPS, NovAtel OEM-V dual-frequency GPS receivers were used for both of the mobile receiver (rover) and the reference station. The rover GPS antenna is mounted to the rooftop of a car. Analog Devices AD16354 6-DOF MEMS IMU device are also fixed on the car body. The rover receiver and IMU were connected to a laptop PC to record raw measurement data. At first we drove the car around the area with clear sky and few obstructions to acquire the raw measurement data of GPS and IMU. We processed the raw measurements of only GPS in the simulated RTK-GPS mode of RTKLIB. RTKLIB is a GPS post processing analysis software developed by the authors but has no function of the IMU data handling originally. Under such good condition, few cycle slips occurred and the RTK-GPS solutions showed the smoothed ground track. Next, we added the artificial integer cycle jumps to the raw carrier phase measurement of GPS to simulate the cycle slips. In this case, the availability of precise solution much decreased and some miss-detections of the cycle slips caused the sudden jumps of the car track. Furthermore, we implemented the proposed tightly coupled GPS/IMU integration and cycle slip detection and repair functions described above. The cycle slip detection and repair function with the IMU could fairly detect and repair the simulated cycle slips and made the ground track of the solutions smooth. The evaluation results are also demonstrated in more realistic situations like at the downtown streets with many cycle slips.