Cycle Slip Detection and Fixing by MEMS IMU/GPS Integration for Mobile Environment RTK-GPS

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Background

RTK-GPS under Open Sky   RTK-GPS on Downtown Street

• Fixed Solution   • Float Solution
Mobile RTK-GPS in Urban Area

• A lot of issues to be resolved:
  – Multipath (code, carrier-phase)
  – Signal outage/data gap
  – False tracking in receiver
  – Communication link interruption
  – ...
  – Cycle slip
Cycle Slip

• Discontinuity in the carrier-phase measurement caused by loss-of-lock of signal tracking in a GPS receiver

• Integer cycle (or +half cycle) jump appears in carrier-phase ambiguity

• Most slips are caused by signal obstructions due to surrounding obstacles, like buildings, trees, bridges, poles, cars,…

• Far more slips in the mobile condition
Cycle Slip in Urban Area

Sky Plot of Satellites: Cycle Slips
Typical Cycle Slip Pattern

Carrier-Phase

Receiver Detects Loss-of-Lock

Signal Outage/Data Gap

Cycle Slip

Reacquisition (<1s)

Half-Cycle Ambiguity Resolution (0-12s) *

* Depend on Receiver
Statistics of Cycle Slips

- Most data gaps are shorter than 10 s.
- With short data gaps, cycle slips could be fixed aided by INS?
- If slips fixed, availability of solution could be much improved.

T<1s: 724 (68.2%)
T<3s: 869 (81.8%)
T<5s: 932 (87.8%)
Cycle Slip Detection

• Various ways:
  – Receiver loss-of-lock indicator or lock-time
  – Detect jump of L1-L2 Geometry-Free LC
  – Phase prediction with delta-range
  – Innovation test in navigation filter …

• Combination of multiple methods to ensure the reliability

• It’s effective aided by INS?
Cycle Slip Fixing

- Most receivers have no cycle slip fixing. If detecting a slip, just reinitialize and restart the ambiguity estimation.
- Someone employ “slip-free” solutions, like instantaneous AR. But its performance greatly depends upon the quality of code observables. May not be practical under ill multipath environment.
- It’s hard, but feasible aided by INS?
Conventional RTK-GPS

Rover

GPS Receiver

ρ_r, φ_r

RTK-GPS

ρ_r, φ_r

Rover Position

ρ : Pseudorange
φ : Carrier Phase

ρ_b, φ_b

Base Station
INS Aided RTK-GPS

**IMU**
- $\omega_i, a_i$

**GPS Receiver**
- $\rho_r, \dot{\rho}_r$
- $\rho_r, \phi_r$

**INS/GPS Navigation**
- $\hat{v}_{ins}, Q_{\hat{v}_{ins}}$

**INS/RTK-GPS Integration**
- $\hat{r}_{rtk-ins}$

**Rover Position**

**GPS Receiver**
- $\rho_b, \phi_b$

**Base Station**

- $\rho$: Pseudorange
- $\dot{\rho}$: Delta Range
- $\phi$: Carrier Phase
- $\omega$: Angular Rate
- $a$: Acceleration
INS/GPS Navigation

IMU

$\omega_i, a_i$

INS Navigation

$\tilde{\psi}_i, \tilde{v}_i, \tilde{r}_i$

INS/GPS Integrated EKF

$(\delta\psi_i, \delta v_i, \delta r_i, b_g, b_a)$

GPS Receiver

$\rho_r, \dot{\rho}_r$

$\hat{\psi}_{ins}, \hat{v}_{ins}, \hat{r}_{ins}$
INS/RTK-GPS Integration

\[ \hat{r}_k(\cdot) = \hat{r}_{k-1}(\cdot) + (\hat{v}_{ins,k} + \hat{v}_{ins,k-1})(t_k - t_{k-1}) / 2 \]

\[ P_{r,k}(\cdot) = P_{r,k-1}(\cdot) + (Q_{\hat{v}_{ins,k}} + Q_{\hat{v}_{ins,k-1}})(t_k - t_{k-1}) / 2 \]
Cycle Slip Detection/Fixing

- Cycle slip detection
  - Innovation test in RTK-GPS Filter
  - Test threshold is determined by position covariance with INS velocity covariance
- Cycle slip fixing
  - Slip amounts are estimated as float values with predicted position aided by INS
  - Estimated slips are resolved into integer values in usual RTK-GPS ILS solver process
Experiments

Drive Rover with GPS/IMU

Under Open Sky

Baseline Analysis

Raw GPS Data (4Hz)

Cycle Slip Simulation

Raw IMU Data (50Hz)

Proposed Algorithm

Simulated GPS Data

Evaluation

Reference Trajectory

INS-Aided RTK-GPS Solutions
Configuration

Rover (Car)
- NovAtel GPS-702
- Splitter
- MEMS-IMU
- NovAtel OEMV-3 (L1/L2)
- u-blox AEK-4T x 3 for Reference Attitude

Base Station
- NovAtel OEMV-3 (L1/L2)
- SPI/USB Adapter
- USB Hub
- Laptop PC (Data Logger)
MEMS-IMU

- Analog Devices ADIS16354
  - Tri-axis Gyros+Accelerometers
  - 23 x 23 x 23 mm
  - Range: ±300°/s, ±1.7g
  - Embedded ADC/Filter, SPI I/F
  - Factory calibrated sensitivity, alignment with temperature sensors
  - Price: $700/sample
Snapshots

MEMS-IMU

GPS-702 Antenna

MEMS-IMU
Reference Trajectory

2008-09-05
5:42:00 - 5:49:30 GPST
7 min 30 s

Baseline Length: 0.0 - 0.9 km
Simulated Cycle Slips

(1) A Few Slips

(2) Moderate Slips

(3) Extreme Slips

# of slips:

- A Few Slips: 81
- Moderate Slips: 388
- Extreme Slips: 718
(1) A Few Cycle Slips

Without INS

With INS

Position Error

1m

Fixed Solution

Float Solution
(2) Moderate Cycle Slips

Without INS

With INS

Position Error

1m

Fixed Solution

Float Solution
(3) Extreme Cycle Slips

Without INS

- Position Error

With INS

- Position Error

Fixed Solution

Float Solution
<table>
<thead>
<tr>
<th>Case Description</th>
<th>Without INS</th>
<th>With INS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Availability of Fixed Sol. / RMS Error E-W,N-S,U-D (cm)</td>
<td></td>
</tr>
<tr>
<td>(1) A Few Slips</td>
<td>92.9%</td>
<td>93.0%</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>(2) Moderate Slips</td>
<td>58.8%</td>
<td>64.5%</td>
</tr>
<tr>
<td></td>
<td>74.2</td>
<td>125.6</td>
</tr>
<tr>
<td>(3) Extreme Slips</td>
<td>28.4%</td>
<td>48.4%</td>
</tr>
<tr>
<td></td>
<td>346.6</td>
<td>573.4</td>
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</tbody>
</table>
Summary and Conclusions

• A simple integration scheme of GPS/INS Navigation to RTK-GPS filter is proposed
• Cycle slip detection and fixing aided by INS is feasible and effective especially on the condition with extreme cycle slips
• Needs more experiments in the real situations with ill multipath environment
• Direct integration of INS measurements to RTK-GPS filter improves the performance?