Implementation and performance evaluation of a fast relocation method in a GPS/SINS/CSAC integrated navigation system hardware prototype

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Abstract: In this paper, a fast relocation method is proposed, implemented and evaluated in a DSP/FPGA based GPS/SINS/CSAC deep integration hardware prototype. For the GPS receiver, when signal appears after the signal blockage or signal interference, the precise time information based on the reference of the CSAC and the position information from the SINS combined with the ephemeris can be used to calculate the frame counts and aid the realization of the fast relocation. A field test is conducted to verify and evaluate the performance of the algorithm. The results demonstrate that the proposed fast relocation algorithm can largely reduce the receiver relocation time. The result shows the relocation can be realized during 1 second while the traditional receiver usually needs at least 6 seconds for the relocation after the signal blockage.

Keywords: chip scale atomic clock, deep integration, fast relocation, signal blockage, field test

Classification: Integrated circuits

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1 Introduction

Positioning, navigation and timing (PNT) is very important for vehicles, aircrafts, robots, pedestrians and military use. The Strap-down Inertial Navigation System (SINS) is an autonomous navigation system which can provide short-term reliable navigation information (attitude, velocity and position) for most vehicles [1, 2, 3]. The SINS measures the acceleration and the angular velocity by the inertial sensors, and calculates the position, velocity and the attitude based on a navigation algorithm. However, the accuracy of the provided information depends on the inertial sensors (gyrosopes and accelerometers) and the navigation errors accumulates with the time [4, 5]. The Global Positioning System (GPS) is a radio-defined navigation system which can provide real-time, all-weather, and global navigation information (position, velocity, and time). However, the satellites are thousands of kilometers away from the ground and the signal transmission power is weak. The signal blockage and the signal interference can cause the interruption of the navigation. The integration of the navigation systems is an effective way to overcome the drawbacks and improve the PNT performance. The introduced SINS is usually to aid the signal acquisition and signal tracking. The errors of the SINS can be corrected by the integration filter. Previous study focused on the modeling and analysis and implementation of the SINS aided tracking loop and this method definitely improves the performance of the tracking loop in several GPS denied environments [6, 7].

Atomic clocks can provide the most-precise frequency reference for humans. The frequency accuracy of atomic clocks is several orders of magnitude higher than that of crystal oscillators. The chip scale atomic clock (CSAC) is fabricated by USA National Institute of Standard and Technology in 2002. The size, weight, power, and cost of CSAC are considerably better than those of traditional rubidium atomic clocks. CSAC has higher than $10^{-10}$ at 1 s stability [8, 9, 10, 11]. For PNT applications, CSAC can be treated as the time reference and improves timing accuracy.

In this paper the CSAC was introduced to GPS/SINS integration system. A GPS/SINS/CSAC coupled navigation system based on DSP+FPGA was devel-
oped. The system can still provide precise PNT in the signal challenged environment for short time. And when signal appears after the signal blockage or signal interference, a fast relocation method was proposed and tested in the integration system.

The paper is organized as follows: The section two introduces the design of the hardware prototype. And the section three introduces the principle of the frame synchronization. And the section four introduces the principle of the proposed algorithm. The section five describe the details of the field test and the results.

2 The design of the hardware prototype

The architecture of the GPS/SINS/CSAC integration is described in the Fig. 1. The integration system is composed of six blocks, namely GPS RF front end module, strap-down inertial navigation system module, GPS baseband signal processing module, integration filter module, chip scale atomic clock module (CSAC) and the aided function module. The details are as follows:

1) GPS RF front end module: GPS RF module receives the signal through all visible satellite antenna, and then converting it to intermediate frequency signal. Finally it is sampled by Analog to Digital (A/D) chip, and then the analog IF signal is processed as discrete digital signal.

2) SINS module: The SINS calculates the position, velocity and attitude using the data from the IMU. And then the information is converted to GPS receiver to aid the signal acquisition, signal tracking and relocation.

3) GPS baseband signal processing module: The task of the GPS baseband signal processing module is to generate the copy signal of the received signal, and then the local signal is mixing with the receiver signal. In this way, the Doppler frequency shift and the code phase can be acquired to calculate the velocity and position.

4) Integration filter module: The main task of the integration filter module is to estimate the correctness of the SINS module. A Kalman filter is the commonly used algorithm. The pseudo range/pseudo range rate information is usually to build the
observation vector. The estimated errors of IMU device are feedback to the SINS module to correct the navigation solutions.

5) Aided function module: The time information from the CSAC and the navigation information from the SINS are employed to aid the signal reacquisition and relocation of the system.

6) Chip scale atomic clock module: The CSAC is used as a time reference at 10 MHz. When the signal is blocked, the CSAC can provide the precise time to aid the frame count calculation and the relocation of the GPS receiver.

3 Frame synchronization

The section is about the position principle of the GPS receiver and the relationship with the GPS navigation message. The GPS navigation message is in units of frame, each frame is divided into five sub-frames. Sub-frame data block consists of 10 words at a length of 30 bits, each bit length is 20 ms. The beginning of each sub-frame is the telemetry word (TLW) and handover word (HOW). TLW contains a fixed 8-bit preamble (10001011) which is used to identify the beginning of each sub-frame. The HOW provides the time of a GPS week and a sub-frame corresponding to the next starting edge. Taking into account that the definition of pseudo-range is:

$$p = c \times (t - t^{(i)})$$  \hspace{1cm} (1)

In order to get the transmit time of the satellite signal, the start of the frame must be determined and get the week counts, second counts, word counts, and bit counts. And the Fig. 2 is the details of the composition of the transmission time. The formula of calculating the transmit time is as the following formula:

$$t^{(i)} = TOW + (30W + b) \times 0.02 + \left( \frac{CP}{1023} + \frac{CDP}{1024 \times 1023} \right) \times 0.001$$ \hspace{1cm} (2)

Where the $TOW$ represented the GPS time-of-week modulo 6 seconds and corresponding to the leading edge of the next sub-frame. $W$ indicates the counts of the received words in the current frame. The variable $b$ represents the counts of the received bits in the current word. The variable $d$ means the counts of the
received C/A cycle (ms), $CP$ indicates the current code phase measurements, $CDP$ indicates the current carrier cycle count.

When the signal is blocked, the navigation messages cannot be acquired any more. Under this circumstance, the variables in the equation (2) cannot be calculated from the navigation message. Then the receiver cannot provide precise PNT information. When the signal appears again, it needs at least several second to get the navigation message to calculate all the variables.

4 The fast relocation method

Once the signal appears, the receiver should provide navigation information as soon as possible. The traditional method cost at least 6 seconds from the above analysis. When the GPS receiver fails to output the position, velocity and timing information during the signal blockage, the inertial system can still provide precise navigation information within several minutes, the CSAC can provide precise local time. The precise local time from the CSAC, the position and velocity information form the SINS and the ephemeris are combined to calculate the pseudo-range and the Doppler shift. The known pseudo-range can be used to figure out the transmission time according to the following equations:

$$t^{(s)} = \left[ t^{(r)} - \rho_{sv} / c \right] / C_{26}$$

$$\rho_{sv} = \sqrt{\left( x_{\text{Sat}} - x_{\text{SINS}} \right)^2 + \left( y_{\text{Sat}} - y_{\text{SINS}} \right)^2 + \left( z_{\text{Sat}} - z_{\text{SINS}} \right)^2} / C_{138}$$

Where the $x_{\text{Sat}}, y_{\text{Sat}}$ and $z_{\text{Sat}}$ are the position of a satellite in ECEF coordinate. The $x_{\text{SINS}}, y_{\text{SINS}}$ and $z_{\text{SINS}}$ are the SINS position in ECEF coordinate. The $t^{(s)}$ is the precise local time from the CSAC time reference system.

Since the time length of a bit is only 20 ms, so tracking loop can enter the bit synchronous state instantly. After entering the first bit synchronization state, the designed fast relocation method is a better solution. Then all the variables in the equation (2) can be calculated based on the precise time, the SINS information and the ephemeris. The detailed implementation steps are as the following four steps.

Step One: Getting the precise local time form CSAC time reference and the ephemeris information to calculate the position and velocity of the available satellites.

Step Two: Getting the SINS information. On the basis of step 1, calculating the corresponding pseudo-range and pseudo-range rate of the available satellites.

Step Three: On the basis of the step two. Using the time from CSAC time reference and the pseudo-ranges to calculate the variables in the equation (2).

Step Four: On the basis of the results from the step 2, calculating the signal transmission time. And then using the time from CSAC and realize relocation.

5 Field test and result

The proposed fast relocation method is implemented in a GPS/SINS/CSAC integrated navigation system hardware prototype based on DSP+FPGA. The DSP means digital signal processor and the FPGA is the field-programmable gate array. The CSAC is employed as the time reference in the system. When the vehicle such as a car is travelling below an overpass or in a tunnel, it is highly impossible
for a receiver to capture and track the weak satellites signal. In this way, the GPS receive cannot provide time and position information. However, after several minutes or several seconds the signal reappears again, the environment is highly suitable to test and verify our hardware prototype and the proposed algorithm. The time cost to capture at least four satellites is employed as the indication to evaluate the performance of the algorithm. Fig. 3 is the overview of system and the car employed in the field tests. The filed test was carried out near the Nanjing University of Science and Technology and Fig. 4 is the trajectory in the google map. A signal interference device is employed to block the signal and the time of the blockage is about 6 seconds.

The integrated navigation system has experienced ten signal outages, then the system work in a pure inertial navigation mode, the position and velocity diverge gradually over time. The details of the available satellites and the PDOP values are

![Vehicle used in the field test](image1.png) ![Overview of the equipment](image2.png)

**Fig. 3.** Overview of the primary testing equipment

![Tested trajectory plotted in Google Maps](image3.png)

**Fig. 4.** Tested trajectory plotted in Google Maps

![Available satellites amount](image4.png) ![PDOP values](image5.png)

**Fig. 5.** Overview of the Available Satellites and PDOP values
described in Fig. 5. The Table I and Table II are the detailed changes of the satellites and the PDOP values during the signal outages (SN mans the number of the available satellites). The number of the locked satellites is zero during the signal outages and meanwhile the PDOP is large. When the signal appears again, the number of the satellites quickly get to be normal and PDOP also converges during 1 s. This demonstrates that the accuracy of the position information converges quickly. It can be concluded that the system can quickly realize the relocation. The Fig. 6, Fig. 7, Fig. 8 are the details of the number of the satellites and the PDOP values respectively for signal outage 2, signal outage 5 and signal outage 9.
Conclusion

This paper designed and tested a fast relocation algorithm in the DSP+FPGA based GPS/SINS/CSAC deep integration hardware prototype. For the GPS receiver, when signal appears after the signal blockage or signal interference, the precise time information based on the reference of the CSAC and the position information from the SINS combined with the ephemeris can be used to calculate the signal transmission time. Finally, a road driving test with 10 signal outages was operated to verify the performance of the proposed algorithm. The results demonstrate that the proposed fast relocation algorithm can largely reduce the receiver relocation time. The result shows the relocation can be realized during 1 second while the traditional receiver usually needs at least 6 seconds for the relocation after the signal blockage. And this definitely improves the performance of a scalar-based GPS/SINS/CSAC integrated coupled navigation system.

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| Table I. | The satellites number and PDOP changing details |
|-----------|--------------------------------------------------|
| Sn        | Outage 1 | PDOP | Outage 2 | PDOP | Outage 3 | PDOP | Outage 4 | PDOP | Outage 5 | PDOP |
|-----------|----------|------|----------|------|----------|------|----------|------|----------|------|
| 7         | 1.38     | 7    | 1.6      | 7    | 1.38     | 7    | 2.27     | 8    | 1.98     |
| 0         | 8.66     | 0    | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99    |
| 0         | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99    |
| 0         | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99    |
| 7         | 1.38     | 7    | 1.59     | 7    | 1.38     | 7    | 4.34     | 3    | 2.13     |
| 7         | 1.29     | 7    | 1.29     | 7    | 2.19     | 7    | 1.39     | 7    | 1.39     |

| Table II. | The satellites number and PDOP changing details |
|-----------|--------------------------------------------------|
| Sn        | Outage 6 | PDOP | Outage 7 | PDOP | Outage 8 | PDOP | Outage 9 | PDOP | Outage 10 | PDOP |
|-----------|----------|------|----------|------|----------|------|----------|------|-----------|------|
| 7         | 1.60     | 9    | 2.20     | 9    | 2.41     | 8    | 1.54     | 8    | 1.82      |
| 0         | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99     |
| 0         | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99     |
| 0         | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99     |
| 0         | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99     |
| 0         | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99     |
| 0         | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99     |
| 0         | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99     |
| 0         | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99    | 0    | 99.99     |
| 8         | 1.40     | 9    | 1.76     | 9    | 6.39     | 6    | 2.73     | 7    | 2.9       |
| 9         | 1.39     | 9    | 1.40     | 9    | 1.40     | 8    | 1.67     | 8    | 1.68      |