Design and implementation of a dual-antenna GPS receiver

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Abstract. In the Global Position System (GPS) technology, the GPS receiver (GPSR) has to receive the satellite signal to locate its position in a 3D space. For the GPS applications where the GPS carrier (vehicle) is rotating, the signal-receiving-path could be temporarily blocked by the attitude of the vehicle. And, once the GPSR loses track of the signal, it takes at least 6 seconds for the GPSR to resume its positioning task. This paper proposes a novel dual-antenna GPSR system (hardware architecture and algorithms) that can solve the intermittent signal problem when the vehicle is rotating and continuing on its positioning task. Current experimental results indicate that the proposed GPSR design can successfully output its position when the vehicle is rotating at 7.5 rpm. At 22 rpm, some satellite signals remain on-lock but some do not, depending on the strength of receiving signals.

1. Introduction

Conventional GPS receiver uses one antenna to receive signals from Satellite for its positioning task. However, in the applications where the GPSR carrier is rotating (such as rocket launch), the antenna rotates with the vehicle and thus the signal-receiving-path of the GPSR could be temporarily blocked by the vehicle. Once the signal-receiving-path is broken for more than 20 ms, the GPSR would lose track of the satellite signal. And, if the GPSR receives the satellite signal again, it takes, at least, 6 seconds to retrieve the information from the receiving signal; 18 seconds to acquire all the information needed for calculating the position. For these reasons, the conventional GPSR cannot continuously output the correct position when the vehicle is rotating.

Most of the existing methods solve this intermittent signal problem by dual-antenna method shown Figure 1, which placing two antennas on two sides of the vehicle to ensure that, at least, one antenna “sees” the satellite. And, the key challenge of this method is how to process signals from two antennas to retrieve the satellite information embedded in the received signals. According to the literature survey, there are three major approaches along with this dual-antenna method. The first one uses an RF combiner to superimpose signals from two antennas and then send the signal to a conventional GPSR [1]. The advantage is that the hardware is simple and no change on the signal processing. Nevertheless, the shortcoming is that it may cause destructive interference and cyclic C/N0 for the receiving signals. Another method uses two independent GPSR to obtain two “pseudo-range” for the positioning task [1]. This method does not have the signal-destructive-problem, but it may not work when the period of the intermittent signal is less than 6 seconds. The last one uses a hardware architecture that consists of two
RF front-ends, two baseband processors, and one navigation processor [2]. Unfortunately, it does not disclose any information on the signal processing.

Figure 1. A schematic of dual-antenna deployment.

This paper proposes a novel dual-antenna GPSR system (hardware architecture and algorithms) that can overcome the intermittent signal problem and output its position continuously. This paper is organized as follows. Section 2 introduces the basics of the conventional GPSR system. Section 3 presents the proposed hardware and software architecture of the dual-antenna GPSR. Section 4 discusses the implementation issues of the proposed system and some experimental results. Section 5 concludes this paper.

2. Basic principles of GPS operation

2.1. Conventional GPSR signal processing

The composition of the GPS signal transmitted by each satellite is shown in Figure 2. The satellite information (navigation data, 50 Hz) is modulated by the satellite-dependent C/A code (1.023 MHz), and the carrier signal (1.5 GHz). Since the antenna-received signal is a composition of several satellite signals, the received signal should go through a series of signal processing to retrieve the navigation data of each satellite. Figure 3 shows the signal processing flow of conventional GPSRs [3] [4]. The satellite signal is received by the antenna and then passed to the three function blocks which are RF frontend, baseband processor, and navigation processor. After the RF frontend, the RF signal is down-converted in the mega-hertz (IF) range, and digitized for the subsequent signal processing. The baseband processor demodulates the incoming IF signals to retrieve the information embedded in the received signals. The navigation processor uses this information to calculate the position, speed of the GPSR carrier, and the ephemeris time of the signal transmitting.

![Figure 2. The composition of the satellite signals.](image)

![Figure 3. Signal processing flow of conventional GPSRs.](image)

2.2. GPS signal demodulation

The baseband processor demodulates the incoming IF signal by locally generating C/A codes and carrier signals for each satellite-transmitted signal. And, those local generated signals should be in sync with
the received IF signal. However, the GPSR has no prior information of the phase of the received C/A codes. Besides, the carrier frequency may be varied due to the Doppler effect. Therefore, The GPSR has to rely on two tracking loops to track the phase information of the C/A code and carrier signal. Figure 4 shows the block diagram of these two tracking loops [4]. One tracking loop is the phase-lock-loop (PLL)/ frequency-lock-loop (FLL) for the carrier signal. The other one is the delay-lock-loop (DLL) for the C/A code.

![Block Diagram of Signal Tracking Loops](image)

**Figure 4.** Block diagram of signal tracking loops. This tracking loop consists of PLL/ FLL loop for the carrier signal and DLL loop for the C/A code.

### 2.3. Challenge for conventional GPSR in rotating

According to the Figure 4, the correlation value between the locally generated signal and received IF signal (“incoming signal” shown in Figure 4) is obtained by the signal multiplication and accumulation. This correlation value is then sent to the discriminator to determine the phase difference between the locally generated signal and incoming signal. And then, the phase information is processed by the filter to adjust the frequency of the locally generated signal to be in sync with the incoming signal. Note that, most of the PLL uses “atan” as the discriminator which has the working range (-π/2 ~ π/2). Meaning that, the PLL tracking loop could stable at the either “0” phase difference or “180” phase difference for these two signals. Conventional GPSRs solve this phase ambiguity problem by inserting the “preamble code” into the navigation data, which code appears every 6 seconds. This implies that, after the tracking loops locked onto the incoming signal, it still needs another 6 seconds for the GPSR to ensure its phase information and output the correct navigation data. This could be problematic when the GPSR carrier is rotating because the line-of-sight of the antenna could be blocked by the carrier body, and thus the signal lock-on period is less than 6 seconds.

### 3. Dual antenna GPS receiver

Figure 5 shows the conceptual design of the proposed dual-antenna GPSR system. It consists of two antennas, two RF front-ends, one baseband processor, and one navigation processor. Two antennas connect to two RF frontend, respectively. Two RF front-ends share one reference clock to synchronize the output signal from each RF front-end. The baseband processor consists of 14 channels. And, each channel can carry out the tracking-loop operations shown in Figure 4. In the baseband processor, two channels are assigned to process the signals transmitted by the same satellite, but received by different antenna. Within these two channels, the one that achieves better tracking quality is selected for demodulating the incoming signal and to obtain the navigation data. In this case, we have 7 pairs of channels that can track down signals transmitted by 7 satellites simultaneously. The advantages of this architecture not only that it works when the vehicle is rotating, but also that there is no destructive interference between signals from two antennas, and a redundant system when the vehicle is not rotating.
3.1. GPS signal demodulation in the dual-antenna system

As discussed before, the frequency of the carrier signal is 1.5 GHz, and the frequency of the C/A code is 1.023 MHz. Therefore, the wavelength of the carrier signal is 19 cm, and is 293 meter of the C/A code. When placing two antennas on the opposite side of the rocket which having the diameter of 60 cm, the received carrier signal by each antenna is likely to be different from each other while the C/A code signal is almost the same. Therefore, instead of using one PLL/FLL loop and one DLL loop in one channel, we used one DLL loop and two independent PLL/FLL loops to process the incoming signal for the same satellite. For example, channel 0 and 1 shown in Figure 5 are a pair of channels that is dedicated for one satellite. This channel pair shares one DLL loop to track the C/A code of the same satellite, and independent loops to track their respective carrier signals. Figure 6 shows the realization of one channel pair of the proposed signal demodulation.

Since two channels are employed to track down the same satellite signal, we need to determine which channel information is used for the subsequent navigation data acquisition. One way of doing it is to set a threshold value for that. The channel that achieves a larger correlation values and above the threshold would be chosen for retrieving the navigation data and the subsequent positioning task.

3.2. Phase coordination for the signal demodulation

Since antennas are mounted on a rotating vehicle, the antennas would receive and not-receive the satellite signals periodically. And, in the best situations, each tracking channel would go through the lock/unlock phases periodically. According to the phase ambiguity problem discussed in section 2.2, the carrier tracking loop may not stable at the same operation point (0° or 180°) as last time when it was in sync with the incoming signal. Consequently, the retrieved navigation data is erroneous.

Luckily, when two antennas are mounted on the opposite sides of a rotating vehicle, each antenna would take turns to receive (not-receive) the signal from satellites. Even better, there exists a period of 45° to 90° within one revolution that both antenna can receive signal from the same satellite simultaneously. Furthermore, when both antennas receive signal from the same satellite, the corresponding channel pair should output the same data bit (1 or -1) after correcting their phase ambiguity problem. We then propose using this relationship to coordinate the phase ambiguity for a channel pair.
Figure 6. Realization of signal tracking loops for one channel pair of the proposed dual-antenna GPSR system.

In this approach, we set a threshold for the correlation value of the channel output. In a channel pair, if the correlation value of one channel just exceed the threshold value while the other channel has been above the threshold for some time. The one newly entered would be forced to have the same data bit as the one that has already in. This concept is realized by using a parameter named “phase_info” shown in Figure 7. The “phase_info” can be either one of these three values: -1, 0, 1. When the “phase_info” is 0, the correlation value of that channel is less than the threshold value, and its carrier phase is not trustworthy as the reference for correcting others. When the “phase_info” is 1, the correlation value is larger than the threshold, and the data bit has the same sign as its correlation value. Lastly, when the “phase_info” is -1, the correlation value is larger than the threshold, and the data bit has the opposite sign as that of its correlation value. The detail procedures of using “phase_info” to coordinate the carrier phase ambiguity of a channel pair are shown in Figure 7.

4. Experimental result

4.1. Experimental environment
The antenna used in this experiment is the ANN-MS-0 [5] from the company Ublox, which is an active antenna with the 20 MHz bandwidth and 29 dB gain (typical). The RF front-end is a homemade circuit board which incorporating a receiver chip MAX2769 from the company Maxim Integrated [6]. This chip integrates two low noise amplifiers, a fractional frequency division phase-locked loop, a multiplier, an IF filter and an analog-to-digital converter, and is down-converted with a super-heterodyne architecture.
Figure 7. UML diagram of coordinate the phase ambiguity problem within one channel pair.

The baseband processor and navigation processor were implemented using Terasic DE0-Nano-SoC platform [7], which mainly composed of the integrated ARM Cortex-A9 processor and field-programmable-gate-array (FPGA). Both the FPGA and ARM (CPU) have the computation power to implement the proposed algorithms. The FPGA has its strength on real-time and parallel signal processing, while the CPU is capable of developing complicated algorithms. We then distribute the signal processing work into FPGA and ARM according to the timing requirement of each function module and the respective strength of the FPGA and CPU. In this case, the channel modules such as NCO, code generator, correlator, clock, etc. were realized using the FPGA. The discriminator, controller of the code tracking loop and carrier tracking loops, navigation processor, etc. were realized using the ARM. Those channel modules realized in FPGA exchange the information with ARM at the frequency of 1 kHz using the data bus and CPU interrupt controls. Since the processor and the programmable logic
gate are integrated on the same chip, system power, cost, and board size can be reduced. Figure 8 shows the hardware implementation of the proposed dual-antenna GPSR.

![Figure 8](image)

**Figure 8 (a)** Hardware implementation of the Dual-antenna GPSR. It consists of 2 antennas, 2 RF synchronized frontend, one development board (DE0). **(b)** Realization of GPSR algorithm on the development board.

### 4.2. Experimental result

Figure 9 shows the experiment setup for verifying the performance of proposed dual-antenna GPSR. This platform consists of a rigid arm (68cm) and a servomotor that can control the rotating speed and angle of the arm. Two antennas were attached to two ends of the rotating arm and rotates with the arm. When the arm rotates, the antenna on the top is able to “see” the satellites while the antenna at the bottom will be block and receive no signal from the satellites.

![Figure 9](image)

**Figure 9.** A rotation platform to verify the performance of the dual-antenna GPSR.

Two sets of GPSR data were recorded during the rotation. In Figure 10, the channel 0 and 1 have the same sign of correlation value at the beginning, and their status parameter “phase_info” are both at “-1”, according to the algorithms shown in Figure 7. At around $3.86 \times 10^4$ second, the view angle of one antenna is blocked (channel 1), and the correlation value of that channel gradually decreases to zero. In this case, the “phse-info” of channel 1 is switched to “0”. At around $3.865 \times 10^4$ second, the antenna associated with channel 1 receives the satellite signal again. Its correlation value increases and has the
same sign as channel 0. Therefore, the “phse-info” of channel 1 is switched to “-1” to be the same as channel 0. Similarly, At around $3.945 \times 10^4$ second, the antenna associated with channel 0 loses track of the signal and then get it back again. The “phase_info” of channel 0 is switched to “0” and back to “-1” to be the same as channel 1.

**Figure 10.** Coordination of phase ambiguity in channel 0 and 1. Both channel 0 and 1 go through the receiving and not-receiving cycles.

Figure 11 shows another set of recorded data. As shown in the plot, at the beginning, both channel 0 and 1 have large correlation values but different sign. Therefore, their status parameter “phase_info” are read as “-1” and “1”, respectively. Between the time $3.65 \times 10^4$ to $3.66 \times 10^4$ second, channel 1 gradually loses track of the incoming signal and then reconnect to it again. However, after the reconnection, the sign of its correlation values is the same as that of the channel 0. Therefore, the “phase_info” of channel is switched from “1” to “-1”. This example shows that the carrier-tracking loop may not stable at the same operation point each time it in sync with the incoming signal. Moreover, with the assistance from the proposed phase coordination techniques, the tracking loop can keep track of its phase information without the previously discussed “6-second” limitation.

With the proposed dual-antenna algorithm and hardware implementation, the GPSR can correctly output the position when the arm rotates at the speed of 7.5 rpm. Some channels start losing track of the satellite signal when the arm rotates at around 15 rpm. However, some channel remain connected up to 22 rpm. Since channels lost track of the satellite signals at different rotation speed, we believe that the current results of the signal unlock at high rotation speed are mostly due to the bad signal quality instead of the algorithms itself. In addition, according to our experiences, one possible cause of the bad signal quality is due to the electromagnetic interference transmitted by our circuit board. More experiments are ongoing to verify the performance of the current design.
Figure 1. Coordination of phase ambiguity in channel 0 and 1. Channel 1 stables at different phase when it reconnects with the incoming signal.

5. Conclusion

This paper proposes a novel dual-antenna GPSR that can overcome the intermittent signal problem due to the vehicle is rotating. The system consists of two antennas, two RF front-ends, one baseband processor, and one navigation processor. The proposed method solve this problem by incorporating several techniques including RF-frontend output synchronization, assigning a pair of tracking channels to process signals from one satellite, phase coordinating within one channel pair, etc. To cope with the large amount of computations and restrict time requirements of the GPSR, the proposed signal processing algorithms were implemented on a development board that consists of a CPU and FPGA. Experimental results indicated that the dual-antenna GPSR can output the position correctly when the vehicle is rotating at 7.5 rpm. When the vehicle rotates at 22 rpm, some channels still lock on to the satellite signals but some do not, depending on the signal quality. More experiments are ongoing to verify the performance of the proposed dual-antenna GPSR design.

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