The Global Positioning System and Embedded Receiver Applications

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Introduction

The NAVSTAR Global Positioning System (GPS), although military in origin, has enabled and enhanced a wide variety of civilian applications, including uses in science, transportation, information technology, and everyday life. Although the system is comprised of three components, space, control, and user, the primary focus of this paper is for an embedded systems designer to gain an understanding of the aspects of the system affecting receiver design. As a 24-hour per day, all weather, passive, receive-only system, GPS can support an unlimited number of receivers at any time. More and more embedded applications are becoming possible through more efficient processing, receiver miniaturization, and by augmenting GPS with other technologies. The future of global positioning promises improvements in all areas where GPS is currently lacking. In order to gain an understanding of current GPS receiver design, a historical background of the system is presented along with the a detailed description of the current state of the system, what the future holds, and finally a survey of some state of the art embedded receiver applications.

History of GPS

In 1973, the U.S. Department of Defense approved the development of what we know today as the NAVSTAR Global Positioning System to enable U.S. forces to navigate anywhere in the world without revealing their presence through transmissions. The launches of two prototype satellites in 1974 and 1977 allowed proof-of-concept for using spread-spectrum radio signals and precise time information to calculate position. From 1978 to 1985, the first phase of the GPS system, Block I, was realized and the first prototype ground control station was constructed at Vandenberg Air Force Base, California. Even though the early system had severe availability limitations, various user equipment was created for nautical, aerial, and land-based vehicles. In addition, the geological sciences community quickly adopted satellite surveying and information technology industry immediately found use for the time-transfer capabilities of GPS, paving the way for civilian applications.

In 1983, in response to a civilian Korean jet that was shot down after straying into Soviet airspace, President Reagan announced that the GPS system would be made available for civilian use. Despite budget cuts and set-backs, the second phase, Block II, was initiated in 1989. The Block II satellites included reliability, security, and feature enhancements in addition to better error detection to maximize system integrity. The Gulf war of 1990-91 was the first large-scale military use of GPS and following its successful application, the proliferation of both military and civilian receivers began. Shortly after the war, the United States committed to offering the standard positioning service (SPS) to the public free of charge while the higher-accuracy precise positioning service (PPS) would remain encrypted for use exclusively by the U.S. Federal agencies, military, and allied forces. By March of 1994, a constellation of 24 Block II satellites had been placed in orbit and in 1995, after completing military testing, the U.S. Air Force declared full operational capability of the system. Until 2000, a security measure known as selective availability (SA) was enabled to purposely reduce the positional accuracy of SPS receivers by adding dither to the clock. However as more augmentation systems appeared, increasing the accuracy beyond what even PPS offered, the need for SA reduced and on May 2, 2000, President Clinton announced that SA would be permanently deactivated.

Current Status and Operation of GPS

The operation of the GPS program is controlled by a joint military and civilian task force to ensure all interests are accounted for while the U.S. Air Force maintains the space and control segments of the system. The GPS constellation currently consists of 31 Block II satellites, with more recent units containing feature and reliability enhancements. The satellites are distributed across six orbital planes and operate from an altitude of 12,550 miles. Twelve monitoring stations around the globe are used to control the satellites, including the master station at Schriever Air Force Base in Colorado. Updated timing and orbit information is transmitted to each satellite at regular intervals.

Today’s SPS uses the L1 (1575.42 MHz) band for transmitting a course acquisition (C/A) code along with orbital (ephemeris) data, clock behavior, system time, system health, and rough orbits of other satellites (almanac). The data is sent at 50 bits per second (bps) with 1500-bit frames taking 30 seconds each. Each frame consists of clock and ephemeris data in addition to other pieces of the message. An entire message takes 12.5 minutes. SPS provides an accuracy of 13 meters horizontally and 22 meters vertically, in addition to a time transfer accuracy of 40 nanoseconds, in 95% of trials [11]. The higher precision and more secure PPS uses both the L1 and L2 (1227.6 MHz) bands for transmitting the military (M) code and precision (P/Y) code which uses encryption to guard against false transmissions. The encoding of the signal in both services uses code division multiple access spread spectrum technology with a 20 MHz bandwidth. Pseudorandom noise (PRN) codes generated in a tapped feedback register architecture are modulated on to the carrier. Each satellite has its own unique set of codes, allowing the receiver to differentiate the signals. The fundamental differences between the two services are the number of codes used: SPS uses a 1.023 MHz chip rate with a period of 1 millisecond making it easy to acquire, while PPS uses a more precise 10.23 MHz chip rate with a period of seven days, making it difficult to spoof.
On the receiver side, both code and carrier tracking loops are used to generate a set of PRN codes identical to the ones transmitted by a satellite. The time-delay between its codes and the ones received from the satellite is calculated and then multiplied by the speed of light to obtain the satellite’s pseudorange. Using trilateration, a standard GPS receiver uses four rather than three different satellite signals to determine three-dimensional position since there is an unknown timing offset between the receiver and the satellites. Since a minimum of six satellites are always in view, most modern GPS receivers are capable of tracking at least 12 satellites at a time to maximize accuracy and reliability. Velocity measurements are obtained by determining the difference in carrier phase over time. The other navigational data is modulated on top of the C/A and P coded carriers.

Despite all of its advantages, GPS is not perfect. The signal transmitted is not powerful enough to penetrate water, soil, trees, or roofs. The data transmission rate is slow causing uncomfortably long times-to-first-fix (TTFF). In addition, several sources of error exist for typical GPS receivers causing inaccuracies. The sources include atmospheric effects, clock error, ephemeris error, receiver noise, and multipath reception. Consequently, many augmentation services have been developed to help eliminate these problems and increase accuracy. The services include the U.S. Coast Guard maintained Differential GPS (DGPS) service which uses ground-based transmitters to provide accuracies of 1 to 3 meters along the coasts for harbor navigation [8], Assisted GPS (AGPS) which uses a mobile phone network to deliver ephemeris and error correction information giving TTFFs of six seconds [15], an experimental system called BGPS which uses preloaded, forecasted ephemeris data to achieve TTFFs of one second [16], the Wide Area Augmentation System (WAAS) which is a satellite-based DGPS system, and an experimental broadcast TV-based positioning system for indoor navigation. The latter two are now described.

One such augmentation service is the Wide Area Augmentation System (WAAS) which is a differential GPS system developed by the FAA to provide sufficiently accurate and reliable GPS signals to land an aircraft. In reality, all receivers in the coverage area are able to take advantage of the system. Using ground-based wide-area reference stations scattered across North America to monitor GPS signals, the WAAS determines ionospheric, position, and clock errors caused by the previously listed sources. Corrections are calculated and then sent to two satellites in geosynchronous orbits for broadcasting on the L1 band to WAAS-equipped receivers. The corrections provide a worst-case accuracy of 7.6 meters and an accuracy of 1 meter horizontally and 1.5 meters vertically, 95% of the time [13]. In addition to WAAS being available across the majority of North America, the Japanese MTSAT Satellite-based Augmentation System and the European Geostationary Navigation Overlay Service broadcast WAAS compatible signals, making highly accurate positioning available in many countries around the world. Since the signal is transmitted on the same carrier as the SPS signal, integration into receivers does not involve an additional antenna and RF circuitry, only WAAS decoding hardware.

Another intriguing service promises to overcome one of GPS’s biggest drawbacks – needing a good portion of open sky to receive satellite signals. Densely populated urban areas with tall buildings and indoor situations do not lend well to GPS signals, however broadcast TV signals are transmitted with significantly more power and have much less difficulty in the same environment. Rather than directly augmenting the signal, TV-based positioning is a complement to GPS meaning receivers need additional UHF and VHF compatible hardware. A receiver uses the precise timing of the PRN codes in the synchronization field of Advanced Television Systems Committee (ATSC) digital TV signals and the ghost-cancelling reference of the NTSC analog TV signals to calculate pseudoranges and then transmits the data to a location server for positioning. Regional monitors provide timing corrections to the system giving a positional accuracy of 13 meters 95% of the time in an open area, 56 meters 95% of the time in downtown urban centers, and 96 meters 95% of the time in an underground transit system [17].

Future Direction of GPS

There are many improvements to the GPS system slated for deployment. The current lot of satellites being launched is referred to as Block IIR-M. Starting in 2009, Block IIF satellites will begin to replace older Block II satellites until Block III satellites are ready in 2014. Both the current and new satellites will enable an additional civilian carrier in the L2 band, referred to as L2C. This second carrier will help eliminate ionospheric errors, increasing accuracy and provide a redundant signal, increasing reliability. In addition, the new satellites improve support for the military (M) code, giving the military receivers a redundant signal with additional data. On the Block III satellites, the M code will gain the unique feature of being broadcast by both full-Earth and directional antennas, allowing normal wide-area coverage in addition to 20dB greater signal strength in a smaller region a few hundred miles in diameter. This will allow greater jamming resistance and more reliable reception under cover. To further increase the reliability of reception, Block IIF satellites will broadcast a third civilian signal in the L5 (1176.45MHz) band with 3dB more power. The last scheduled modernization effort is the addition of the L1C signal on Block III satellites which will both update the existing civilian carrier for improved reception and allow greater compatibility with both Europe’s upcoming Galileo satellite navigation system and Japan’s Quazi-Zenith Satellite System (QZSS).
Embedded Receiver Applications

In 1989 Magellan introduced the first hand-held GPS receiver. Prior to that, receivers were mounted in and powered by vehicles or carried in backpacks. In current times, embedded GPS receivers are beginning to show up in many objects and for many different applications as miniaturization continues. Civilian-grade receivers operate using SPS, normally incorporate WAAS or another DGPS technology, and are user-friendly or embedded and completely hidden from direct use. Until more recently, these receivers tend to suffer from poor reliability, long TTFFs, and low sensitivity. Survey-grade and fixed-installation receivers also operate using SPS but offer higher sensitivity and other more accurate DGPS support. However, the improvements come at a cost usually in price and size. Potentially the highest-grade receivers are produced for the military or monitoring stations, using redundant, top-of-the-line components to take advantage of multiple signals, giving the best reliability, accuracy, and performance. Regardless of size and cost, all GPS receivers have similar basic building blocks: an antenna and preamplifier, RF front-end, reference oscillators, carrier and code trackers, microprocessor, and power supply [20]. For units that are designed for human interaction, controls and a display are added to the mix. The design of each section must be carefully engineered in the context of the application. This section provides an overview of three different embedded receiver applications and associated design parameters of interest.

In the past couple of years, GPS has been included with cell phones as a result of an FCC mandate to be able to extract position information from an E911 call. Embedding a GPS receiver in a cell phone has proven challenging as the platform is one of the most noisy and cramped in existence. The interference to GPS reception from the high-power transmitter in the handset is a significant problem, in addition to the small form factor which severely compromises antenna design. The solution, although more costly, is to provide aggressive filtering in the GPS RF path allowing concurrent operation of the receiver and transmitter. In fact, new designs have greatly improved the sensitivity of GPS receivers allowing them to make code measurements—and thus calculate pseudoranges—even on the severely attenuated signals inside buildings, but the signal is insufficient for successful navigation data decoding. This is where Assisted GPS designed to help. It is possible for a cell phone to ignore the 50 bps navigation data stream and use a significantly attenuated signal because the network can provide the required navigation data. With AGPS capable of using the network to deliver the navigation message in milliseconds rather than several minutes, the cell phone gains the ability to provide location fixes indoors and within six seconds of first attempting a fix. One other significant result of cell phones adding GPS is an explosion of location based services because the phone knows where you are and can provide very relevant assistance. The commercial possibilities are just starting to be tapped.

Recently cameras and camcorders with embedded GPS receivers have appeared on the market. Although the problems are similar to cell phones, network access is not guaranteed. In addition, the form factor may be slightly more conducive to antenna design and the RF section does not have to compete with a high-power transmitter. Even though in recent years receivers have become much faster at acquiring a pure GPS fix, the 50 bps data rate only provides ephemeris data every 30 seconds. Because the user will generally not wait for the GPS receiver to acquire a fix before taking a picture, the main problem for camera design is GPS’s inherently long TTFFs. BGPS is currently in the development stages as a potential solution to this problem. With BGPS, the camera would occasionally be loaded with predicted ephemeris data, perhaps when it is idle and in range of a wireless network. Combined with an accurate clock in the camera, BGPS has been shown to provide TTFFs of 1 to 2 seconds, which is well within the time frame of turning on a camera, framing the shot, pressing the shutter, and storing the picture to memory.

The third intriguing embedded application for GPS is in non-GPS satellites. In order for satellites to carry out their tasks correctly, they must maintain correct orbits. For years, low-earth orbit spacecraft have had the advantage of the medium-earth orbit GPS satellites above them for automated orbit correction and precise time. However high-earth orbit (HEO) and geosynchronous (GEO) spacecraft have not had this luxury until recently. Because GPS transmissions are already very weak by the time they reach the ground, the GPS satellite antennas are designed to broadcast so that nearly all energy reaches earth. However, there is a very weak cone from the transmitter that skirts the earth. A special highly sensitive antenna and receiver have been developed so satellites that are on the other side of the earth from the transmitting satellites can capture the signals and extract positioning and timing information [23]. The automated timing and navigation of HEO and GEO spacecraft both reduces maintenance costs and increases reliability.

Concluding Remarks

There are myriad ways to use GPS and more being developed each year and as the system provides more features. Understanding the system as a whole and what is in store for it is fundamentally important to embedded receiver design. Now, more than ever there are many solutions to the limitations of GPS and the designer must make the best decisions given the tradeoffs. Thankfully there is a vibrant community sharing advancements in GPS technology and ample information available to make the best design decisions.
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