GPS-enabled Handheld Cartographic Display Systems: A Survey

Igor Ikodinović, Veljko Milutinović

Department of Computer Engineering
School of Electrical Engineering
University of Belgrade
P.O. BOX 35-54
11120 Belgrade, Serbia, Yugoslavia

igi@eunet.yu, vm@etf.bg.ac.yu

Zoran Dimitrijević

Department of Computer Science
University of California at
Santa Barbara
Santa Barbara, CA 93106

zoran@cs.ucsb.edu

Antonio Cosimo Prete

Department of Electronics,
Informatics and Telecommunications
University of Pisa
Via Diotisalbi 2, 56100 Pisa, Italy

prete@iet.unipi.it

Abstract

Handheld cartographic display systems for precise positioning and navigation via GPS (Global Positioning System) require fast graphics, excellent computational capabilities, and low power consumption. Commercial low-power general-purpose microprocessors, despite their advanced power-saving features, are not fully adequate for use in handheld systems of this type. Since fewer chips mean smaller size, lower power consumption, higher performances, and lower price, designers of handheld systems tend to integrate all digital circuits on a single chip, including the microprocessor. That is why instead of commercial power-efficient microprocessors on a chip (like Intel StrongARMs, Hitachi SHs, or Transmeta's Crusoe), they rather use microprocessor cores (like ARM7 and ARM9 series of microprocessor cores from ARM, Motorola's MCORE, or STMicroelectronics' ST20) and complementary logic circuits developed for use in embedded applications, or develop custom microprocessors and circuitry to incorporate on the chip. Technology today allows for microprocessor and other digital circuits to be placed on a single chip. The analogue RF front-end circuit, used to track GPS signals and convert them into the digital form, is integrated on another, companion chip. On the market they are offered as a two-chip set ready to be embedded into GPS-based handheld platforms.

Performances of chips of various manufacturers vary significantly. We give an overview of technological and performance indicators of the chips most commonly found on the market. Conventional chip architectures already do not provide sufficient performances, so that new designs are now used in high-performance devices. A deeper look reveals a number of different design solutions. In the future we expect the appearance of new, more powerful, systems with improved user interface, incorporating highly integrated and fast chips for better performance, which will be followed by the introduction of new applications and services.

1. Introduction

Cartographic display systems are becoming increasingly popular with the advent of GPS and related technologies. Basically, cartographic display systems are used to show the current user position (determined via GPS) on the screen where a cartographic map of the area is displayed. However, their use is not limited to that basic function. They often include various navigational tools, databases, communication services, etc.

Handheld cartographic systems are equally used for marine, terrestrial, and airborne applications. Each of the three application environments has its specific requirements regarding performance and design of the product. For example, systems used in airborne navigation need high accuracy and good dynamics; systems used in marine navigation must be waterproof and need large displays for good visibility in adverse weather conditions, but not necessarily outstanding accuracy or dynamics; systems used for navigation of city vehicles need high precision and sensitive RF receivers capable of receiving and filtering signals in urban areas; etc.

While fixed cartographic display systems can be built around a standard personal computer platform, handheld systems are designed with completely different requirements. Limited dimensions of the device and the need for low power consumption make standard electronic components inadequate for use in such systems; instead, special low-power processor cores and other custom designed components are used. Manufacturers mostly offer two-chip sets (RF front end chip + chip with a microprocessor and other digital circuits) for GPS-dedicated devices. A problem that designers meet is that general-purpose microprocessors for embedded applications are not well suited for computationally intensive tasks like those found in high-precision satellite-based navigation, or to handle other specific tasks like intensive graphics or intensive I/O communication. This problem is further exacerbated with the appearance of better user interfaces, larger number of devices in the system, and new demanding applications. Standard system architecture with a single general-purpose microprocessor also tends to become a limiting factor. That is why some manufacturers have come forward with architectures that go beyond the conventional solutions. These advanced solutions include on-chip caches and SRAM, second processor, DSP (Digital Signal Processor), graphics accelerator, or similar.

This survey paper is organized as follows [1]: Main facts about General Positioning System are given in Section 2. An overview of commercial handheld GPS-based cartographic display systems and their features are given in Section 3. A discussion on system architectures is given in Section 4. Issues in digital chip architecture and technology are discussed in Section 5. Later in this section we give an overview of chips found on the market that are used in GPS-dedicated handheld systems, with all the relevant performance and technology indicators. Also, one advanced design solution is presented as a case study. Conclusions, future possibilities, and a list of possible new services and applications are given in Section 6.

2. Global Positioning System

GPS [2] is a satellite navigation system funded, developed and controlled by the U.S. Department of Defense. Although the system was designed for and is operated by the U.S. military, there are thousands of civil users of GPS worldwide. The system provides 24-hour positioning information regardless of weather. GPS consists of the Space Segment (the satellites), the Control Segment (the network of tracking stations which monitor and control the GPS satellites in orbit), and the User Segment (receivers).

The Space Segment of the system consists of the GPS satellites. These space vehicles (SVs) send specially coded satellite radio signals from space that can be processed in a GPS receiver, enabling the receiver to compute position, velocity and time. The nominal GPS Operational Constellation consists of 24 satellites that repeatedly broadcast their position and the time. The Constellation provides the user with between five and eight SVs visible from any point on the earth.

The Control Segment consists of a system of tracking stations located around the world. These monitor stations measure signals from the SVs that are incorporated into orbital models for each satellite. The models compute precise orbital data (ephemeris) and SV clock corrections for each satellite. The Master Control station uploads ephemeris and clock data to the SVs. The SVs then send subsets of the orbital ephemeris data to GPS receivers over radio signals.

The GPS User Segment consists of the GPS receivers and the user community. GPS receivers convert SV signals into position, velocity, and time estimates. GPS receivers are used for navigation, positioning, time dissemination, and other research.

2.1 GPS Satellite Signals

Each satellite broadcasts three binary coded signals [3]: one for commercial use (C/A-Code), a more accurate one for military use (P-Code), and one with navigational data. Signals are transmitted in two frequencies, called L1 (1575.42 MHz) and L2 (1227.60 MHz).

The C/A Code (Coarse Acquisition) modulates the L1 carrier phase. It is a repeating 1.023 MHz Pseudo Random Noise (PRN) Code. The C/A code is not encrypted and is therefore available to all GPS users. It is the basis for the civil Standard Positioning Service.

The P-Code (Precise) modulates both the L1 and L2 carrier phases. It is a very long (seven days) 10.23 MHz PRN code. In the so-called Anti-Spoofing (AS) mode of operation, the P-Code is encrypted into the Y-Code. The encrypted Y-Code requires a classified AS module for each receiver channel and is for use only by authorized users with cryptographic keys. However, more advanced commercial receivers can compensate by correlating the components of the P-Code for continued use in high resolution positioning. The P(Y)-Code is the basis for the Precise Positioning Service.

The Navigation Message is superimposed on both the C/A and P(Y)-Code signals before they modulate the carriers. It is a 50 Hz signal that contains the following data: the time of transmission of the message, a Handover Word (HOW) for the transition from C/A-code to P(Y)-code tracking, clock correction, ephemeris (precise orbital) and health data for the transmitting satellite, almanac (coarse orbital) and health data for all satellites, coefficients for the ionospheric delay model, and coefficients to calculate Universal Coordinated Time (UTC). The receiver can obtain critical satellite-specific data within 30 seconds. Almanac data and low-precision clock corrections, simplified health and configuration status for every satellite, user text messages, and the coefficients for the ionospheric model and UTC calculation are less critical for a receiver to acquire quickly, and they can be obtained every 12.5 minutes.

2.2 GPS Services

The Precise Positioning Service (PPS) is an accurate positioning, velocity and timing service that is available only to authorized users. Because GPS was designed for military use, the data for precise positioning are restricted for general use. In addition to the Anti-Spoofing, there is another restriction called Selective Availability, or SA, in which the data transmitted by the satellites contain deliberate errors for all but military receivers. If SA is turned on, the accuracy of commercial receivers drops from around 30 meters to around 100 meters. Encryption keys and techniques are provided to PPS users, which allow them to remove the effects of SA and AS and thereby attain the maximum accuracy of GPS. USA government has announced that SA will be removed in the future, but it is not known if and when will this happen.

The Standard Positioning Service (SPS) [4] is a less accurate positioning and timing service that is available to all GPS users. The SPS is primarily intended for civilian purposes, although it has potential peacetime military use. This service is restricted by the application of both AS and SA modes. System accuracy degradations with SA can be increased if it is necessary to do so, for example, to deny accuracy to a potential enemy in time of crisis or war.

2.3 Inaccuracy

In addition to SA and AS restrictions, there are other reasons that prevent the position to be determined accurately (however, there are ways to mitigate or remove these effects):

Satellite clock error: Even though the satellites are equipped with very accurate (Cesium) atomic clocks and despite the best efforts of the control centers in monitoring the behavior of each satellite clock, the satellite clock error cannot be precisely determined. The error accumulates typically to about a few nanoseconds, which causes a distance error of about one meter.

Ephemeris data error: The accuracy of the computed position depends on how accurately the location of the satellites is known. The orbits of satellites are monitored continuously from several monitoring stations around the earth and their predicted orbital information is transmitted to the satellites, which they in turn transmit to the receivers. The history of GPS has shown, so far, that the accuracy of the orbital prediction is in the order of a few meters, which creates about a few meters of error in computing the position.

Atmospheric errors: GPS signals travel through the atmosphere and their speed varies due to atmospheric conditions, which influences the accuracy. The effect of the ionosphere, if not mitigated, can introduce measurement errors greater than 10 meters. Some receivers use a mathematical model for the effects of the ionosphere. With the approximate knowledge of the density of the charged particles in the ionosphere (broadcasted by satellites), the effect of the ionosphere can be reduced by about 50%. The remaining error is still significant, so some receivers track both L1 and L2 signals, measuring the time difference between them. By using known formula for frequency dependency of the ionosphere delay, ionosphere effect can be removed. It is exactly for this reason that all GPS satellites transmit information in two frequencies. The effect of troposphere, which contains water vapors, cannot be removed using dual frequency systems. The only way to remove its effect is by measuring water vapor content, temperature and pressure, and applying a mathematical model that can compute the delay of the troposphere. Mathematical models used to remove atmospheric effects are complex and it is one of the reasons why is calculating position via GPS so computationally demanding.

Multipath: In addition to the direct signal from satellite, there are reflected signals from the ground, nearby structures, and objects near the antenna, that also reach the antenna through indirect paths and interfere with the direct signal. If the indirect path is considerably longer than the direct path (more than 10 meters) such that the two patterns of signals can be separated, then the multipath effect can be substantially reduced by signal processing techniques. In cases where signals are reflected off the ground *below* the receiver, the multipath distance is often less than 10m, and in that case choke rings are used to reduce the multipath effect.

Receiver errors: Receivers may introduce some errors by themselves in measuring code or carrier signals. In high quality receivers, however, these errors are negligible - less than one millimeter for carrier phase and a few centimeters for code phase.

Geometric dilution of precision: This effect describes the influence of the number of satellites and geometry of their positions on the calculated position error. If the satellites are clustered near each other, then one meter of error in measuring distance may result in tens or hundreds of meters of error in position. But if many satellites are scattered around the sky, then the position error may be less than 1.5 meters for every meter of error in measuring distances. Tracking as many satellites as possible can solve this problem.

2.4 Differential Mode

Neither the accuracy of 100 meters (SA on) nor the accuracy of 20 meters (SA off) is enough for many civilian applications. Since the inception of GPS, methods have been, and are still being developed to reduce errors and enhance the accuracy, even with the implementation and presence of SA and partial availability of L2 (AS).

In Differential mode it is assumed that two receivers, not too far from each other, and with one of them fixed, are able to communicate (via radio modem). The errors due to the satellite clock, the satellite orbit, the ionosphere, the troposphere and SA affect both receivers the same way and with the same magnitude. Errors in the measurement are then accurately calculated for the fixed receiver (for its position is known exactly), and reported to the other receiver, so that it can compensate for them. As the distance gets longer, the correlation between the range errors becomes weaker. As a rule of thumb, one can expect an additional one millimeter of error or uncertainty for every kilometer of distance (this is abbreviated as 1 ppm), when dual frequency receivers are used (both L1 and L2 are tracked). For single frequency receivers (only L1 is tracked) this error increases to 2 ppm.

2.5 Improving Navigational Performance with GLONASS

Combining GPS receivers with GLONASS receivers can enhance the performance of GPS positioning systems. GLONASS is the Russian equivalent of GPS. By combining GPS and GLONASS, we have a combined satellite constellation with many more than the standard 24-satellite constellation of GPS alone, which offers much better system availability and integrity. In some environments, such as urban canyons, mountainous areas, or under trees, GPS performance can be affected by visibility to satellites in the sky. Because GLONASS adds another 24 satellites to the 24-satellite GPS constellation, GPS+GLONASS offer performance advantages in tracking satellites, simply because there are more satellites. Additionally, because GLONASS does not employ positional degradation such as SA, autonomous (non-differential) positioning is accurate to within 15 meters.

3. Handheld Systems for GPS-based Navigation

At the time the GPS system was conceived, only professionals used GPS receivers, which were big and expensive. As chip and display technologies improved over time, GPS receivers became smaller, while retaining or improving their performances. As a result of advances in power-efficient display and IC technologies, portable and handheld systems appeared at an affordable price. Since that segment of the market brings large profits (because of the high selling volumes), it further motivates the industry to invest. In turn, new GPS-based products and applications are introduced.

3.1 Applications of Handheld GPS-based Systems

There are many types of products on the market that utilize the possibilities of GPS. Highly accurate GPS receivers, for example, are indispensable in professional navigation. Other, perhaps not so capable receivers, can be helpful tools that can improve quality of work in some domains (like professional fishing, or agriculture) or activities (like outdoor recreation). Sometimes GPS receivers are just neat add-ons, for example in mobile or satellite phones, or wristwatches. Some of the applications where handheld GPS receivers are used include:

- Airborne, marine, and terrestrial navigation
- Automotive navigation (in urban areas, foreign environments, unknown areas, etc.)
- Navigation and positioning in construction, mining, and agriculture
- Recreational and outdoor navigation
- Tracking and finding persons (lost children, injured or lost people in dangerous or hardly accessible areas, etc.)

This list will get longer with time. Possible applications are still being discovered and new services will be introduced in the future.

3.2 Commercial Handheld GPS-enabled Cartographic Display Systems

GPS receivers are usually classified according to the following criteria:

- Application environment (aviation, marine, automotive, recreation and outdoor)
- Size and portability (handheld, portable, fixed-mounted)
- Display type (mono/color, size, resolution)
- System features (communication capabilities; system software; included databases)
- GPS performances (No. of satellites that can be tracked simultaneously; type of signals that can be tracked - C/A, P, L1, L2, GPS, GLONASS; Cold/Warm/Hot/Reacquisition time and Update rate)
- Price

These criteria are not independent. For example, systems with color graphical displays are more expensive, and systems used in aviation usually have navigational databases included. An overview of features of commercial handheld GPS-based cartographic display systems is given in Table 1.

Producer / Product	Power consumption / Autonomy	Display		GPS		Price (US$)
		Type	Resolution/ Diag.	Signal/ channels	Cold / Warm / Hot / Reacq. (Update rate)	
Garmin / GPS III	0.75W / 36h	Mono, EL FTN backlit LCD (4 level grey)	100x160 / 6.7 cm	C/A / 12	5 min / 45s / 15s / - (1/s)	260
Garmin / GPS III Plus	0.75W / 18-36h	Mono, EL FTN backlit LCD (4 level grey)	100x160 / 6.7 cm	C/A / 12	5 min / 45s / 15s / - (1/s)	345
Garmin / GPS III Pilot	0.75W / 10h	Mono, EL FTN backlit LCD (4 level grey)	100x160 / 6.7 cm	C/A / 12	5 min / 45s / 15s / - (1/s)	600
Garmin / StreetPilot	- / 16h	Mono backlit FTN LCD (4 level grey)	240x160 / -	C/A / 12	5 min / 45s / 15s / - (1/s)	400
Garmin / StreetPilot ColourMap	- / 2.5h	Colour backlit LCD (16 colours)	240x128 / -	C/A / 12	5 min / 45s / 15s / - (1/s)	600
Garmin / eMap	1W / 14h	Mono EL backlit FSTN LCD (4 level grey)	120x160 / 7 cm	C/A / 12	2 min/ 45 s / 15 s / - (1/s)	200
Garmin / eTrax	1W / 22h	Mono EL backlit LCD	- / 6 cm	C/A / 12	2 min/ 45 s / 15 s / - (1/s)	-
Garmin / GPS 12	1W / 24h	Mono EL backlit LCD	- / 6.7 cm	C/A / 12	5 min/ 45 s / 15 s / - (1/s)	160
Garmin / GPS 12XL	1W / 24h	Mono EL backlit LCD	- / 6.7 cm	C/A / 12	5 min/ 45 s / 15 s / - (1/s)	200
Garmin / GPS 12CX	1W / 36h	Colour backlit (3 levels) LCD (3 colours)	- / 6.7 cm	C/A / 12	5 min/ 45 s / 15 s / - (1/s)	250
Garmin / GPS 12MAP	0.75W / 18-36h	Mono backlit FTN LCD	100x160 / 6.7 cm	C/A / 12	5 min/ 45 s / 15 s / - (1/s)	360
Garmin / GPS 48	- / 24h	Mono backlit (3 levels) LCD	- / 6.7 cm	C/A / 12	5 min/ 45 s / 15 s / - (1/s)	220
Garmin / GPS 89	- / 15-20h	Mono LCD	- / 6.7 cm	C/A / 8	7.5 min/ 2.min / 15 s / - (-)	400
Garmin / GPS 90	- / 15-20h	Mono backlit LCD	- / 6.7 cm	C/A / 8	7.5 min/ 2.min / 15 s / - (-)	500
Garmin / GPS 92	0.75W / 24h	Mono LCD (4 level grey)	- / 6.7 cm	C/A / 12	5 min/ 45 s / 15 s / - (1/s)	500
Garmin / GPS 175	1.5W / 10h	Mono LCD (4 level grey)	160x240 / 10.4 cm	C/A / 12	5 min/ 45 s / 15 s / - (1/s)	500
Garmin / GPS 195	1.5W / 10h	Mono LCD (4 level grey)	160x240 / 10.4 cm	C/A / 12	5 min/ 45 s / 15 s / - (1/s)	950
Garmin / GPS 295	6W / 2.5h	Colour LCD (16 colours)	305x160 / 10.4 cm	C/A / 12	5 min/ 45 s / 15 s / - (1/s)	1450
Lowrance / GlobalNav 12	- / 11h	Mono backlit LCD	100x65 / -	C/A / 12	- / - / 15 s / - (1/s)	180
Lowrance / GlobalNav 212	- / 11h	Mono backlit LCD	100x65 / -	C/A / 12	- / - / 15 s / - (1/s)	255
Lowrance / GlobalMap 12	- / 11h	Mono backlit LCD	160x160 / 8 cm	C/A / 12	- / - / 10 s / - (1-5/s)	600
Lowrance / GlobalMap 100	- / 20h	Mono backlit LCD	104x160 / 8 cm	C/A / 12	- / - / 15 s / - (1/s)	425
Lowrance / AirMap 100	- / 20h	Adjustable white EL backlit FST LCD	160x104 / 6.3 cm	C/A / 12	- / - / 15 s / - (1/s)	600
Lowrance / AirMap 300	- / -	Adjustable white EL backlit FST LCD	160x160 / 8.1 cm	C/A / 12	- / - / 15 s / - (1-5/s)	800
Magellan / Blazer12	- / 20h	Mono, EL backlit LCD	- / -	C/A / 12	- / - / - / - (-)	120
Magellan / GPS 300	- / 24h	Mono, EL backlit LCD	- / -	C/A / 12	- / - / - / - (-)	100
Magellan / GPS 315A	- / 15h	Mono backlit EL LCD	104x160 / 6.7 cm	C/A / 12	- / - / - / - (-)	150
Magellan / GPS 320	- / 15h	Mono backlit (2 levels) EL LCD	104x160 / 6.7 cm	C/A / 12	- / - / - / - (-)	200
Magellan / MAP 410	- / 12h	Mono backlit LCD	120x240 / -	C/A / 12	- / - / - / - (-)	350
Magellan / Colour TRAK	- / 30h	Colour backlit LCD	128x64 / 8 cm	C/A / 12	- / - / - / - (-)	280
Magellan / SkyStar Plus	- / 10h	Mono backlit LCD	160x130 / 7.4 cm	C/A / 12	- / - / - / - (-)	650
Magellan / NAV 6000	- / 12h	Mono backlit LCD (4 level grey)	240x320 / 8 cm	C/A / 12	- / - / - / - (1/s)	590
Raytheon / Apelco GPS 11	- / 13h	Mono FSTN Backlit LCD	100x64 / 7.4 cm	C/A / 12	3 min / 90 s / 20 s / - (-)	220
II Morrow / Apollo PRECEDUS	- / -	Mono EL backlit (3 levels) LCD	- / 8.4 cm	C/A / 8	- / - / 20 s / 2.5 s (-)	1000
Skyforce / Skymap II	- / 10h	Mono RST backlit LCD	- / -	C/A / 8	15 min / 45 s / 20 s / - (-)	1000

Table 1: Features of commercial handheld cartographic display systems

Legend: EL : Electro-Luminescent; FSTN : Film Super-Twisted Nematic; - : data not known or not available

Note: The discrepances that exist between receivers' prices and performances in some cases come from the fact that some receivers are equipped with special navigational databases. The price of databases are included in the products' price.

4. System Architectures

Chip sets available on the market dictate the system architecture design. Generally, system architectures of GPS-enabled handhelds are simple and resemble each other, because the architectures of GPS-dedicated chips of various vendors do. System usually consists of a (passive or active) antenna attached to the RF front-end that is further connected to the digital chip. Depending on what controllers/resources the chip already contains and what are the system requirements, RAM, ROM, and various devices can be attached via the system bus externally. Typical system architecture is presented in Figure 1.

The leading trend in system architecture is toward system integration. Higher integration reduces the price of the system, raises performances, and makes the system design easier (which in return also reduces the price). The goal is to design a system-on-a-chip. Integration is performed through migration of digital circuits onto the digital chip and through migration of analogue blocks onto the RF front-end. Most system architectures today include a general-purpose RISC microprocessor. It is often incorporated on the digital chip, and if not, then the chip has an appropriate interface to include the microprocessor on a system level. General-purpose microprocessor is one of the first resources that migrated onto the digital chip since most GPS systems need some sort of data processing. SRAM, ROM, and cache memories followed it. Following the system-on-a-chip trend, various device controllers are now being incorporated onto the digital chip. This leads toward a system design where only external memory and communication ports will be off the digital chip. Similarly, the complexity of GPS RF front-end circuit grows and RF front-end chips are now designed to track greater number of GPS signals (whether to track both C/A and P-code signals from GPS, or to track signals from both GPS and GLONASS).

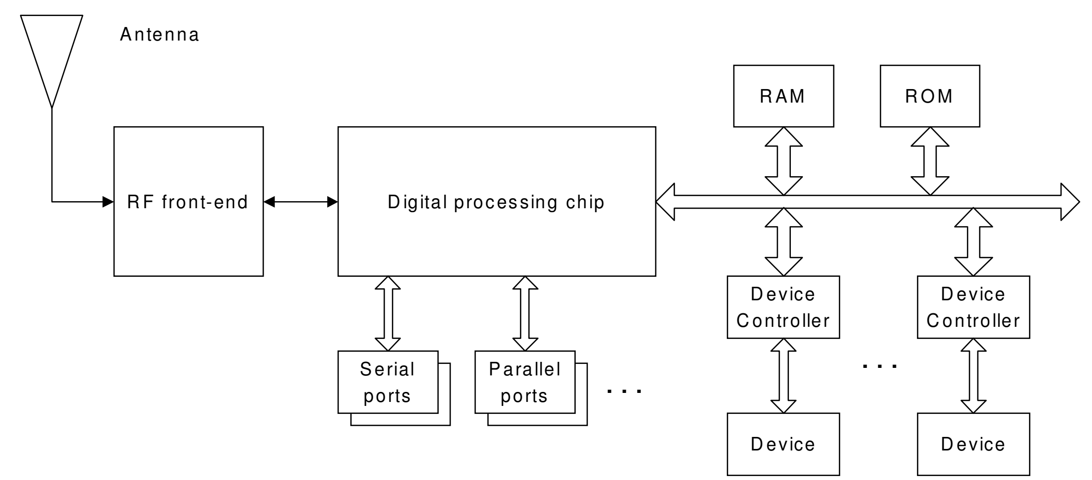

Figure 1: Typical architecture of a GPS-enabled handheld system

Description: RF front-end is an analogue circuit in charge of the satellite signal detection coming from the antenna and converting it to a digital signal. Digital processing chip performs the calculations of the position based on the data coming from the RF front-end. It is also in charge of running the whole system: running OS and application software, I/O communication, etc.

Explanation: This system architecture naturally extends the bus-based architecture of the digital processing chip. System bus enables RAM, ROM, and other elements of the system that are not incorporated on the chip to be connected. Controllers for serial and parallel communication are usually incorporated on the chip. The same case is with all the devices supported with on-chip controllers.

5. Chips for Use in Handheld GPS Receivers

Each GPS receiver has a core that consists of an RF front-end circuit (analogue) and a GPS signal processing circuit (digital). Analogue and digital circuits are usually manufactured by different lithographic processes; hence, GPS receiver chip set usually consists of two types of chips - analogue and digital[1]. Production technology nowadays allows that RF front-end on one side and all digital circuits on the other side can each fit on a single chip. Thus, most vendors offer two-chip sets.

Generally, the chips are designed to include only the resources that will be needed by most GPS systems where they will be potentially used. By reducing the number of resources on the chip, their size also reduces, and their price as well. It allows them to be used in cheaper products, whose production volumes are high and bring most profit. On the other hand, resources that are chosen to be on the chip must have performances sufficient to make the system usable in a number of predefined applications. That, however, rarely covers high-end systems. Vendors try to find the best solution that can satisfy these contradictory requirements.

The digital chip architecture usually includes a single bus with a general-purpose RISC microprocessor, an attached DSP, and other system elements such as serial and parallel communication controllers, interrupt controller, real-time clock, on-chip RAM and ROM, etc. In such a configuration the DSP performs all GPS-related calculations, and the general-purpose microprocessor is there to enable work with various devices in the system and to run the OS and the application programs. Many producers employ such a concept. Others design chips without an integrated RISC microprocessor (but still with a possibility that a microprocessor chip can be incorporated into the system). That way the designers can implement various solutions regarding the general-purpose microprocessor. However, the price of a complete system is higher in that case. A typical chip architecture is presented in Figure 2.

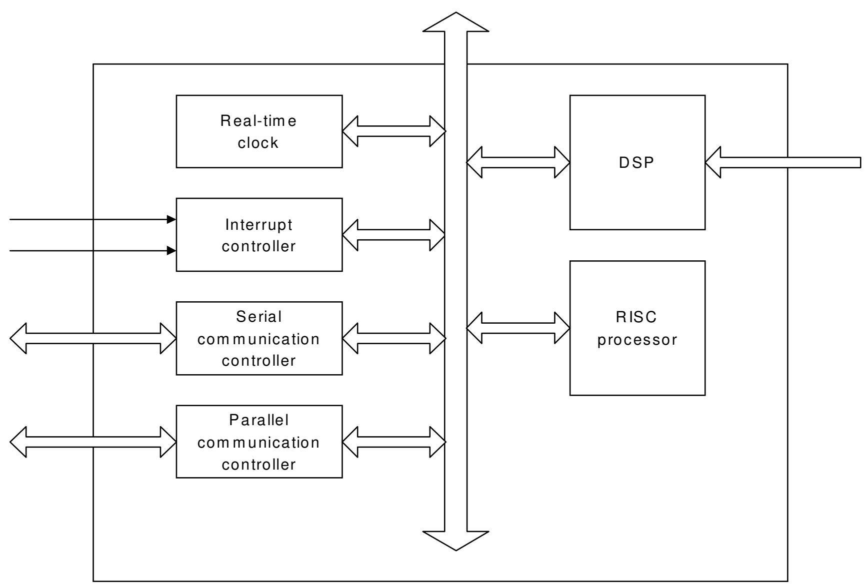

Figure 2: Typical architecture of the digital chip used in GPS-oriented handheld systems

Legend: GPS RF front-end : part of the GPS receiver that tracks signals and converts them into digital form; DSP : Digital Signal Processor.

Description: The DSP performs all GPS-related calculations, RISC core runs OS and applications, and the system bus connects all system elements. It extends out of the chip so that other devices can be attached externally.

[1] Integration of both analogue and digital circuits on one chip is still not widely used in the industry.

Almost all chips have power-saving features. Low power consumption is a necessary requirement in handheld devices. Designers pay much attention to it in the design process. Processor cores with low power consumption are used in the system design, and latest chip production processes[2] are used to reduce power consumption, increase speed and decrease die area. Sometimes a special low-power controller is included on a chip.

Many devices that use GPS have only rudimentary display capabilities, like wrist watches, mobile and satellite phones, and simple GPS receivers. It would be costly to have the graphics controller on the chip if many of the products where the chips will be possibly embedded are not going to use it. That is one of the reasons why no chips currently on the market have it. The other reason is that graphics controllers are device-dependent, i.e. they are designed according to the type of the display they should drive. However, if the chip is to be used in specific products with possibly intensive graphic, it is then cost-effective to have the graphics controller on the chip. This sort of reasoning can be applied to all other device controllers and system resources.

Some of the most important features of commercial chip sets for GPS-dedicated systems are given in Table 2. The acquisition modes are defined as follows:

Cold Start - In Cold Start mode the receiver has no knowledge on last position, approximate time, or satellite constellation. The receiver starts to search for signals blindly. This is standard behavior if no backup battery is connected. Cold Start time is the longest startup time for most GPS receivers.

Warm Start - In Warm Start mode, the receiver knows, due to a backup battery, his last position, approximate time, and almanac[3] . Thanks to this, it can quickly acquire satellites and get a position fix faster than in cold start mode.

Hot Start - In Hot Start mode, the receiver was off for less than few hours. It uses its last ephemeris[4] data to calculate a position fix.

Reacquisition - The reacquisition figure gives the time required to get lock on a satellite if the signal has been blocked for a short time. This is important in urban areas.

Update - Update time designates at what maximum rate the receiver can update positions, provided that there are no obscurations.

5.1 Case Study: Paradigm+JPScore Chip Set

Paradigm® RF/IF chip

So far no RF/IF (Radio Frequency/Intermediate Frequency) receiver chips have been designed that can track more than 12 GPS channels. GPS has 24 satellites in total, of which no more than 12 are visible from any point on earth. The chip designers also had in mind that only L1 satellite signal is available for civil use. However, a newly founded company (1997) Javad Positioning Systems (JPS) has recently designed an RF/IF GPS receiver chip (Paradigm®) that has integrated 40 universal super channels that each can track all signals of either L1 or L2 frequencies of either GPS or GLONASS, or can be used for high data rate (32 Kbit/sec) communication (patent pending). It uses the state-of-the-art low power integrated circuit technology.

The technology employed in Paradigm® provides significant enhancements in the accuracy of positioning, speed of satellite acquisition, and in the ability to track satellites under adverse conditions (see Table 2). In particular, it has new quality level for tracking GPS L2 in the presence of AS (patent pending). In addition, C/A code has been implemented on all L2 channels in anticipation of possible

[2] The following technologies are used in the production of GPS-dedicated chips nowadays: Silicon (0.35 micron, 0.25 micron, and soon 0.18 micron) - for both RF front end and digital chips; Gallium-Arsenide - for fast RF front end chips; Silicon-Germanium - a technological process from IBM that recently presented a 5mm^2 GPS chip die using this technology.

[3] Almanac is a set of orbit data, used to determine satellite visibility.

[4] Ephemeris is a precise set of satellite orbit data, used for navigation solutions, i.e. for solving a system of four equations whose result is a set of three space coordinates (x,y,z) and the time.

		Chip set Digital chip RF/IF chip	*MGPSCS-A1* MMC2003 PSRF1111A	*ST-GiPSy* ST20-GP6 STB5600	*SiRFstar II* GSP2e GRF2i	*Sierra* Scorpion Scott	*GP2000* GP2021 GP2015	*Zodiac* Scorpio Gemini+Pisces	*VSGPS* VSGPS_B1 VSGPS_R1	- JPScore Paradigm	*PoleStar* PoleStar -
Producer			Motorola (www.motorola.com)	STMicroelectronics (www.st.com)	SiRF (www.sirf.com)	Trimble (www.trimble.com)	Mitel Semiconductors (www.mitelsemi.com)	Conexant (www.conexant.com)	VLSI Solution (www.vlsi.fi)	Javad Positioning Systems (www.javad.com)	I.C.COM (www.iccomm.com)
Embedded RISC/DSP/SSP			MCORE / - / -	ST20 / custom / -	ARM7TDMI / - / -	68330 / custom / -	- / - / custom	AAMP2-8/ custom / -	- / VS-DSP / -	2xARM7TDMI / - / -	custom / - / -
GPS	Input Channels	Type of signal	GPS L1 C/A	GPS L1 C/A	GPS L1 C/A	GPS L1 C/A	GPS L1 C/A	GPS L1 C/A	GPS L1 C/A	GPS L1 C/A+P GLONASS C/A Differential	GPS L1 C/A GLONASS C/A
		No. of channels	12	12	12	8	12	12	12	40	8
	Timing	Cold start	60 s	90 s	45 s	-	180-300 s	150 s / 10s*	-	~ 5 s	60 s
		Warm start	40 s	45 s	38 s	45 s (90%)	60 s	45 s / 5s*	30 s	~ 3 s	32 s
		Hot start	15 s	7 s	8 s	20 s (90%)	30 s	15 s / 1s*	5 s	~ 0.5 s	1 s
		Reacquisition	1 s	1 s	100 ms	2 s (90%)	1s (obscur.<5s) 5s (obscurt.<1h)	1 s	100 ms (obscur.<5s)	0 s (no cycle slips)	100 ms (obsc.< 5min)
		Update	-	-	10/s	1/s	5/s	1/s	10/s	20/s	1/s or 2/s
	Accuracy	With SA on	100 m	100 m	-	-	100 m	15 m	100 m (95%)	-	-
		With SA off	25 m	30 m	-	25 m (CEP)	30 m	-	20 m (95%)	-	25 m (CEP)
		Differential	-	1 m	-	2 m (CEP)	2 m	1-5 m	3 m	-	2-5 m (95%)
		Time (SA on)	500 ns	-	-	500 ns	-	350 ns	-	-	1 µs
		Velocity	-	-	-	0.1 m/s	-	-	-	-	0.1 m/s
	Dynamics	Altitude	18000 m	-	18000 m	18000 m	-	-300 to 12200 m -300 to 45750 m **	Unlimited	-	-
		Velocity	515 m/s	-	515 m/s	515 m/s	-	500 m/s	Unlimited	-	500 m/s
		Acceleration	4 g	-	-	4 g	-	-	4 g	-	4 g
		Jerk	5 m/s³	-	-	20 m/s³	-	-	4 m/s³	-	20 m/s³
Supply voltage			3.3 V ext. (1.8 V int.)	3.3 V	2.7V - 3.3 V	5 V or 3.3 V	3 V	3.3 V	3.3 V	2.5 V	2.5 V
Power consumption		Digital chip	225 mW	150 mW (16 MHz)	360 mW - 450 mW	700 mW (5V) 350 mW (3.3V)	150 mW	250 mW	100 mW	-	-
		RF chip		-		160 mW (5V) 100 mW (3.3V)	200 mW		30 mW	-	-
Production technology		Digital chip	CMOS 0.36µm	CMOS 0.35µm	CMOS	CMOS	-	CMOS	-	CMOS 0.25µm	CMOS 0.25µm
		RF/IF chip	Bipolar	HS Bipolar (ECL)	Bipolar	Bipolar	-	Gallium Arsenide	-	-	-
Released			1998	March 1998	August 1999	1997	May 1997	1999	March 1999	September 1999	September 1998

Table 2: Features of commercial GPS-dedicated chip sets (Data acquired from manufacturers' publications and web sites)

Legend: * : with additional hardware accelerator
** : with environment enclosure
- : data not known or not available
~ : estimated

DSP : Digital Signal Processor
SSP : Spread-Spectrum Signal Processor
CEP : Circular Error Probability 50%

inclusion of C/A code on L2. The chip also includes 6 separate high data rate spread spectrum communication channels that operate both in frequency hopping (64 Kbit/second) and direct spread spectrum (32 Kbit/second). Furthermore, the spread spectrum communication technique has perfect time synchronization using tight integration with GPS timing (patent pending). Also integrated in this chip is an Interference/Jamming Suppression System (patent pending) that can simultaneously suppress up to 6 in-band jammers. The Paradigm® chip also includes an innovation in signal processing technique for multipath mitigation for both code and carrier which uses less hardware and better performance than other published techniques (patent pending).

JPScore® digital chip

JPScore (see Figure 3) is the most advanced and complete digital GPS/GLONASS chip for general use. It is a complete digital chip that includes over a dozen system blocks. The 50-Channel GPS/GLONASS/WAAS module incorporates advanced solutions like the in-band interference suppression feature. The dual-processor architecture allows independent operation of different applications. For example, one processor can be dedicated to GPS/GLONASS tracking and position computation while the other processor is deployed for user interfaces like map displays. The big number of flexible GPS channels and chip' s structure give possibility to use it in various GPS applications, like reliable GPS/GLONASS/WAAS navigation, multi-antenna attitude receiver, GPS receiver with radio communication channels, etc. It makes possible to underuse civil signal from all-in-view GPS satellites on the second and third GPS frequencies that will be available in next few years. The advanced power-saving technique implemented in chip and flexibility in reference oscillator and sampling frequency selection allow it to be used in power-sensitive handheld systems.

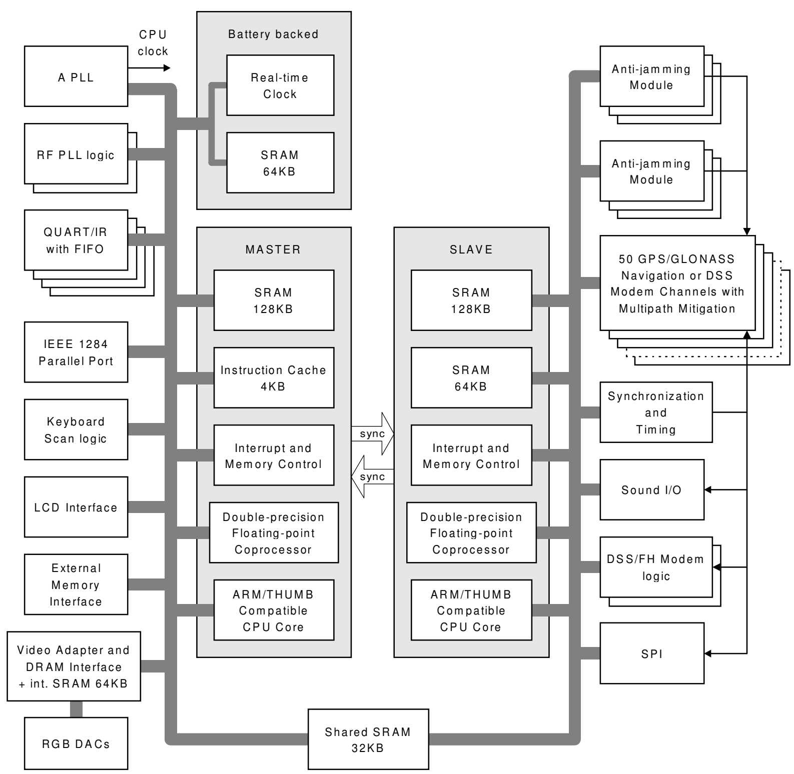

Figure 3: JPScore chip architectre

Description: JPScore architecture extends the conventional bus-based architecture with another general-purpose microprocessor instead of the DSP, on-chip SRAM, FPUs for both processors, and instruction cache for the master processor. In addition, a multitude of device controllers is placed on the chip, which reduces the price of the system. Assuming that device controllers occupy relatively small die area, compared to the area occupied by the two processor cores, cache, and SRAM, they are inexpensive to incorporate on the chip.

The chip includes:

- Two ARM-compatible processor cores with THUMB instructions and two FPU coprocessors
- 480KB on-chip SRAM
- Video Adapter with 64KB and 3 basic modes of operation:
  - video adapter not used
  - video adapter and on-chip video memory are used (resolutions up to 256x256)
  - video adapter and external video memory are used (resolutions up to 1024x1024)
- Real-time Clock with one-second accuracy, separate power supply, and alarms for system wakeup
- Two FH/DSS Modem Channels that can be configured as either receiving or transmitting (up to 128Kbit/s)
- Four RS232-C/Infrared Transceivers (baud rates from 300 bit/s up to 460.8 Kbit/s)
- IEEE 1284-compatible parallel interface controller that supports transfer rates up to 1 Mbit/s
- Keyboard interface that supports two modes, for keyboards with 64 or 16 keys
- Glue logic with:
  - two sets of PLL dividers and detectors for RF extension
  - synchronous serial peripheral interface (SPI) with four chips selects
  - sound module
  - interface that provides sampling and syntheses of signals suitable for voice communication
  - general purpose I/O port
  - an interface for LCD controllers of any kind except those that need CPU provided regeneration
  - IDE interface

5.2 Research Avenues in Chip Technology and Design

Improving fabrication technology and design are two mutually independent ways to obtain faster chips that consume less power. If design is improved, introducing new technology will not reduce benefits from the new design, and vice versa (however, it is possible that these two factors have a synergistic effect. That happens, for example, when circuit design is especially suited for fabrication of chips in some specific technology (e.g., GaAs) [5]).

Advances in fabrication technology constantly tend to reduce the size of integrated circuits. In CMOS, power consumption increases with the square of the power supply voltage; hence, new chip fabrication technologies that enable ICs to work on lower voltages will reduce the power consumption. Also, smaller gates can work on higher frequencies, so chips will be faster; unfortunately, as power consumption depends linearly from working frequency, this partly reduces the effects of lower supply voltage. In overall - improved chip technology reduces power consumption and increases speed.

Another way to improve chip performances is to introduce new and more efficient designs. In this domain, it is not easy to predict what will happen. Chip processing power can be increased either by using more powerful uniprocessors (of higher complexity) or by introducing multiprocessor architectures [6]. Though the main researches of future multiprocessor chip architectures are not directly targeted at chips for use in handheld systems and embedded applications, work is done in that direction as well [7].

A bus-based cache coherent SMP (Symmetrical Multi-Processor) is a natural extension of the bus-based uniprocessor architecture, and it could be a good candidate for the chip architecture of the future for handheld systems [8]. It can be based on commercial low-power low-complexity microprocessor cores, which can significantly reduce the effort needed to design the system. It is also a scalable architecture, which allows that applications once written in a multithreaded fashion can be used on systems with any number of processor cores, provided that OS can support it. Some embedded operating systems for handheld devices, like Windows CE or ThinLinux, already support multithreading.

6. A Look into the Future

Advances in fabrication technology will inevitably drive handheld GPS-enabled cartographic display systems toward even greater integration in the future. Integration reduces size, power consumption, and the cost of the system, and at the same time increases system performances and usability. The ultimate designers' goal is to get a system-on-a-chip. Since all digital and analogue circuits can already fit each on one chip, the next logical step in integration will be merging of both types of circuits on a single analog-digital chip. At the same time complexity of both RF-circuit and digital circuits will rise.

Increase in the chip complexity must be followed by the appropriate architectural solutions. It is evident that multiprocessing is entering the world of chips for embedded applications. Even though it is still an advanced solution that can be found only in one or two products on the market, it may soon be a widely adopted answer to an ever-increasing demand for more powerful systems that offer high-precision positioning and navigation, and excellent graphics. Multiprocessor systems are naturally scalable, and once the OS and applications are written for it, it will by default support any future improvements in hardware. It will be easily possible to add processors with only minimal changes in the system architecture. This, in turn, will save design time, and reduce the cost of development.

Commercial microprocessor cores and logic blocks are already implemented as part of many GPS-dedicated chips. In the future, the design will be probably heavily based on use of digital-logic cores, whether they come from within the same company or from third-party vendors. Multicore chip design rises the questions of system testability [9] and compatibility [10]. Digital-logic cores are intellectual property blocks and vendors do not allow insight into their structure, which complicates system testing. Cores can also be in different formats: soft cores (HDL description like VHDL or Verilog), hard cores (fixed layout for specific process), or firm cores (covers a range of representations, from floorplanned RTL blocks to fully placed netlists); this further complicates design and testing. Furthermore, systems can include cores from different vendors, which causes the problem of their compatibility; hence, standardization of core interfaces (i.e., of on-chip buses, device controllers, etc.) is needed.

Some of the handheld systems may soon include support for operating systems for use in embedded environments, enabling a multitude of application programs to run on these platforms. This will make them a real Swiss-knife of the digital world. Trend of integration will lead us eventually toward merging of GPS-based cartographic display systems with other handheld systems into a universal positioning/navigation/communication/computation/data-storage unit that will incorporate the functionality of today separate systems.

6.1 New Services and Applications

A list of new services and applications that GPS-enabled cartographic display systems could support in the future may include:

Meteorological information

- Graphical and numerical display of position-dependent meteo-elements (tides and currents; winds and storms; temperature, pressure, and humidity)
- Weather reports

Navigation

- Autopilot control and programming
- Display of current speed-over-ground and course-over-ground information

Help

- Disaster help service (S.O.S.)

- Medical help system (emergency calls with automatic position identification)
- Navigational help system

Communication and data update

- Download of maps
- Electronic booking and tourist information
- Internet access - including Web, email, telnet, and all low-bandwidth services
- Satellite communication enabled via IRIDIUM or similar satellite systems

Tracking and Security

- Broadcasting the current position to others
- Vehicle alarm system with automatic position identification to enable tracking
- Tracking enabled when moving in insecure areas

References

[1] V. Milutinovic, "The Best Method for Presentation of Research Results," IEEE TCCA NEWSLETTER, September 1996, pp. 1-6

[2] NAVSTAR GPS User Equipment Introduction, September 1996, US Coast Guard Navigation Center, [Online,] Available WWW: http://www.navcen.uscg.mil/gps/geninfo/gpsdocuments/

[3] Interface Control Document, September 25, 1997, US Coast Guard Navigation Center, [Online,] Available WWW: http://www.navcen.uscg.mil/gps/geninfo/gpsdocuments/icd200/

[4] Global Positioning System Standard Positioning Service Specification, 2nd Edition, June 2, 1995, US Coast Guard Navigation Center, [Online,] Available WWW: http://www.navcen.uscg.mil/gps/geninfo/gpsdocuments/sigspec/

[5] V. Milutinovic, "Surviving the Design of a 200 MHz RISC Microprocessor: Lessons Learned," IEEE CS PRESS, Los Alamitos, California, 1996

[6] L. Hammond, B. A. Nayfeh, K. Olukotun, "A Single Chip Multiprocessor," Computer, September 1997, pp. 79-85

[7] C. E. Kozyrakis, D. A. Patterson, "A New Direction for Computer Architecture Research," Computer, November 1998, pp. 24-32

[8] I. Ikodinovic, Z. Dimitrijevic, V.Milutinovic, "Scalable Peripheral Processor," Technical Report, 1999, [Online,] Available WWW: http://galeb.etf.bg.ac.yu/~dsm/gps

[9] J. Lipman, "Add testability now to core-based chips, or pay later," EDN, February 16, 1998, Available WWW: http://www.ednmag.com/ednmag/reg/1998/021698/04df_01.htm

[10] J. Lipman, "Multicore chips challenge system-on-chip designers," EDN, June 18, 1998, Available WWW: http://www.ednmag.com/reg/1998/061898/13cs.htm