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End to End Continuous Indoor Positioning

Greg Turetzky, J. Blake Bullock, Dimitri Rubin, Don Leimer, Mahesh Chowdhary, Murray Jarvis
CSR, plc
Sunnyvale, CA, USA
greg.turetzky@csr.com

***Abstract*— GPS receivers are found on nearly every smart phone today enabling a wide range of location-based services such as mapping, search, and navigation. Users expect their devices to work in all environments including indoors, parking garages, and in dense urban canyons. Recent advancements in Assisted-GNSS technology have enabled improved positioning indoors, but GNSS receivers are still not sensitive enough to determine position everywhere that users carry their devices. Any solution to improving coverage and accuracy indoors must be low cost and low power.**

This paper introduces a new product from CSR Technology, Inc. – the SiRFstarV location chip with SiRFusion. The latest in a family of innovative GPS chips, this ground-breaking receiver combines the latest A-GPS and A-GLONASS advancements with Wi-Fi positioning and dead reckoning using low-cost Micro-Electro-Mechanical Systems (MEMS) sensors. Smart phones are equipped with an increasing array of MEMS sensors including accelerometers, magnetometers, gyroscopes, and barometers. The SiRFstarV chip acts as a gateway to receive input from all available MEMS sensors so that the output signals can be combined with the GPS, GLONASS, and Wi-Fi measurements. The observations from all of these sources are fused together using a Kalman Filter. Smart location management is employed to make use of the best combination of sensors at any given time in order to maximize coverage and accuracy while keeping power draw to a minimum. The result is continuous position availability in indoor environments.

To achieve these results, the system also uses data from a cloud based server for A-GPS, A-GLONASS, extended ephemeris data, and Wi-Fi positioning data. The improved coverage and accuracy indoors allows the system to crowd source the location of Wi-Fi access points indoors to a better level of accuracy than previously possible without surveying the sites. This in turn allows devices even without MEMS sensors to perform better than previously possible indoors without the need for surveyed infrastructure.

This paper describes the architecture of SiRFstarV, SiRFusion and SiRFCloud architectures and a typical application in a handset. The end-to-end system is described including the server components and measurement fusion approach. Performance measurements in real-world environments are presented. Introduction

I. INTRODUCTION

The explosive growth of the smartphone market, fueled by the combination of embedded GPS receivers, internet connectivity, advanced color displays and an open application development has opened many new applications, navigation being one of the biggest. Many of these applications have been essentially turning the phone into a connected Personal Navigation Device (PND). Now that users have that experience in their hands, there is a need to add indoor location to create a truly ubiquitous experience. CSR is addressing that need through its SiRFstarV location chip combined with SiRFusion software and a cloud based service framework to combine GNSS, WiFi and MEMS into a complete, continuous indoor solution.

II. TARGET PERFORMANCE AND USE CASES

Expanding location to indoor environments, creates a new set of use cases and therefore performance requirements. Indoor positioning today consists mostly of A-GPS solutions combined with some cellular backup methodology such as Advanced Forward Link Trilateration (AFLT). The disparity of performance of these two solutions, in particular the fact that the indoor accuracy is much worse than outdoor, has made development difficult. Furthermore, the switch creates significant discontinuities and an unacceptable user experience. For indoor navigation (such as Point-of-Interest (POI) related functions), users need sufficient accuracy for them to switch from watching the screen to looking around, this is typically on the order of 10-20m with regular 1Hz updates. For cameras, the use case is different. A fast time to first fix at low power is required, but 1Hz updates are not. Asset tracking is another important use case where the primary requirement is low power operation and a guaranteed fix, but 10m is not required in many instances. Trying to create a solution that can handle all these use cases is a difficult challenge and one that requires a variety of techniques.

III. GNSS POSITIONING

SiRFstarV positioning combines range measurements from all-in-view GPS, GLONASS, QZSS, and SBAS satellites for state-of-the-art GNSS positioning, and is hardware-ready to enable Galileo and Compass measurements when these constellations are operational. Immunity to interference, cross-correlation, and multipath impairments is provided to achieve very high sensitivity, which is critical for indoor positioning. Nevertheless, the utility of reception sensitivities below -165dBm have been found to have limited value for all but static cases, due to the very long integration times required to make reliable measurements and the accuracy of those measurements. Increasing the number of independent range measurements is critical to improving indoor positioning, and using multiple constellations is one way to provide them.

The improvement in indoor positioning by using multiple constellations is similar to the improvement in urban canyon positioning since the impairments are similar. One significant difference is that multipath delays for indoor environments are typically much shorter, and conventional mitigation methods cannot be applied without a very wide RF bandwidth. The shorter delays therefore result in lower signal levels due to phase cancellations and pseudorange bias errors, which are recognized as multipath errors and reduced as part of the innovative SiRFstarV measurement processing. Due to these error characteristics, the performance improvement indoors by adding GLONASS is less than seen in urban canyons. Furthermore, any GNSS satellite measurement would have similar characteristics, so to achieve 100% availability, other measurements are needed.

IV. Wi-Fi Positioning

Opportunistic positioning using observed Wi-Fi signals is a well established method of positioning in GNSS-denied environments. Off-the-shelf Wi-Fi access point hardware is not well suited to positioning using timing observations therefore CSR uses observed signal strengths together with the broadcast unique identifiers (BSSIDs) as the basis for the Wi-Fi positioning sub-system. Signal strength information is by its nature asymmetric. A strong observation of a Wi-Fi Access Point (AP) indicates that one is near it, but it is not safe to infer from a weak observation that you are far away. This is because weak observations may be due to, for example, occlusion, fading or antenna orientation. This means that the performance of Wi-Fi positioning varies considerably with location and time.

There are several limitations to Wi-Fi positioning. The first is that since it is opportunistic there is no guarantee of performance. Fortunately, AP density is typically highest in just the areas where Wi-Fi positioning is most needed, namely, deep indoors and in dense urban areas. Secondly there is also no guarantee that APs will remain in the same locations so the database of AP locations to be dynamically monitored and continuously improved. Lastly, the location of the APs is not known *a-priori* and hence there needs to be some independent means of locating the APs in order for them to be used for positioning. The CSR server implementation uses the other technologies present, namely GNSS and MEMS in order to generate this information.

The SiRFstarV chip supports Wi-Fi receive (sniffing) and positioning via scanning of the ISM band to detect any broadcast 802.11b Barker codes on any of the 11 channels. This process takes approximately 100ms/channel resulting in a scan time of 300ms for the three primary channels or of 1.2s for a systematic scan of the entire band. This sniffer provides a very low power method of obtaining the measurements, without ever associating with the AP.

The usual configuration is for the SiRFstarV chip to be connected to the CSR server via software running on a host processor in the device. On request, the server can then provide the device with all the APs known to be in the vicinity of the user. This data is sent as a sequence of spatially contiguous sets of APs in a tiled structure. The benefit of serving tiles to the user rather than user's position or only the APs instantaneously detected is that the client device can subsequently operate independently with only occasional server contact. In fact, since the SiRFstarV chip supports on-board storage of the AP tile information, it can also operate for extended periods without waking up the host, a feature useful for low power geo-fencing and other location functions.

Another important aspect of the server is that it supports crowd-sourced learning of Wi-Fi APs. Client devices submit anonymous sets of Wi-Fi signal strength data and associated BSSIDs, together with contemporaneous GNSS and relative information from the MEMS devices. By collating all the information available in an area across users, the system is able to calculate the most likely locations for Wi-Fi APs and hence generate tiles available to provide to all users. A key point is that unlike crowd-sourced systems based on GNSS alone, CSR also uses relative data from MEMS Pedestrian Dead Reckoning (PDR) to extend the coverage area of the crowd-sourcing indoors.

V. MEMS Pedestrian dead-reckoning

But WiFi alone is not sufficient indoors, especially since it provides no indication of velocity. So PDR logic is realized using integration of MEMS sensors with SiRFstar5xp GNSS receiver through its dedicated multi-master I2C port for synchronization and processing. Acceleration data is processed by the context (or user mode) detection algorithm [2] to determine the dynamic state of the user (or receiver) in order to select appropriate position determination algorithms.

Generalized navigation equation [3] can be written as

$$\dot{v}_e^n = C_b^n f^b - [2\omega_{ie}^n + \omega_{en}^n] \times v_e^n + g_l^n \quad (1)$$

This equation [2] (in navigation frame) relates the ground speed of an object to measured specific force and measured body rate. The generalized navigation equation when integrated twice, transforms from the acceleration of platform into position represented in North and East reference frame, results in Equation 2.

$$E(t) = E(0) + \int_0^t s(t)\sin(\psi(t))dt$$
$$N(t) = N(0) + \int_0^t s(t)\cos(\psi(t))dt \qquad (2)$$

where, $s(t)$ is displacement and $\psi(t)$ is heading. In case of pedestrian motion, velocity and heading can be assumed to be constant during the interval when a step is taken. With this assumption, the integral form of Equation 2 can be rewritten as a difference equation with piecewise linear approximation.

$$E_t = E_{t-1} + \hat{s}_{[t-1,t]}\sin\psi_{t-1}$$
$$N_t = N_{t-1} + \hat{s}_{[t-1,t]}\cos\psi_{t-1} \qquad (3)$$

This equation describes a method of Dead Reckoning (DR) which is based on step counting rather than integration of acceleration and angular rate. The DR process consists of three important components: the previously known absolute position of the user at time t-1 ($E_{t\text{-}1}$, $N_{t\text{-}1}$), the stride length or distance traveled by the user since time t-1 ($\hat{s}_{[t-1,t]}$), and the user's heading (ψ) since time t-1. The coordinates (E_t, N_t) of a new position with respect to a previously known position ($E_{t\text{-}1}$, $N_{t\text{-}1}$) can be computed as shown in Equation 3. The position initialization of pedestrian dead-reckoning process can be accomplished using any or combination of absolute positioning technologies such as GNSS, WiFi or GSM.

Performance of PDR algorithms is dependent on obtaining calibrated MEMS inertial sensor data continuously. Calibration of sensors is accomplished through collecting and processing sensor data for user motion of device in Earth's gravity and magnetic field. With the given time and location estimate, Earth's magnetic field parameters are computed using World Magnetic Model [3]. Earth's magnetic field parameters are also used to detect occurrences of magnetic disturbances. Magnetic sensor measurements are de-weighted for PDR process during such magnetic disturbances.

The error growth in PDR is typically on the order of 10% of the distance traveled. This level of error growth makes MEMS PDR unsuitable as the sole positioning solution when indoors but in combination with GNSS and WiFi in the SiRFusion filter, it fills an essential gap in indoor motion.

VI. SiRFusion

The GNSS, Wi-Fi, and MEMS PDR solutions offer varying levels of accuracy, coverage, and reliability. CSR developed SiRFusion, a Kalman filter-based fusion engine in the SiRFstarV device. SiRFusion is a critical component and does the job of merging the multiple sources of position information to provide a single best estimate of position and confidence to the user. It takes as input absolute positions from GNSS and Wi-Fi and also any relative information derived from the MEMS PDR sub-system. This Kalman filter has 8 states which include the position and velocity terms. WiFi positioning contribution into to the filter is absorbed as synthetic position update and PDR relative positioning contribution is incorporated as velocity update.

In order to determine how to weight and smooth the different inputs, it is crucial that the individual input technologies provide reliable estimates of their confidence and correlation. As an example, it was mentioned earlier that the quality of Wi-Fi positioning is variable and is best when strong APs are seen. A high quality Wi-Fi position, signified by a low confidence value, will cause the fusion filter to be strongly biased towards this positioning source. When the Wi-Fi position quality subsequently deteriorates, this is reflected in the position confidence and hence the fusion filter down-weights the influence of Wi-Fi. In turn this allows dominance of the MEMS PDR input until another sufficiently high quality absolute position allows the filter to correct. The net effect of this behavior is that the MEMS bridges smoothly between any high quality absolute positions and to a first approximation any low grade information is ignored. Another benefit is that individual Wi-Fi positions can be jumpy because on an individual scan there is considerable variation in the audible APs and their signal strengths. MEMS PDR helps to smooth this out providing a continuous trajectory and a more satisfying user experience.

Another job of the fusion engine is to transition smoothly from indoors where Wi-Fi and MEMS PDR dominate to outdoors where GNSS dominates. This happens automatically in the fusion filter with the GNSS becoming increasingly dominant outdoors as GNSS confidence improves. Conversely the Wi-Fi position accuracy will typically decrease outdoors and the dominant technology will therefore smoothly transition. When technologies are not being used they can be switched off or placed in a maintenance mode in order to reduce any unnecessary power consumption.

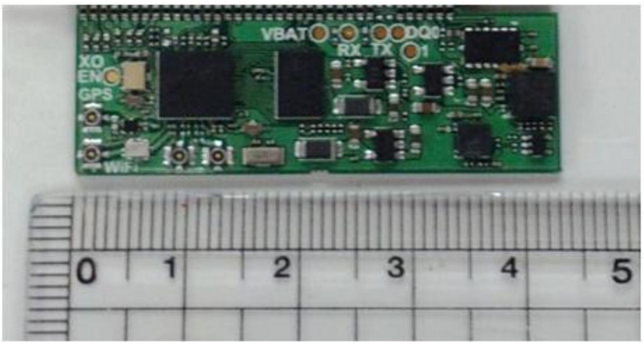

Figure 1. Accessory board with SiRFstarV and 10 DOF MEMS Sensors

VII. Performance Results

CSR has developed a demo platform with SiRFstarV and SiRFusion in a modified HTC Nexus One Android handset. The SiRFstarV and MEMS devices are shown in the module in Figure 1, which was mounted inside a production HTC phone. An Android application was written to display the position on appropriately defined indoor maps and to log data including PDR output, Wi-Fi positioning, GNSS positioning, and the combined SiRFusion solution. The application connected to a CSR server which provided assistance and WiFi AP locations.

Figure 2 shows performance results obtained during a test in Tokyo Station in Japan. The test was done on the B1F level, which is two levels below the track level. The environment has no GNSS signal, lots of magnetic anomalies due to tracks, trains, elevators, and escalators, and many people in motion, which affects Wi-Fi signals. The route walked is shown by the red flags and the SiRFusion output is shown in blue. The SiRFusion solution was able to detect each of the turns made while walking. The largest deviation from the path was ~15m. Typically, the solution was within 10m of the path walked.

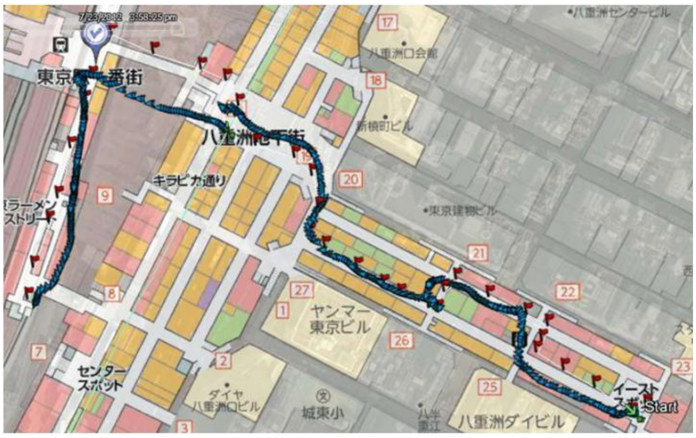

Figure 2. SiRFusion performance in Tokyo Station

VIII. An Indoor Solution

Indoor location technology as provided by SiRFstarV and SiRFusion provides a compelling solution for classic indoor navigation. However, the benefits of indoor location are even greater in expanding applications in social networking, mobile advertising, cameras and asset tracking. The value of providing location to an individual about their own location is valuable, but the value of the location of objects in an M2M application that are somewhere else is even more valuable. The low power, ubiquitous location capability of SiRFstarV and SiRFusion allows anything mobile to be located and in combination with an appropriate communication link (cellular, WiFi or BLE) report that position to the cloud. From there, CSR provides a cloud-based location service to carriers, retailers, malls, government agencies and others to add location to their product mix. This service can even be extended to provide data security such that sensitive corporate information could only be accessed by devices within an authorized area and not in a public place such as an airport. By making ubiquitous location information available on almost any imaginable platform, the use cases are nearly endless.

IX. Conclusion

The combination of an embedded SiRFstarV GNSS chip, with SiRFusion algorithms connected to cloud based server for assistance, has been shown to provide a significant improvement in Indoor positioning. The SiRFusion algorithms have been developed and refined to address the problem of determining position indoors using multiple measurement sources. The performance testing shows that the position availability approaches 100% and accuracy exceeds 10m 50% (CEP). The SiRFusion technology is suitable for integrating in a wide range of consumer and commercial devices. The solution uses existing infrastructure and can be deployed around the world with no new equipment to install or surveying to perform. The combination of embedded technology and a location as a service product, means the capability can be deployed immediately and will continue to adapt as technologies and deployments evolve.

References

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