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TARDEC'S Highly Robust and Accurate Vehicle Time [Synchronization] Platform

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ABSTRACT

Today's warfighter relies on Global Positioning System (GPS) technologies for precise positioning and time synchronization. Reliance upon this technology can significantly handicap vehicles in a GPS-denied environment. Given the challenges of urban terrain, heavily-wooded areas, and electronic counter-measures from the United States' adversaries, there is a strong need to create redundant systems that can operate in lieu of an absent GPS signal. TARDEC VEA created an embedded platform called the "VICTORY PNT Hub", to help address this GPS-related problem as well as the lack of Assured Position, Navigation, and Time (A-PNT) products and solutions. One of the strengths of the VICTORY PNT Hub lies in the "Time" portion of PNT. This paper describes the architecture of the system that is designed to provide highly-accurate and robust vehicle-wide time synchronization with or without a GPS signal. Additionally, a goal of this research will provide quantitative measurements of time accuracy and how this may help existing subsystems integrate with existing time-based protocols.

INTRODUCTION

Today's warfighter relies heavily on GPS technologies to gain battlefield advantages. While GPS provides many benefits, there are also many complex technical and procurement issues that plague most military vehicle platforms. Simply relying upon GPS technologies to maneuver a brigade or engage the enemy may prove to be disastrous in the absence of a GPS signal in a denied environment. In addition to technical challenges, procuring the right GPS equipment also presents an ever-growing hurdle. Traditional stove-piped vehicle sub-systems that depend upon precise timestamping require a "bring your own GPS device" (BYOGD) methodology. Many vehicles have multiple GPS receivers, and, in the worst case scenario, one vehicle configuration has as many as nine required GPS receivers. GPS position, navigation, and time data has typically only been obtained by directly connecting components to a GPS receiver and antenna. This only reinforces the paradigm of BYOGD and is done at the added expense of all vehicle programs. To further complicate the issue, the US Army plans to upgrade all GPS receivers to the new M-Code standard within the next 5 years. At roughly $5000 per receiver, the cost for just GPS devices alone for the example vehicle with 9 devices would be around $45,000. TARDEC VEA developed the VICTORY PNT Hub to address this impending issue. The real strength of this product lies in its ability to distribute position and timing information to the entire intra-vehicle network. The VICTORY PNT Hub is configured to act as the "Hub" that collects PNT data to one central location and publishes it by means of TARDEC's libVICTORY software library and other open source time-synchronization applications. Leveraging the libVICTORY library and existing mature protocols, vehicle LRUs will only require an Ethernet interface to obtain this data. This design effectively alleviates the need for BYOGD, and PNT data will now be distributed throughout the Ethernet bus. Specifically, Local Area Network (LAN) connected devices can now obtain highly accurate time synchronization messages as well as crucial position and navigation data. Mission critical equipment such as tactical radios and fire control equipment require high levels of time accuracy to properly carry out their functions. They all rely on a 1 pulse per second (PPS) input. This 1 PPS signal signifies the start of a new second and is typically accurate to tens of nanoseconds or less. Additionally, it originates from an attached GPS device, but only when the receiver has a solid lock on the signal (Time Figure of Merit (TFOM) of 3 or less). In the absence of a GPS signal, these mission critical components may not function correctly or at all. The VICTORY PNT Hub addresses this issue by integrating a highly accurate atomic clock. This particular clock is known as a Chip-Scale Atomic Clock (CSAC). The CSAC provides nanosecond level time synchronization and is capable of mimicking the GPS' 1 PPS output signal. This clock will continuously provide the same level of accuracy even in the absence of a GPS signal for days.

SYSTEM ARCHITECTURE

The VICTORY PNT Hub is built using an embedded & ruggedized COTS computing system. This low-cost computing system is composed of both an ARM-based computing device and a 16-port 10/100/1000 Ethernet Switch. The computing device contains a quad-core ARM7 CPU, 1GB RAM, 64GB of disk storage, an NVidia Graphics processor, 2 network interface cards (NIC), and has a plethora of available I/O. Included in the system is an embedded military-grade GPS device, the aforementioned CSAC, and additional serial ports necessary to handle multiple RS232 connections. Figure 1 below is an architecture diagram of the system.

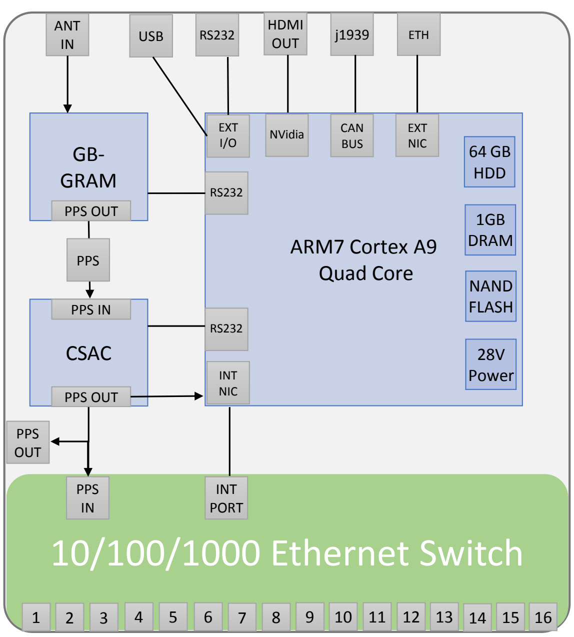

Figure 1 - VICTORY PNT Hub System Architecture

This system has a lot of functionality built into just one hardware unit. In addition to its smaller size, weight, power, and cost (SWaP-C), the unit has also demonstrated the ability to distribute timing and position as well as executing a suitable graphical user interface, and has the capabilities to configure a trusted-boot environment. Furthermore, it is upgradeable to house additional PNT related sensors such as an Inertial Measurement Unit (IMU). Lastly, the internal GPS device will be M-Code upgradeable as soon as TARDEC is able to procure the new GPS hardware.

CSAC CONFIGURATION AND PERFORMANCE

The CSAC device is an extremely accurate and highly sensitive clock. It has the performance of high end atomic clocks, but is married with a small Size, Weight, and Power (SWaP) footprint. Specifically, the CSAC device consumes less than 120 mW on average and has a volume of less than 17 cc. Internally to the VICTORY PNT Hub, the CSAC device is hosted on a dedicated printed circuit board and is managed via an attached microcontroller. The atomic clock is temperature stabilized, closely monitored for health, and utilizes a backup battery to support extended vehicle down-times. The CSAC offers various control methods to match the input PPS signal, namely three different output signal reference algorithms. These algorithms are provided to accommodate different fielded operating conditions; the three types consist of:

- *Manual Synchronization* – the CSAC ignores any input PPS signal until the user commands the device to sync once (on the next rising edge)
- *Automatic Synchronization* – the CSAC will synchronize to every rising edge of the PPS input signal.
- *Disciplined Synchronization* **–** the CSAC uses a high-resolution phase meter for improved accuracy. The phase meter, used in conjunction with the device's steering algorithms built into the microwave synthesizer, can mirror the CSAC PPS' phase and frequency to between 500 femtoseconds (5×10^{-13}), and 5 nanoseconds.

Clearly, for vehicles in theater, manual synchronization does not make logical sense. Neither does automatic synchronization, where it would be implied that the host system would not need to determine the reference source's health state. Logically, using the disciplining mode is the superior mode. This mode has an additional continuation feature known as holdover. In the absence of an input PPS signal (i.e. loss of a GPS fix), holdover will preserve the most recent steering values, continue a stable PPS output signal, and ensure a high level of confidence to all the PPS signal consumers. The importance of configuring the CSAC correctly cannot be understated: “Implemented correctly, disciplining can be utilized to calibrate the CSAC frequency in the field, even if a reference source is only occasionally or sporadically available, thereby improving the long-term performance (phase and frequency drift) of the CSAC.” [CSAC Users guide, page 15]. Inside of the TARDEC VEA SIL, the GPS hardware receives a sub-optimal but usable signal via a GPS repeater. In order to verify the accuracy of the CSAC under test, a scope was attached to the GB-GRAM and CSAC hardware. By attaching the GB-GRAM’s PPS out and the CSAC’s PPS out, the accuracy of the PPS disciplining mode was verified, as the CSAC was disciplined to within a mean of -6.8 nanoseconds. Figure 2 below captures both signals and the rising edge time delta between them. Over the course of 1000 cycles, the following rising edge time delta data points were captured:

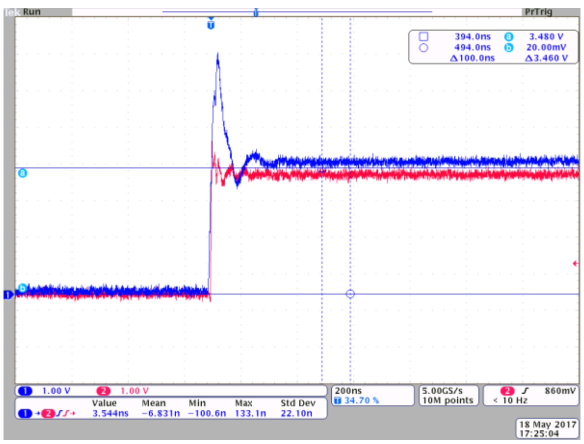

Figure 2 - CSAC PPS Accuracy in Discipline Mode

Current	Mean (μ)	Min	Max	Std Dev (σ)
3.54ns	-6.83ns	-100.6ns	133.1ns	22.10ns

Table 1 - PPS Signal Time Delta Metrics

PHYSICAL HARDWARE CLOCK TUNING

The Linux-based system clock that is available on all Linux distributions is managed in software and suffers from anywhere from 10 to 1000 microseconds of jitter. This level of fidelity will not suffice for a commercial PTP enabled master device. Therefore, this necessitates the addition of a physical hardware clock (PHC) into the system. The PHC is a hardware component that is capable of maintaining a timestamp accurate to tens of nanoseconds. In the Linux Operating System, support is built into the kernel that enables a user to communicate directly to the PHC via a device node named “/dev/ptpX”, where X corresponds to a numbered PHC in the system, or 1 in our case. Typically, and in the case of VICTORY PNT Hub, the /dev/ptp1 device is uniquely tied to an on-board clock built into the physical (PHY) layer on a network interface card (NIC). The VICTORY PNT Hub has an internal Intel i210 NIC that has hardware timestamping capabilities built into it. Timestamps are stored on the i210’s SYSTIML and SYSTIMH timer registers. One register stores the International Atomic Time (TAI, from the French name Temps Atomique International), and the other stores the number of nanoseconds at the sample time. The time reference TAI is used to store the number of seconds elapsed since the start of TAI time on Jan 06, 1980. TAI as a time reference is based upon a precise definition of a second and is not impacted by the slowing of the earth’s rotation. UTC however, is based on the earth’s rotation and orbit around the sun and is subject to aperiodic corrections known as leap seconds. Therefore, TAI time is preferred over UTC, as a software update would not be required after a leap second is added. A PTP-based application is used to initially set the PHC to the current time of day. The on-board GPS device, when it obtains an accurate time figure of merit, will derive its TAI time stamp and will set the correct time of day into the PHC’s time registers. Both elements of the time stamp that are stored in the registers will be used in creating the grandmaster clock that is crucial for configuring an accurate PTP-enabled system. The electronic design of the VICTORY PNT Hub specifically maps the CSAC’s 1 PPS output signal into the Intel i210 NIC. In his master’s thesis, *Hardware Assisted IEEE 1588 Clock Synchronization*, author Bálint Ferencz states that implementing this type of configuration will ensure that the most accurate reproduction of the incoming clock signal is reproduced [page 18]. Ferencz adds that the required fidelity of precise timestamping would not be possible in preemptive scheduled environments (such as the Linux userspace), where concurrent tasks and unrelated non-deterministic interrupts would simply provide too much jitter. Instead, the hardware-enabled autonomous time stamping capabilities facilitated by the NIC itself is the only way to achieve the desired accuracy and cancels out most of the jitter and uncertainty of measurements [page 20]. A Linux kernel and network card driver update was required to handle the 1 PPS signal being mapped directly onto the NIC’s SDP3 pin (Software Defined Pin 3). Now, 1 PPS inputs trigger an interrupt which is used by another PTP-based application named the TS2PHC. TS2PHC adjusts the frequency of its servo loop so that it aligns itself with the interrupt on SDP3 and ultimately tunes the frequency of the PHC. Finally, the Linux daemon named PTP4L allows the VICTORY PNT Hub to act as the PTP master clock. PTP4L is responsible for reading the PHC, encoding the timestamp with the PTP protocol, and distributing this data downstream. Figure 3 below depicts the PPS/PTP subsystem described in detail above.

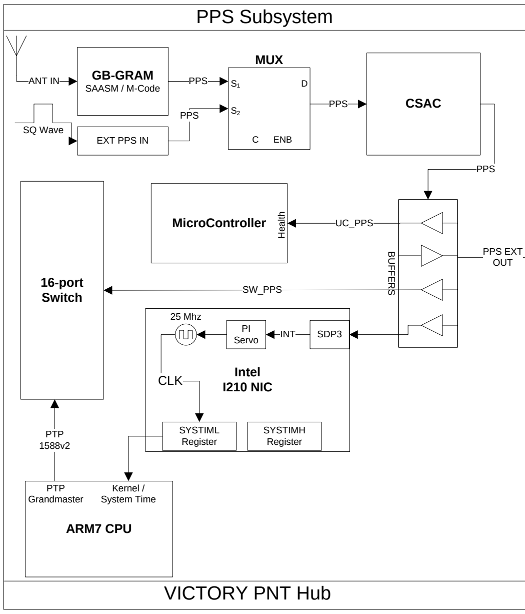

Figure 3 - PPS Subsystem

This design adds robustness to the system, as the job of maintaining accurate time is offloaded to peripherals and the internal network card, and the CPU can be freed to process other important tasks.

PTP (1588v2) CONFIGURATION AND PERFORMANCE

The VICTORY specification has a time service component which leverages existing open-source software and widely used protocols. Network Time Protocol (NTP) and Precision Time Protocol (PTP) 1588v2 are examples of existing protocols. Both have been adopted commercially for many years. The VICTORY specification, for the time service component, currently requires NTP and recommends PTP 1588v2, but the next version will also mandate PTP 1588v2 as required. The previously mentioned hardware modifications made to the PPS subsystem and the internal NIC allows for high-fidelity PTP distributed time synchronization. With these capabilities, the VICTORY PNT Hub becomes the network's so-called "grandmaster clock". A grandmaster clock's role is to transmit synchronized time to a network switch or PTP-enabled clients / slaves on the local network. Additionally, there are network switch configuration changes required to be made. The on-board 16-port network switch also has PTP 1588v2 functionality; it is known as a 'PTP aware' device. The switch's PTP was provisioned to configure all of the 16 ports as a "boundary clock". A boundary clock is a unique setup in that one port enters a slave state to read the grandmaster time and generate the time corrected network packets. Meanwhile, the remaining ports enter into a master state where they disseminate the slave's timestamps downstream.

One benefit to this configuration lies in the fact that 1588v2 protocol is self-aware; it is cognizant of propagation time delay in every PTP message. 1588v2 sends an initial sync message as well as a follow-up message. Given these two packets, slave devices can accurately sync themselves using the time stamp delta measurements observed between packet 1 (sync message) and packet 2 (follow-up message). Having a PTP aware switch adds an ever greater magnitude of robustness into the time synchronization solution. The switch computes the difference between each packet's ingress and egress time and distributes this data to all the slave devices. Regardless of how much bandwidth is being used on the system, slave devices are still able to accurately adjust for the difference in time stamps. An added benefit is that this switch will ultimately lighten the burden off of the master clock and will instead more evenly distribute the load. In order to fully take advantage of the best available capabilities of the PTP aware switch, the switch was provisioned to send 1588v2 traffic via IPv4 and UDP Multicast.

To adequately test the accuracy of the VICTORY PNT Hub, a professional Albedo Ether Genius Gigabit Ethernet Tester was used to help exercise and collect data related to PTP 1588v2 traffic. The Albedo device was used multiple times to ensure consistency between tests. One of the typical tests captured the following data points:

Metric	Value
Capture Time	1 hour
Number of IPv4 RX	3,682,544 frames
Total peak to peak (error) time	134 ns
Grandmaster clock accuracy	76 ns

Table 2 - PTP Test Metrics

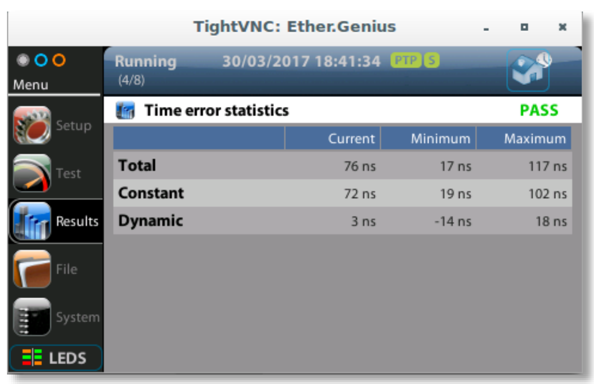

Figure 4 - Albedo Ether Genius PTP Results

To summarize, Figure 4 above is a screen capture that exhibits the fidelity of the PTP configured on the network under test. The green PTP indicator text implies that the Albedo device is currently locked and synced to a master PTP source. The key metric to observe is the "total" time error, which reflects the statistical sum of both the DC error component (constant time error) and the high frequency/jittered error component (dynamic time error). The range between the minimum and maximum values is roughly 135 ns, and the current total time error is only 76 ns. This level of accuracy is on par with more expensive commercial PTP industrial applications like the $6,875 Meinberg commercial grandmaster clock.

PTP ENABLED EQUIPMENT

Vehicle radios and electronic warfare devices are examples of components that require millisecond or greater accuracy. As previously mentioned, most devices have their own dedicated GPS receiver(s) and antenna(s) required to provide precise timing. TARDEC VEA wanted to prove to the greater ground vehicle community that existing vehicle equipment could successfully operate using PTP in lieu of having dedicated GPS equipment. TARDEC VEA, in conjunction with Agile Communications, Inc. modified software in an existing tactical radio to support a PTP client. It was determined that the cost to implement PTP 1588v2 / VICTORY time component service was low: it was roughly $100k of labor over the course of three months (including integration and test). As part of the experiment, a bench-top demo was setup that involved multiple components: a modified tactical radio, an unmodified tactical radio with its' native GPS antenna, and the VICTORY PNT Hub acting as the PTP grandmaster. The demo proved that:

- Both tactical radios could join the same network and operators could communicate as normal.
- Both SRW and WNW network join times are similar with both distributed and direct input. GPS and PTP enabled equipment had SRW and WNW join times within 1 second of each other.
- Large network loads did not hamper radio communications. No network formation drops were encountered.
- It was a low cost, repeatable implementation (Initially $100k for 3 months of labor)

FIELDING IMPLICATIONS

Given the integration and cost predicaments facing vehicle systems engineers, incorporating the VICTORY PNT Hub into vehicular architectures will preclude the requirement for individual vehicle components bolting-on their own GPS receivers and antennas. General Dynamics' Stryker vehicles provide an excellent example of the need for this type of consolidation. Each Stryker variant requires different hardware configurations, and would naturally require differing number of GPS sources. However in the case of the Stryker Commander's Vehicle (CV), there are 2 radios, 1 C4/ISR device, and 6 E/W devices that require GPS, for a total of 9 GPS receivers. This paradigm will become ever more apparent when the Army mandates the switch to new M-Code receivers within the next 5-10 years. Quantitative savings would be quickly realized if the $11,500 M-Code enabled VICTORY PNT Hub were the sole integrator of [distributed] M-Code hardware. If we were to provide a rough estimate that the 40,000 to 60,000 fielded military vehicles had 4 different M-Code GPS devices at approximately $5000.00 each, procurement costs would be ~$800 - $1,200 Million, compared to ~$460 - $690 Million for each vehicle having one VICTORY PNT Hub. This would net the US Army a savings of ~$340 - $510 Million.

SUMMARY

The VICTORY PNT Hub represents a dramatic, yet necessary paradigm shift for the method in which time and GPS data is managed and distributed throughout military vehicles. The features and capabilities of the system makes this an attractive solution at an attractive entry price. Specifically, the VICTORY PNT Hub provides solutions for the following problems:

- Distributed VICTORY time services (NTP, PTP) to provide highly accurate distributed time synchronization.
- Provides infrastructure to operate under GPS denied environments.
- Distributed GPS data and remote management via VICTORY GPS Receiver, Orientation, Direction of Travel, and Position Component Services, which ultimately mitigates the need for BYOGD as well as the mitigating the need for 8 additional GPS serial ports for management.
- Includes PTP-aware and managed 16-port Ethernet switch for vehicles that require this hardware.
- Provides higher levels of assurance for time synchronization in potentially threatening electronic environments.
- Provides the building blocks for sensor fusion and corresponding fusion algorithms, giving greater potential for increased A-PNT levels.
- General purpose computing platform to provide VICTORY adapter software services, such as a CAN network converter / adapter to VICTORY Automotive service messages.

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