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ROBUST TRIGGERING OF MULTIPLE SUBSYSTEMS FOR A TERRAIN MEASUREMENT SYSTEM

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ABSTRACT

One primary system integration challenge for a terrain measurement system is the triggering and time synchronization of all subsystems. Since individual measurement systems vary in their triggering requirements, both in terms of voltage levels and response times, a comprehensive triggering architecture is difficult to implement. Examples of triggering signal inputs include: a transistor-transistor logic (TTL) compliant signal, an RS-232 compliant signal, and an open/close switch circuit. Pulse-triggering signals are also present, and enable continuous time synchronization between instruments. Therefore, a triggering scheme is proposed capable of accurately initiating, synchronizing, and concluding data collection from multiple sensors and subsystems. Simulation of complete circuit designs show that the trigger circuit is capable of properly processing a single physical switch input signal into a TTL-compliant trigger signal. Synchronization pulse signals are likewise amplified to TTL logic levels and broadcast. The high level system design is presented with discussion about the design considerations. A proof of concept demonstrates the approach is valid for the Vehicle Terrain Measurement System (VTMS). Finally, the benefits of this approach and future development to this system are presented.

INTRODUCTION

Accurate terrain topology measurement is critical to ground vehicle and pavement engineering communities. Tire engineers require high-precision surface roughness and texture measurements for assessing tire noise and vibration characteristics. Powertrain engineers utilize measured terrain to capture larger-scale terrain features such as grade for studying vehicle loading scenarios. Pavement engineers concerned with monitoring pavement health utilize measured terrain to detect and diagnose pavement degradation. As the number of applications for measured terrain increases in variety, so does the necessity for sensors capable of measurements of various resolutions and ranges.

Multiple sensor subsystems are integrated into a single terrain measurement system, with each subsystem having unique operating requirements, to support the wide range of applications for measured terrain. Specifically, each subsystem must be triggered simultaneously at the beginning and ending of each data acquisition. This represents the fundamental integration challenge presented by this collection of subsystems. The purpose of this work is to develop a high performance triggering scheme capable of activating a wide variety of subsystems simultaneously, yet have the flexibility to support a wide variety of triggering schemes. The remainder of this work is developed as follows. Background on the target application, a terrain measurement system integrating three scanning laser subsystems, is presented. The specific design issues are defined and a set of design goals for the instrumentation triggering scheme are established. Candidate triggering schemes satisfying these design goals are developed and modeled. One triggering scheme is selected and implemented in hardware to demonstrate the advantages. Results of this work and future applications are discussed, followed by concluding remarks.

BACKGROUND

Terrain Measurement Systems

Terrain measurement systems began as simple 2D road profile measurement devices used by transportation departments to monitor road roughness [1]. As computer power increased and signal processing techniques evolved, 3D terrain surface measurement systems were developed [2, 3]. Typically, terrain measurement systems incorporate a scanning laser [4] that is rigidly mounted to the body of a host vehicle [2, 3, 5]. This vehicle traverses the terrain while simultaneously acquiring terrain measurements. Measured terrain surface data is useful for both vehicle and pavement engineering disciplines. The desired accuracy, precision, and spatial resolution of a sample of measured terrain is highly dependent on the application.

When the vehicle encounters a disturbance, the scanning lasers oscillate with the body of the host vehicle. The body motion of the vehicle must be accurately measured and removed from the laser measurements to obtain an accurate representation of the terrain surface. Modern systems use an Inertial Navigation System (INS) to measure the vehicle movement [6]. The accuracy of the INS depends on the alignment of the Inertial Measurement Unit (IMU) to the laser and satellite coverage of the Global Positioning System (GPS). High frequency host vehicle motion may be captured using three coplanar accelerometers [2].

Each scanning laser records data at a constant sample rate, while the INS determines the position and orientation of the terrain measurement system as a function of time. A coordinate transformation corrects for host vehicle motion and represents the measured terrain in a global reference frame oriented around a fixed base station. When the scanning lasers are combined with other supporting subsystems, a significant challenge exists to ensure each device is triggered in an appropriate manner at the same time.

The Multi-Scale Vehicle Terrain Measurement System (MS-VTMS) [7], built upon the original VTMS architecture proposed by Kern and Ferris [2], captures terrain features at various scales and resolutions, and provides the means to collect both off-road and on-road terrain data. Since no single scanning laser is capable of measuring a path extending beyond the vehicle width with millimeter-scale resolution to capture a wide variety of features inherent in terrain, multiple scanning laser subsystems are selected to operate simultaneously

A toggle switch is typically used to indicate the beginning and end of a typical data acquisition run. The toggle switch is in series with a triggering voltage source, so that when the switch is closed, the subsystems are triggered and begin acquiring data. Once a data acquisition run is complete, the switch is opened and the subsystems stop recording. An example of such an unconditioned trigger signal is shown in Figure 1, where the high and low trigger voltages are appropriate for devices that accept Transistor-Transistor Logic (TTL)-compliant signals. The settling time is approximately 0.005 s, however, and the exact moment the data collection should begin and end is uncertain. This uncertainty is exacerbated by the variety of sampling rates each subsystem may employ (ranging from a few Hertz to several kHz) as well as each device's minimum external trigger threshold voltage. In addition, oscillations due to switch debounce may cause false triggering leading to corrupted data acquisition.

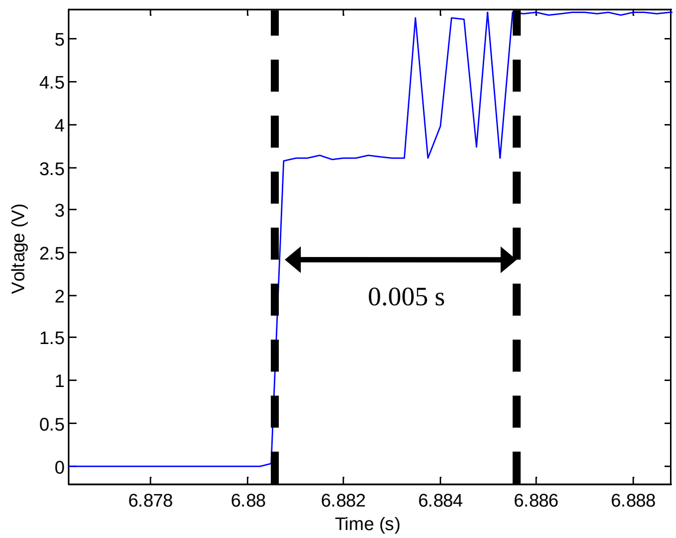

Figure 1. Trigger voltage behavior of toggle switch

Triggering Methods

One approach to triggering instrumentation with an analog signal is by using a simple comparator circuit, typically including an op-amp [8]. However, this approach suffers from two drawbacks. The first issue is that the output signal is susceptible to toggling when the input voltage remains at a level near the reference or switching voltage. Second, the slew rate, the rate at which the voltage rises to the desired level, of this circuit is relatively slow. Since these drawbacks are the same two issues evident in the original triggering signal, the comparator by itself is not a sufficient solution.

The performance of the comparator is significantly improved by adding a positive feedback from the output. This circuit is known as a Schmitt trigger and is widely used as a trigger circuit for many applications [8]. It is a high-performance, robust switching circuit that offers high slew rates, noise reduction, and reduced occurrence of switch debounce. The Schmitt trigger circuit offers these benefits by exhibiting the behavior represented graphically in Figure 2. As the input voltage, V_{in}, exceeds a threshold level in excess of the reference voltage V_{ref}, the output, V_{out}, transitions from V_{lo} to V_{hi}. Likewise, as the input voltage decreases below the lower threshold level, the output voltage returns to V_{lo}. The difference between the two threshold levels creates a hysteretic loop. Strategic selection of threshold levels creates an output signal that is more resistant to toggling due to noise or, in the case of this application, switch debounce.

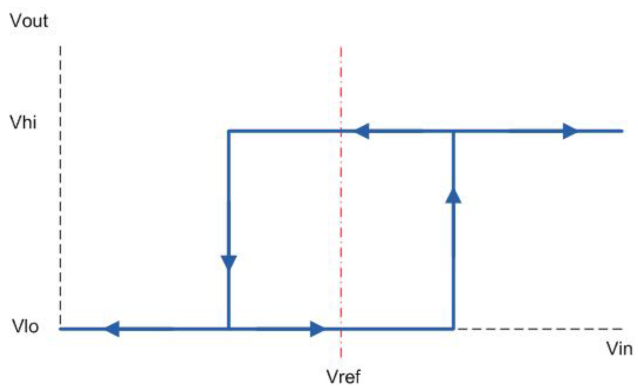

Figure 2. Voltage behavior of the ideal Schmitt Trigger

Several versions of the Schmitt trigger exist on the market. The traditional Schmitt Trigger circuit utilizes an operation amplifier [8]. High-performance low-power Schmitt triggers packaged in an integrated circuit (IC) are also available with propagation delays of on the order of 1ns [9]. The packaged Schmitt trigger differs from the op-amp equivalent in that switching thresholds are set by the manufacturer. While both approaches are valid for constructing a Schmitt trigger, direct performance comparisons between different versions of the Schmitt trigger are beyond the scope of this work.

PROPOSED DESIGN

Design Objectives

An intermediate circuit is developed capable of maintaining TTL-compliant switching signal voltage levels with significantly faster slew rate and protection against switch bounce. There are two primary signals for the case study presented in this work: the switching signal denoting the start and end of data acquisition and a pulse signal used for synchronizing all instrumentation in time. All other signals produced from this system are derived from these two fundamental signals. The following signal requirements are established for this system:

- Switching signal with a settling time on both leading and trailing edges of less than 100 ns. A logic high signal denotes the system is currently acquiring data.
- A functionally equivalent signal to a mechanical switch where its state is determined by an external signal. The circuit is closed when the system is active and open otherwise.
- When using an analog to digital converter (A/D), the triggering signal should be reasonably free of noise, such that the precise moment the system became active can be easily discerned.
- A triggering signal having logic levels suitable for interfacing with a personal computer (PC)
- An amplified pulse signal for synchronizing time-based instrumentation.

In addition to signal requirements, the system must meet the following design criteria in terms of design and fabrication:

- System design insensitive to manufacturing tolerances of the discrete components used in the system fabrication. Typical resistor tolerances range from less than 1% to 5%.
- Triggering to each subsystem must be decoupled from each other, minimizing cross-talk. In addition, ground levels for different instruments should be isolated to eliminate the presence of ground loops.
- Modular design allows quick replacement of a signal board in the case of failure.

Design Assumptions

Data collection is assumed to commence when the leading edge of the triggering output signal transitions from logic-low to logic-high. Likewise, the end of data collection is assumed to occur at the trailing edge of the output signal's transition back to logic low. A single pole, changeover (SPCO) switch allows the user to manually trigger the system. The closed switch connects the battery or power supply to the signal input. This signal, when conditioned properly, then serves as the input to various circuits designed to trigger instrumentation in a variety of methods as shown in Figure 3. A properly conditioned TTL trigger signal attains correct voltage levels corresponding to high and low logic levels and transitions quickly enough to eliminate uncertainty across a wide variety of instrumentation. The signal types addressed in this work include: simple TTL-compliant logic levels, RS-232 compliant logic levels, open/close for devices with their own switch circuitry, and trigger signals resulting from a combination of input signals.

In addition, it is assumed that the total current draw from the instrument receiving the triggering signals does not exceed 100mA for each output. With higher current draws, it is possible that the operational amplifiers driving the output can drop voltage levels with high current draws. Typical instrumentation triggering current draw rarely exceeds 1mA, so higher current draws may indicate a problem with the instrument.

Circuit Design

A diagram detailing the high-level layout of the triggering system is shown in Figure 3. An external switch produces a TTL-compliant switch signal corresponding to the switch state. Individual "signal boards" are supplied power, the switch signal, and the pulse signal described in the design objectives. Each signal board contains a complete set of circuits capable of triggering virtually any subsystem.

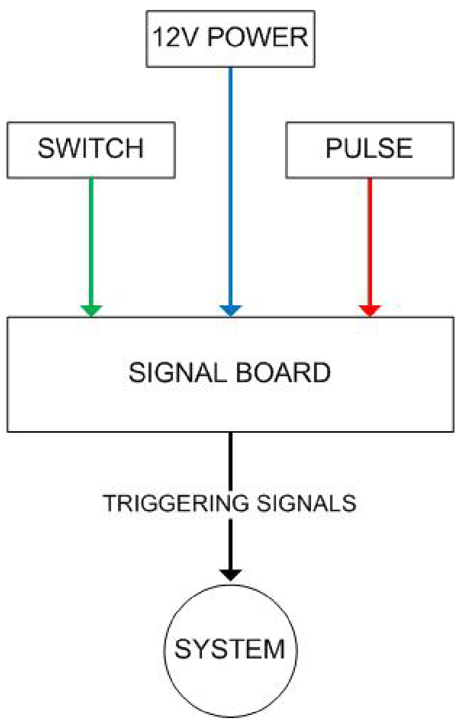

Figure 3. Triggering System Design

A successful triggering solution supplies the equivalent triggering signal to each instrument at the same point in time. One method to ensure the triggering solution is able to accommodate a wide variety of instruments is adopting standardized signals. For this implementation, the two standard signals considered are TTL and RS-232. These signals only differ in the voltage levels corresponding to logic levels. Instruments utilizing a built-in hardware switch are integrated with a switch circuit that replicates hardware switch behavior. Finally, a pulse signal is amplified and rebroadcast, allowing the complete system to allow any measurement subsystem to be both triggered and time-synchronized.

Devices using TTL Logic

In general, TTL voltage levels are considered to be at least 2 V for logic-high and 0 V to 0.4V for logic-low [10]. A packaged Schmitt trigger is chosen as it has been shown to reliably produce a signal with voltage levels coincident with TTL voltage level requirements. The voltage levels in this integrated circuit are determined primarily through the selection of supply voltage. In this case, the supply voltage is 5V. Therefore, the package will output either 0V or 5V, depending on state.

A/D devices

While many devices and standards set strict requirements for voltage corresponding to logic levels, signal level requirements are not as strict for generic analog to digital (A/D) converters. For simplicity, the same TTL-compliant trigger signal described previously is suitable for use by an A/D converter. Second, for input signals operating at higher frequencies, the sampling rate at which the trigger signal is recorded should be considered [11].

Serial/RS-232 Devices

In some instances, it is desirable to read a trigger signal directly into a PC for data logging. The RS-232 standard is one method among many that can be used to interface instrumentation with the PC. The minimum voltage for logic-high is +3V and the maximum voltage is -3V for logic-low, which is significantly different than TTL. For systems powered by a single supply having a common ground, no negative voltage sources exist onboard. To achieve these voltage levels, an RS-232 driver is often utilized. This circuit translates TTL-compliant logic levels to the equivalent RS-232 logic level.

Given the simple nature of this signal, it is not necessary to send the logic state as a packet as is commonly utilized in basic serial communication. Instead, the switch signal can be sent over one of the many status pins on a standard serial port. In this case, the PC receives the trigger signal and interpreted as 1 or 0. A PC data acquisition system, reading the serial port status alone, can then use this value to start or end data collection.

External Switch

Some individual instruments come delivered with a unique hardware switch for triggering. It is impossible for the operator to simultaneously trigger all systems by hand, so the hardware switch must be integrated into the triggering scheme. Since it is assumed the subsystem produces its own switching signal, a comprehensive triggering scheme need only emulate a hardware switch by opening or closing that circuit. In this configuration, logic-high is denoted as "closed" and logic-low as "open".

Devices triggered with a DMI

The triggering system interprets a continuous pulse train and re-broadcasts this to the instrumentation in two forms. The first form is an amplified pulse signal which is active regardless of switch state. The second form only allows the amplified pulse signal to be broadcast when the switch is high. This form is produced using a MOSFET as a switch to enable or disable re-broadcasting of the pulse signal.

Modeling and Simulation

Each circuit is modeled to analyze performance and functionality with two examples of interest shown. For the Schmitt trigger circuit, a simulated switch input voltage rises from ground to supply voltage level in 0.005s. This approximates the behavior of the switch shown in Figure 1. The simulated response of the op-amp circuit in Figure 4 shows that the output voltage increases significantly faster than the input voltage, on the order of 1 ms.

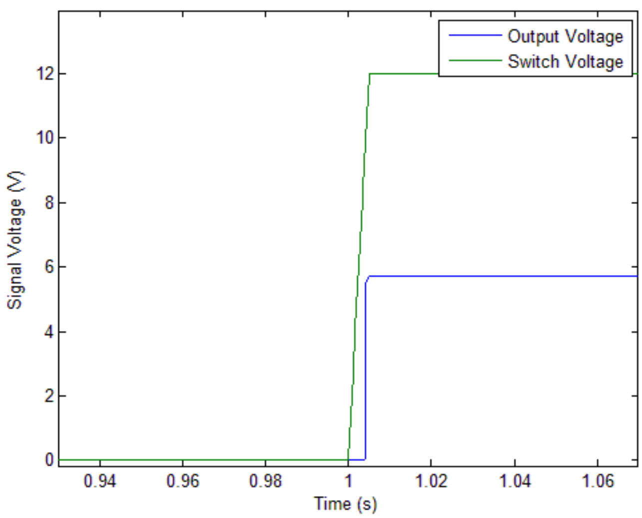

Figure 4. Simulated Schmitt trigger response to switch input

In Figure 4, the switching behavior of the trigger circuitry clearly shows a performance improvement in terms of switching speed. By limiting the output voltage of the switch circuit, the high and low levels maintain compliance with TTL logic levels. This signal is now useful for driving a variety of instrumentation. One example of this benefit is controlling the output of the pulse signal discussed previously. It may be desirable to trigger instrumentation with a pulse signal only when the data acquisition system is active. For this case, the triggered pulse amplifier shown in Figure 5 is modeled with the MOSFET switch, allowing the enabling and disabling of the pulse. When the switch is off, no rise in output voltage due to the pulse is expected. However, when the switch is on, the original low-voltage pulse signal is amplified to TTL levels and re-broadcast.

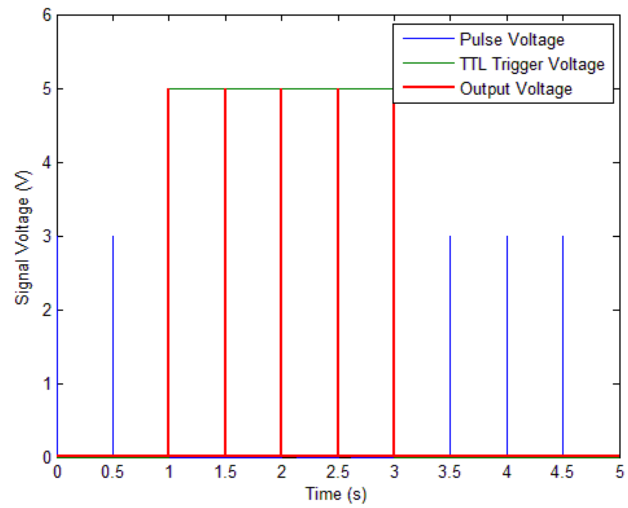

Figure 5. Pulse trigger simulated output

PROOF OF CONCEPT

The Multi-Scale Vehicle Terrain Measurement System (MS-VTMS), developed by the Vehicle Terrain Performance Laboratory is presented as a proof of concept. This system, shown in Figure 6, utilizes a variety of instruments to construct an accurate representation of the terrain surface: three individual scanning lasers, an inertial navigation system (INS), an accelerometer system with A/D converter, and a camera.

Figure 6. Multi-Scale Vehicle Terrain Measurement System

Each subsystem is connected to an individual signal board, reducing the likelihood that low impedance from one instrument would affect the triggering signal voltage sent to the remaining instruments. The configuration is pictured in Figure 7. The connectors at the bottom of the figure (front of the rack) are the three input signals referenced in Figure 3: switch, 12 Volt power, and pulse. Each of the eight boards within the rack generates all the required output signals. It is convenient, however, to provide different physical connectors as outputs, so the connectors at the top of the figure (back of the rack) are of different types, RS-232, LEMO, BNC, etc. If every instrument were to share a single triggering circuit, the varying impedances could influence the signal voltage levels. If the voltage levels were distorted enough, the system reliability and performance in terms of triggering and time synchronization could be compromised.

Figure 7. Triggering subsystem assembly

A diagram outlining the candidate design of the triggering system is shown in Figure 7. The Schmitt trigger dramatically improves the input switch signal, toggling the voltage level with switch debounce protection and minimal settling time. The TTL-compliant output signal then provides logic inputs for the switch circuit and RS-232 driver. The pulse signal is broadcast in two ways: one is simply amplified and passed while the other is only enabled when the TTL trigger signal registers a logic-high value. This design has been shown in testing to successfully trigger all instrumentation aboard the MS-VTMS.

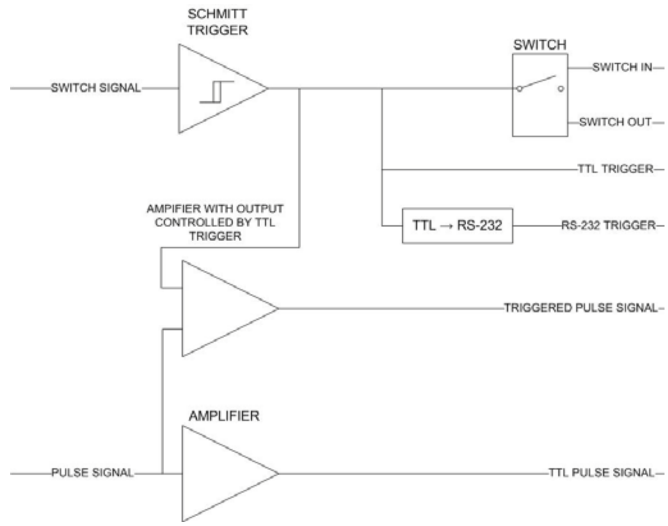

Figure 8. Functional diagram of triggering subsystem

A test was devised to verify the performance of the triggering system. For this test, the TTL trigger output signal was measured at 6kHz, coincident with the highest sample rate measured by any instrument onboard the MS-VTMS. A simple toggle switch provided either 0 or +12V input signal with equivalent characteristic to the signal shown in Figure 1. A successful triggering signal has minimal response time with output levels between 0 and +5V. The measured signal is shown in Figure 8.

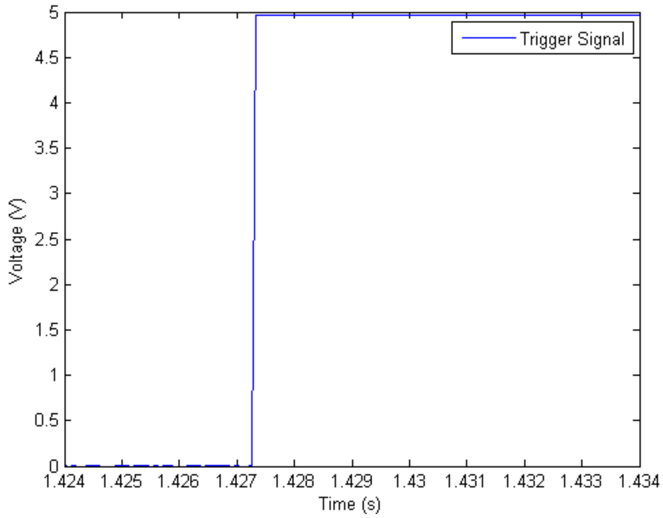

Figure 9. Triggering signal from triggering subsystem

DISCUSSION

The improved signal performance demonstrated in Figure 8 reduces uncertainty in determining the precise moment when data acquisition commenced and finished. This is important for synchronizing measurement instruments with fast sampling rates with other systems in post-processing. For example, individual measurements from a scanning laser could be erroneously rejected, producing a mismatch in the number of scans corresponding to the amount of time estimated during the individual data acquisition test.

Future developments to this system include the addition of logic and sensor circuitry for automatic triggering. This is especially useful when reflective markings on the terrain are used as references to start and end data acquisition. By using these markings, it is easier to control run-to-run variation in terrain measurements of the same section of terrain, which is critical for capturing and removing biases due to INS system drift [12].

CONCLUSION

The triggering scheme presented in this work improves the triggering signal behavior enables compatibility with a wide variety of measurement devices. This solution enables precise triggering and time-synchronization of scanning laser data with inertial data, thereby reducing uncertainty during post-processing. The solution was demonstrated to improve triggering performance both in simulation and in testing. By utilizing accepted standard signal types such as TTL and RS-232, the MS-VTMS can easily integrate new instrumentation to further improve study of the terrain.

REFERENCES

1. Wambold, J.C., et al., *State of the Art of Measurement and Analysis of Road Roughness*. 1981: United States. p. 9p.
2. Kern, J.V. and J.B. Ferris. *Development of a 3D Vehicle-Terrain Measurement System Part I: Equipment Setup*. in *Proceedings of the Joint North America, Asia-Pacific ISTVS Conference*. 2007. Fairbanks.
3. Wagner, S.M., et al. *Development of a 3D Vehicle-Terrain Measurement System Part II: Signal Processing and Validation*. 2007. Fairbanks, Alaska: Proceedings of the Joint North America, Asia-Pacific ISTVS Conference and Annual Meeting of the Japanese Society for Terramechanics.
4. Herr, W.J., *Highway Profile Measuring System*. 1996: United States of America.
5. Liu, F., et al. *A Kalman-filter based multi-sensor terrain profile measurement system: Principle, implementation and validation*. 2008. Bellingham WA, WA 98227-0010, United States: SPIE.
6. Kennedy, S., J. Hamilton, and H. Martell. *Architecture and system performance of SPAN-NovAtel's GPS/INS solution*. 2006. Piscataway, NJ 08855-1331, United States: Institute of Electrical and Electronics Engineers Inc.
7. Binns, R., Ferris, J.B. *Development of a Multi-Scale Terrain Measurement System*. in *ISTVS: International Society of Terrain-Vehicle Systems*. 2009. Bremen, GermanyProceedings of ISTVS.
8. Rizzoni, G., *Principles and Applications of Electrical Engineering*. Fourth ed. 2003, New York: McGraw Hill.
9. Barna, A., *Nanosecond Trigger Circuits.* IEEE Transactions on Nuclear Science, 1973. **NS-20**(Compendex): p. 17-21.
10. Incorporated, T.I., *The TTL Data Book*. Vol. 2. 1984, Dallas, TX: Texas Instruments.
11. Jerri, A.J., *Shannon Sampling Theorem - Its various extensions and applications: A tuorial review.* Proceedings of the IEEE, 1977. **65**(Compendex): p. 1565-1596.
12. Chemistruck, *Correcting INS Drift in Terrain Measurements.* Submitted to Journal of Dynamic Systems, Measurement, and Control, 2010