Low-Cost Precision Tracking of Vehicles using Optical Navigation Technology

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Abstract-The majority of vehicle tracking solutions are designed for general navigation, and as a result have low positional accuracy requirements. Projects requiring above average accuracy quickly run into high costs, while projects requiring sub-meter accuracy are limited by cost and availability. This paper presents a novel low-cost approach for using off-the-shelf components to provide relative-tracking precise to ±5 cm over a limited spatial domain.

Keywords—Tracking, navigation, GPS, positioning, optical navigation, correlation, java, wireless, dead-reckoning.

1 Introduction

WHILE several technologies are available for position tracking of vehicles, few solutions offer accuracy beyond better than standard GPS. Of those that do offer a higher level of accuracy, costs are prohibitive in most applications. In this paper, a discussion is provided of a novel method for tracking a moving truck to within 5 cm of positional accuracy within a spatially limited domain. The solution uses a novel concept consisting primarily of off-the-shelf components.

2 Background

Before discussing the latest results, it is important that some background and a few terms and limitations of the solution discussed in this paper be explicitly defined.

2.1 Research Problem

The Alabama Department of Transportation (ALDOT) performs bridge load testing to test the capacity of highway bridges to carry heavily loaded vehicles. The testing involves the use of carefully loaded test vehicles Fig. 1.

Fig. 1. Tri-axel test truck loaded with concrete filled weights.

The bridge is instrumented with strain gauges and vibration sensors which are monitored using a digital data acquisition system, Fig. 2. The test vehicles must be carefully driven along predetermined painted lines Fig. 3 in order to generate maximum strain responses in the bridge. Predetermining the location of the lines requires extensive planning and analysis using a finite element model of the bridge in question. Once the exact location of the truck is not known, these lines are used in an attempt to place the truck along a known track (position is approximated using an assumed constant velocity).

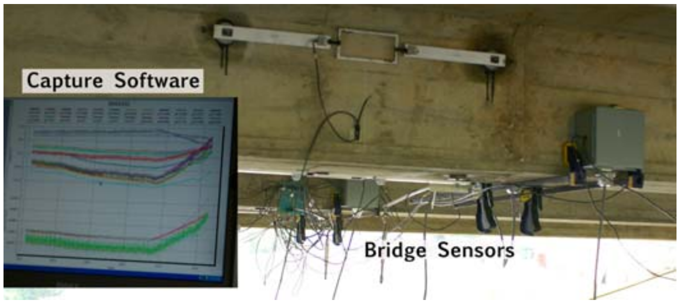


Fig. 2. Bridge sensors and data acquisition software.

Both static and a dynamic testing are performed. The static test is performed at very low speeds while the dynamic test is performed at 50mph (80.47 km/hr). While directing a slow moving truck is relatively low risk, there is no simple method to accurately direct a fast moving test vehicle at high speed.

Fig. 3. Driver's side, front tire following the desired longitudinal line.

In order to meet the needs of ALDOT the following goals related to position accuracy were set by the research team [1].

- Solution must operate at a maximum speed of 60mph (96.56 km/hr).
- Solution must provide better than 2 inches (10 cm) of accuracy for 1000 ft (330m). This requirement is the most intensive portion of the requirements since 2 inches represents a .02% error for a 1000 ft span.
- Modules must cost less than $1000. (Assuming a modular system.)

2.2 Key Terms

Relative position – The proposed solution provides relative position as opposed to absolute position [2] [3]. In this scenario, the tracking mechanism provides position information with respect to a reference point as opposed to tracking systems which provide global coordinates using longitude and latitude.

Limited domain – The proposed solution is not required to work over unbounded distances or geographical areas. Instead, the requirements for the research project specify a minimum 30.48 m (1000ft) of road on which the proposed solution must work. This decreases the physical requirements of any wireless links required, as well as the ability of the system to cope with extremely large distances (>1km).

Consumer off-the-shelf (COTS) – COTS is a methodology for component selection that requires that final products minimize the use of custom components [4]. COTS reduces production and design time, as well as total cost, by integrating existing components and minimizing the costly development and manufacture of custom electrical and mechanical components. Along with these “front end” savings, COTS also makes repairs and replacements simpler and cheaper.

2.3 Units of Measurement

The funding agency has specified all project requirements using English units as is standard for U.S. state agencies. As such the majority of the work has been done in English units rather than SI metric units. Where relevant, the metric equivalent will be displayed in parentheses, however many calculations will be provided in English units only.

2.4 Prior Research

Previously, [5] the authors have discussed the downfalls of using an accelerometer-based approach for the current project. The authors have also provided an analysis of available technologies and argued the appropriateness of using optical navigation technology [5].

In short, while other solutions exist that meet precision and velocity requirements, most were too costly. The optical navigation technology used in optical mice remained as the most promising solution.

3 Theory

This section will present an introduction to optical mouse operation followed by theoretical limitations for the suggested approach. A theoretical study and justification is made for the suggested approach in [5].

3.1 Optical Computer Mouse Operation

Optical computer mice operate by taking consecutive digital pictures and performing a two dimensional correlation. The optical sensors of interest are produced by Avago, formerly the semiconductor arm of Agilent. Avago is one of the largest producers of optical navigation sensors for use in computer mice.

An optical navigation chip, Fig. 4, combines the functionality of a digital camera, digital image processor, and microcontroller into a single package. The ADNS-3060 model optical navigation sensor includes a 30x30 pixel 8 bit grayscale camera [6]. The ADNS-3060’s camera is capable of ~6500 frames per second at 800 counts per inch [6]. The microcontroller provides a three wire serial peripheral interface (SPI) [6].

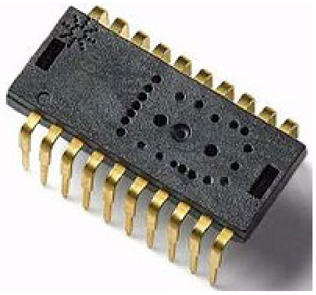


Fig. 4. An Avago ADNS-3060 optical navigation sensor.

The standard mechanical configuration, Fig. 5**,** accomplishes two important tasks. First, it sets a static height above the surface being tracked. The height must be known, as will be shown later, for precise conversion of perceived motion to actual motion. Second, the configuration supplies a specialized, dual purpose lens. The lens simultaneously focuses LED light onto the surface while focusing the illuminated image onto the ADNS-3060's camera. Any alternative uses of an optical navigation sensor must replace both functions: it must focus the correct image correctly, and supply sufficient light.

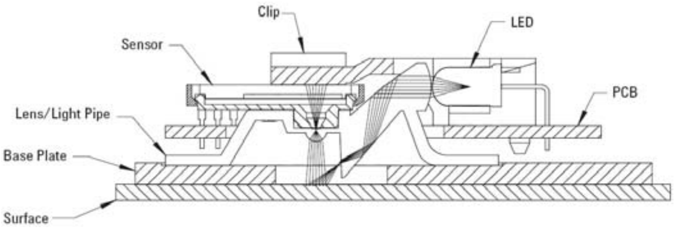


Fig. 5. The standard mechanical configuration of an ADNS-3060 in a computer mouse, cross-sectional view. (Copyright Avago technologies, used with permission).

3.2 Theoretical Limits

The theoretical justification in [5] assumed a static height of 22 inches. Unfortunately this is not realistic on a moving vehicle as the suspension system and road profile allow significant vertical travel. Therefore, it is necessary to continuously measure the sensor's height. This height measurement is accomplished through the use of an ultrasonic rangefinder and a microcontroller with a timer resolution of 8.68µsec. This section will present some theoretical limits for this system.

Ultrasonic rangefinders measure distance by detecting the echo of an ultrasonic pulse. Assuming a distance of 22 inches and the speed of sound to be 1100 ft/sec the round trip travel time can be determined as follows.

$$22*\frac{1ft}{12inches}*\frac{1\sec}{1100\,ft}*2=3.33ms \tag{9}$$

Given a resolution of 8.68µsec, this corresponds to:

$$\frac{3.3\overline{3}ms}{8.68\mu s}=384ticks \tag{10}$$

The resolution of the rangefinder in ticks/inch can be determined separately.

$$\frac{384ticks}{22inch}=17.5\frac{\text{ticks}}{\text{inch}} \tag{11}$$

Equation (12) illustrates the problem of quantization, or roundoff, error with the timer system. For a height of 22 inches, this results in an error of 3% (13).

$$22*17.5=385 \tag{12}$$

$$\frac{384}{385}=99.7\% \tag{13}$$

Assuming that the height measurement is the primary source of error, a maximum distance with 2 inch accuracy can be calculated.

$$\frac{100}{0.3}*2*\frac{1}{12}=55.6\,ft \tag{14}$$

According to these calculations, with the given timer resolution the maximum distance over which the desired accuracy can be maintained is 55.6 ft.

The maximum operating speed of the ADNS-3060 may be calculated as well. This calculation requires the use of RF, a relative factor determined by the focal length of the lens.

$$\frac{32000\,\text{counts}/\text{sec}}{\text{RF}*800\,\text{counts}/\text{inch}}=2235.2\frac{inches}{\text{sec}}=127mph \tag{15}$$

3.3 Results of Theoretical Analysis

While the ADNS-3060 is well within operating limits for the desired range, the accuracy of the system is limited by the height sensing mechanism. These results may be acceptable in practice, however, as many bridge test sections are typically less than 50 feet in length. Future improvements to the height sensing mechanism may further increase the horizontal accuracy of the system.

4 Current Work

Two prototypes have been built.

4.1 Prototype I

The first prototype, shown in Fig. 6, used the ADNS-3060 chip and included an adjustable magnetic mount for quick attachment to a test vehicle.

Fig. 6. Prototype I mounted magnetically to an ALDOT test vehicle.

The prototype did not provide any height sensing or integrated control functionality, but consisted of three major components: the ADNS-3060 with support circuitry (Fig. 7), a 10mm lens train, and a Visual Basic control program for PC interface and control (Fig. 8). PC interface was accomplished through a standard parallel or LPT printer port. In Prototype I, the PC interface allowed raw image capture for focusing and aiming. The prototype provided automatic conversion to real world units assuming a static height.

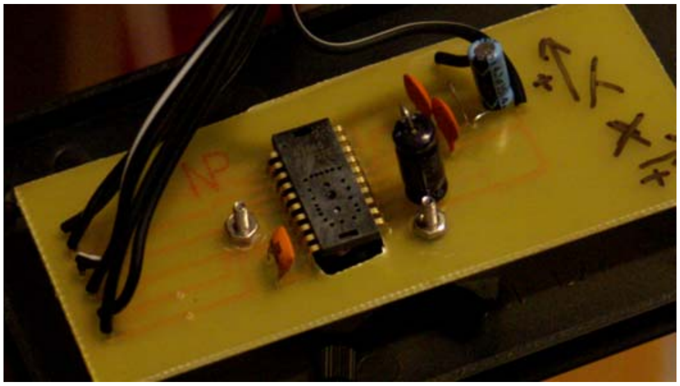
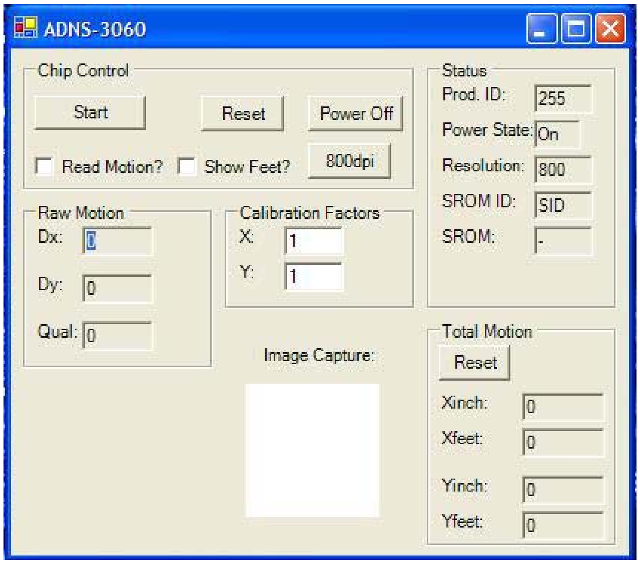


Fig. 7. Prototype I - ADNS-3060 with support circuitry.

Prototype I provided a base for quantization of required light levels, required surface detail, and required height stability and demonstrated correct feature recognition in the outdoor environment, performing correctly even in heavy cloud cover conditions. Prototype I also provided data to prove the need for a height sensing mechanism in future prototypes and products.



Prod. ID: 255
Power State: On
Resolution: 800
SROM ID: SID
SROM: -
Dx: 0
Dy: 0
Qual: 0
X: 1
Y: 1
Xinch: 0
Xfeet: 0
Yinch: 0
Yfeet: 0

Fig. 8. Visual Basic program for control and interface with Prototype I.

4.2 Prototype II

Prototype II represented the first fully integrated tracking solution. Prototype II used an ultrasonic rangefinder for continuous height measurement, Fig. 9.

Fig. 9. Ultrasonic rangefinder used in Prototype II for automatic height sensing.

User feedback is provided through an LCD, with a single pushbutton for input. An RF modem is also integrated for wireless transmission of measurements. All operation is automated through the use of a microcontroller. Prototype II also makes improvements over I in the way it mounts to the vehicle. Instead of a magnetic mount, like I, II uses a mounting rail with a quick release system, Fig. 10 and Fig. 11. This is a two part system. Spring loaded pins are permanently mounted to the vehicle followed by the removable rail.

The prototype has an articulated mount that slides on the rail, Fig. 12. This allows multiple devices to be quickly added or removed from the mounting system.

The microcontroller used in Prototype II is a Parallax Javelin, Fig. 13.

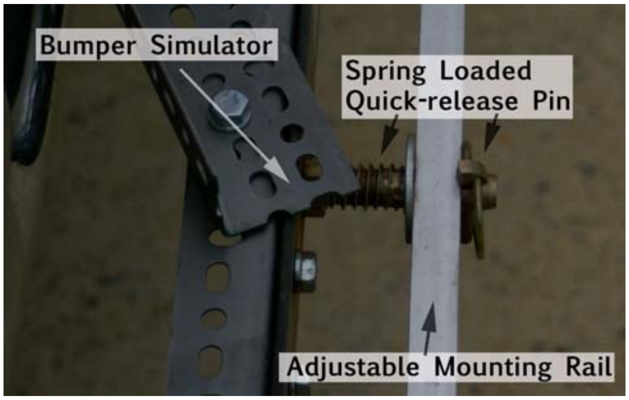


Fig. 10. Prototype II removable mounting system.

Fig. 11. Broader view of removable mounting system.

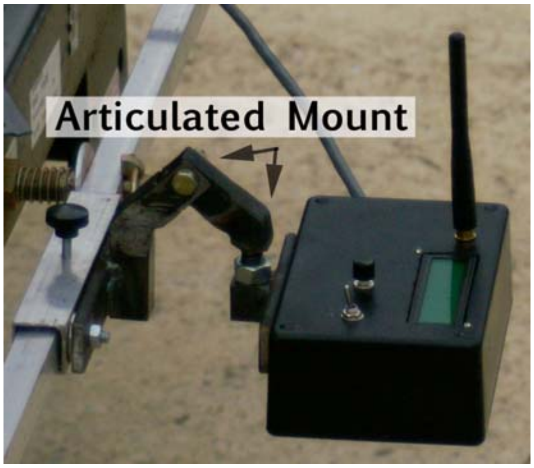


Fig. 12. Prototype II mounted to the removable rail using the articulated mount.

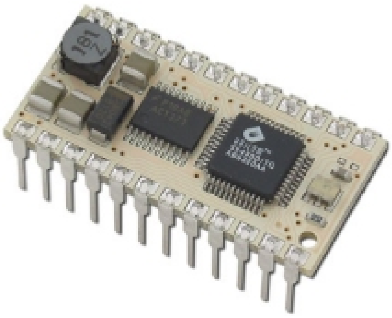


Fig. 13. Parallax Javelin Stamp Java microcontroller.

The Javelin was selected because it is programmed in the Java programming language, reducing overall complexity, and because it provides significant flexibility in the delegation and use of I/O pins. The Javelin does have two major shortcomings which were discovered to be issues in testing. First, the Javelin does not support floating point operations – all math operations and variables are integer only. The seriousness of this problem is further elevated by the fact that the Javelin is limited to 16bit, signed integers [7]. While there are algorithmic methods for storing and manipulating numbers with increased accuracy they add complexity and processing time. Instead, the research team augmented the Javelin with a floating point unit (FPU), Fig. 14, an auxiliary processor designed specifically to handle mathematical operations and storage of large numbers, specifically 32bit floating point and long integers. This additional FPU allows greater delegation of specific tasks within the prototype reducing overall microcontroller load and responsibility.

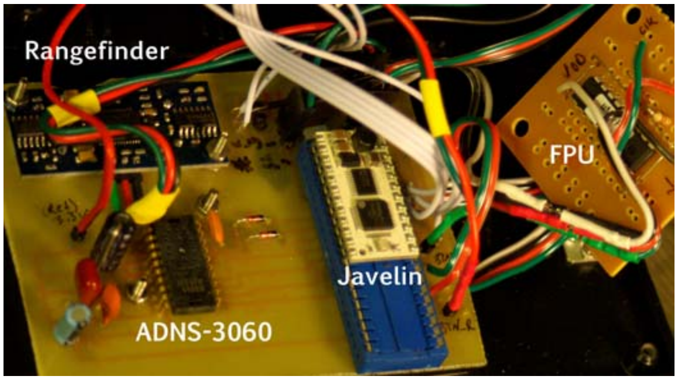


Fig. 14. Printed circuit board layout for Prototype II.

The second drawback of the Javelin was mentioned in the theoretical section. The timer of the Javelin provides a 8.68µsec resolution. This limits the accuracy of the height sensing mechanism, thereby contributing to the cumulative error. Future revisions may delegate height sensing to a dedicated microcontroller with more precise timing.

4.3 Calibrating the Position

Optical navigation systems provide a relative position, as defined previously. For some applications this may be suitable, but for many it is necessary to correlate the relative position to some absolute or arbitrary coordinate system. The following section proposes a method for calibrating position using the capabilities of the optical sensor already in use.

The proposed method involves a pattern placed in the path of travel. The position of the pattern is known to the user, and has a fixed position with respect to the reference point. An example of one possible pattern is shown below, in Fig. 15. The optical sensor in use provides access to the average grayscale value of the current image. This value allows for rudimentary detection of changes in color, as might occur when passing over the colored portions of the example pattern in Fig. 15.

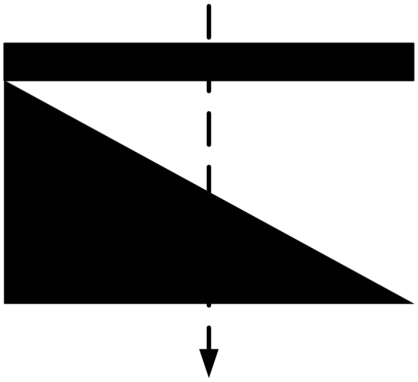


Fig. 15. An example pattern for position calibration, with direction of travel shown.

A candidate pattern must meet several criteria assuming the vehicle is passing overhead and storing the times at which each boundary is crossed:

- It must be possible to calculate the vehicle's speed from two of the stored times.
- It must be possible to calculate the vehicle's lateral position from two or more stored times.
- It must be possible to calculate the vehicle's longitudinal position from one or more stored times.

The example pattern in Fig. 15 meets these criteria in the following ways, assuming a direction of travel as shown:

- The first stripe's width is known. The width divided by the elapsed time while the vehicle is passing over the stripe gives the instantaneous speed.
- The time it takes to cross the white region between the stripe and the dark triangle along with the speed yield a trigonometric solution for the lateral position.
- At the instant the first stripe is crossed, the longitudinal position is known.

It is important to note that this system requires precise measure of time and will lose precision as the axis of travel is very close to either edge.

5 Results

Several performance tests have been performed on both prototypes. The immediate goal of this research is to achieve consistency and repeatability. One highly desired characteristic of data would be consistent proportionality between measured and actual distances.

5.1 Prototype I Results

In one outdoor vehicle mounted test the prototype was tested over a distance of 50ft. The measured distance was extremely inaccurate due to the height variations of the vehicle. Interestingly, when the vehicle returned to the start point following the same path in reverse, Prototype I registered the correct position within the rough precision of the measuring tape used. For an example of the impact of height variations, consider Table II. All measurements are in inches and error is the absolute difference between measured and actual distance.

TABLE I. IMPACT OF HEIGHT INACCURACIES ON ERROR SIZE.

Meas	Actual	Error	Height
12.97	12.6	0.37	19
10.73	10.5	0.23	
13.33	12.75	0.58	18.6
6.88	6.75	0.13	
49.47	47.5	1.97	
24.73	23.75	0.98	19
26.23	25.5	0.73	
31.18	29.5	1.68	

With height a major consideration, subsequent error testing of Prototype I was done on a test cart with fixed height (no suspension), Fig. 16.

Fig. 16. Test cart to provide static height.

In a fixed height test over 75 feet, measurements were taken every 12 inches. The graph in Fig. 17 shows the proportionality of actual distances vs. measured distances as percentages.

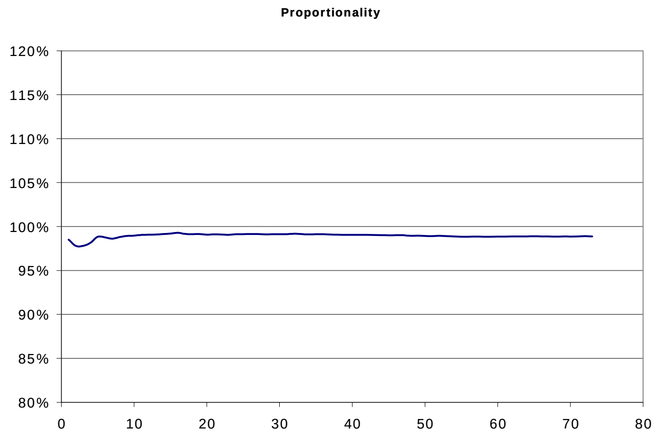


Fig. 17. Proportionality of actual distances vs. measured distances for static height test of Prototype I (y-axis runs from 80% to 120%).

The average deviation and standard deviation of the proportionality were 0.16% and 0.26% respectively. The mean proportionality was 98.4%

5.2 Prototype II Results

Prototype II testing was carried out on a moving vehicle. The test data displayed here was gathered using consecutive 100 foot tests where the actual and measured distances were recorded. Again the desired result is consistent proportionality. Fig. 18 shows the proportionality while Table III displays some of the statistical data about the results.

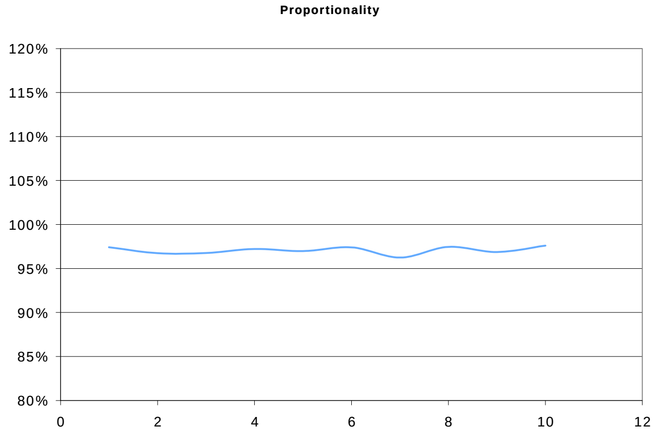


Fig. 18. Proportionality of actual distances vs. measured distances for a 100ft test of Prototype II (y-axis runs from 80% to 120%).

TABLE II. STATISTICS FOR PROTOTYPE II PROPORTIONALITY DATA.

Average Dev	0.351%
Std. Dev.	0.425%
Average	97.069%

This data matches the prediction of the theoretical section. Average deviation was 0.35%, very close to the predicted performance of the ultrasonic rangefinder. Similarly, the standard deviation is higher than desired, however this is explained by the fact that the fact that the test distance exceeded the max distance calculated to produce desired precision.

A subsequent test was performed over lengths of 40 ft. In this test the numbers were automatically scaled by the Javelin using scaling factors from previous tests. Because the proportionality graph is similar to those shown, it is not shown here. Table III shows the absolute error in inches for 10 ~40 ft tests as well as other result statistics. The absolute error in Table III is within 0.2% of the desired 2 in precision. Examining the absolute errors, Fig. 19, reveals that a group of data points were anomalous. These three data points are nearly double the value of any other point. While the cause of these anomalous points was unknown, the average absolute error with those data points excluded was 1.82 in. While this is within the desired precision, success cannot be declare until further testing shows consistent performance within the desired precision constraints.

TABLE III. AVERAGE ABSOLUTE ERROR IN INCHES AS WELL AS ERROR PERCENTAGE STATISTICS FOR 40 FT TESTS OF PROTOTYPE II.

Average Error:	3.0035
Average Dev	0.366%
Std. Dev.	0.464%
Average	100.606%

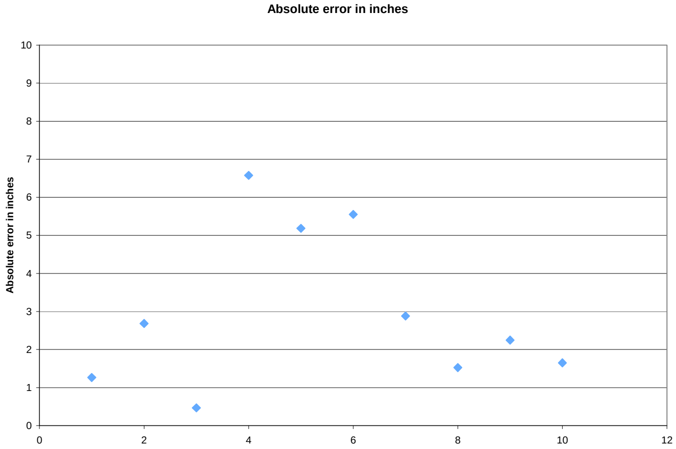


Fig. 19. Absolute error in inches for the 40 ft test showing anomalous data points.

5.3 Position Calibration

Initial research in this area attempted to use a white pattern on a moveable, dark mat. Tests were also conducted with white and black paint on standard, black asphalt pavement (Fig. 20).

Fig. 20. Test pattern of black and white paint on asphalt.

The initial testing found a problem with using an extreme dark-to-light transition for calibration. The problem was caused by the sensitivity of the optical sensor to infrared radiation (IR). IR radiation occurs with wavelengths in the 750 nm to 1 mm range. As shown in Fig. 21, the ADNS-3060 responds to this wavelength. This response to IR is problematic because on hot, sunny days the IR reflection of the dark surfaces appear "brighter" to the sensor than the light surfaces. On cooler days the opposite will be true, the dark surfaces will not radiate infrared "brighter" than the reflection off the light surfaces. This problem represents inconsistent behavior that is difficult to reliably detect. Future work will investigate surfaces that are consistently distinguishable regardless of environmental conditions.

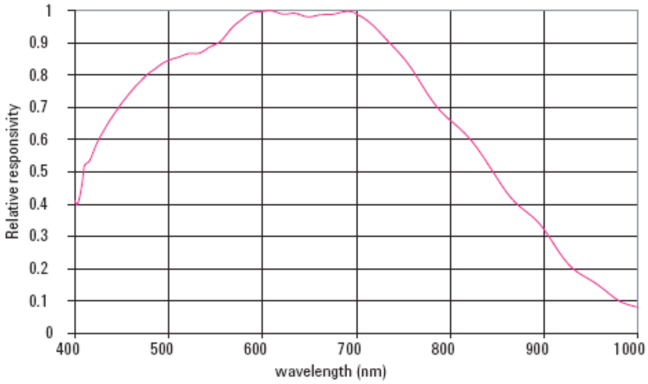


Fig. 21. Responsitivity of the ADNS-3060 (Courtesy of Avago, used with permission).

6 Conclusion

Two working prototypes have been constructed and functioned correctly. They have demonstrated that the concepts are sound, and they have behaved as predicted by the theoretical work. Initial results from both prototypes suggest that the desired accuracy is attainable, but requires significant accuracy in all associated systems.

The research team believes this work can have broad applications for navigation systems where accuracy is a requirement and other factors may limit the use of alternate technologies.

Future work on this project will concentrate on two areas: fine tuning to achieve the highest accuracy; and trials of a complete, modular system with multiple tracking modules as well as GPS for time and heading information.

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