MICHIGAN DEPARTMENT OF TRANSPORTATION
M•DOT

DEVELOPMENT OF AN INSTRUMENTED VEHICLE TO MEASURE ROADWAY CURVE AND GRADE

MATERIALS and TECHNOLOGY DIVISION

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Leo E. DeFrain
Robert D. Miller
John R. Darlington

Research and Technology Section
Materials and Technology Division
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This report, authorized by the transportation director, has been prepared to provide technical information and guidance for personnel in the Michigan Department of Transportation, the FHWA, and other reciprocating agencies. The cost of publishing 125 copies of this report at $.56 per copy is $70.05 and it is printed in accordance with Executive Directive 1991-6.

ACTION PLAN

1. R. A. Welke, Deputy Director, Bureau of Highways

   A. Transmit report to the FHWA.

2. Materials and Technology Division

   A. Project completed, no further action necessary.

3. Engineering Operations Committee

   A. No action necessary upon approval of this report.

EXECUTIVE SUMMARY

A vehicle has been instrumented to accurately measure roadway curves and grades while traveling at highway speeds. The instrument produces a measure of the vehicle's position and orientation every four feet of travel. The data collected includes heading and relative latitude, longitude and elevation from the beginning reference point. Vehicle roll, pitch, and yaw are also available for other applications. The system is capable of plotting a map of the traveled path. Data are collected using a PC (with a 386 microprocessor) and stored on a floppy disk for post-processing. The software is menu operated and provides an easy way to display and edit the data, compute the vertical grade and horizontal degree of curvature, and graph the roadway data on the screen. This report also suggests other transportation related uses for the instrument.

INTRODUCTION

In 1989, the Federal Highway Administration (FHWA) requested that state departments of transportation provide roadway data as part of the Highway Performance Monitoring System (HPMS). In addition to roadway capacity and serviceability data, the FHWA wanted to know the percent grade and radius of curvature for each of the 960 HPMS roadway sections located in Michigan. The curve and grade data for each test section were to be classified into as many as 13 different groups. Each group classified curves by degree of curvature and grades by degree of slope. The test sections varied in length from several hundred feet to over 20 miles. The nearly 4,000 miles of roadway sites to be evaluated were scattered throughout the 12,000 miles of state trunkline.

Upon receiving this request from the FHWA, the department began the process of collecting the required data with the exception of curve and grade information. Several people were assigned the task of retrieving as-built plans for the roadway sections and extracting the required information. The process was slow, it did not have a high priority for completion and considerable difficulty was incurred in finding out what pavement section had been updated and which set of drawings were applicable. After several attempts to extract the required curve and grade data, the department contacted other states to learn how they were complying with the FHWA request.

It was learned that the Oklahoma Department of Transportation had made an inquiry of all 50 states concerning the HPMS data collection and that 23 states had responded. The survey indicated that approximately ten different methods were being used to collect the data. Most departments used construction plans, others used topographic maps, global positioning satellite systems (GPS), special crews, contractual forces and some, like Michigan, were not reporting these two items.

In December of 1990, the FHWA wrote a letter to the department indicating that the required data must be submitted, and indicated that lack of response might jeopardize federal funding of the department's $7.1 million dollar State Planning and Research (SPR) program. In response to the letter, the department indicated that it would explore the use of other methods to collect the required data.

In January 1991, the Bureau of Planning requested that the Bureau of Highways explore collecting curve and grade data using electronic methods.

In June 1991, the department submitted an estimate of cost to the FHWA for development of a vehicle by the Research Laboratory to collect the required data. The $101,000 estimate included the cost to purchase necessary equipment and labor to build the instrument and collect data. In September 1991, the FHWA approval was received.

In May 1992, the vehicle was completed by the department's Research Laboratory personnel and preliminary testing and calibration were begun. Upon completion of this work in July 1992, the data collection phase of the project began. Four months later, in October, all of the data were collected and processed according to the FHWA requirements. The cost of completing the work was within budget. Following is a report on development of the curve and grade instrument.

BACKGROUND

A vehicle capable of accurately measuring roadway curve and grade must be instrumented from its initial position at the start of a roadway test section to measure and record all changes in vehicle position while the vehicle travels along the roadway. Accuracy was deemed sufficient if the instrumentation was capable of closing the loop. This required that beginning and ending heading, latitude and longitude be essentially the same after traversing a closed test loop. The longer the test distance and the more complex the route, the more precise the instrumentation must be to accurately record the route. In order to meet accuracy requirements of the FHWA curve and grade classification data, the system had to meet the following specifications.

The system must be able to detect a change in heading of 0.10 degree and a change in pitch of less than 0.01 degree. The instrument must be stable with respect to its position and orientation long enough to run a complete test section and to provide repeatable measurements. Accuracy of the system must be independent of the vehicle's speed because some of the data is collected while driving at normal highway speeds, while other data could only be collected in urban areas with slower traffic. The data sampling rate should be based upon equal spatial distances and not on equal time intervals. The sampling distance is a requirement of the mathematical procedures in the post-processing phase.

In order to comply with FHWA reporting requirements, the data collected must either include latitude and longitude, pitch, heading and distance travelled of the instrument or it must return enough information so the required items can be calculated. The next section will discuss this data collection, filtering and roadway feature extraction in more detail.

In 1973, the department contracted with a Canadian firm to develop a vehicle which could measure the *x*, *y*, *z*-coordinates of points along a roadway. They used instrumentation designed for use in aircraft. After many attempts to resolve hardware, software and theoretical problems, it was determined that aircraft-type sensors could not produce the required accuracy.

A recent search of companies producing such equipment indicated that most gyro-accelerometer based navigation equipment was not suitable for this application. Most equipment was designed for aircraft where travel speeds are high and the change in vertical and longitudinal position is large.

After reviewing specifications from twelve manufacturers of navigational equipment, it was determined that only one manufacturer produced a sensor capable of meeting the requirements for the curve and grade project. Smiths Industries of Grand Rapids, Michigan produced a navigation system for the Abrams M1A2 tank which could be modified for this roadway application. This inertial system is commonly referred to as a PosNav unit.

After purchasing the sensor and modifying its design for the roadway application, the following parameters were measured.

Compensated heading error is less than 1.0 degree/hour. The sensor provides corrected output data in the form of vehicle roll, pitch, and yaw. The minimum instrument resolution is 0.1 degree of heading. The self-contained unit has dimensions of 10 by 12 by 6 in. and operates at 28 volts (DC). Commands are sent and data are retrieved from the unit via a serial communication line. After establishing latitude, longitude and heading of the vehicle and traversing a 200 mile long circular route, the ending latitude, longitude and heading were almost identical to the starting values. The cost of the instrument was $69,000.

VEHICLE INSTRUMENTATION

The inertial navigation system is mounted in an existing Department-owned half-ton van equipped with a gasoline powered 110 volt generator. The vehicle has an optical distance sensor mounted on the left front wheel spindle of the vehicle. The encoder produces a pulse approximately every 0.5-in. of vehicle travel. The navigational sensor is mounted on the floor of the vehicle near the left center in line with the left wheel track of the vehicle. The system is mounted on an adjustable aluminum plate to facilitate alignment with the vehicle's line of travel. This plate permits removal and quick re-installation of the sensor. A DC power supply was installed to provide the required voltage to the sensor. A standard 386-microprocessor based computer with a small 9-in. monochrome screen and keyboard is mounted in the vehicle for data acquisition and processing. The computer equipment is shock-mounted to isolate it from vehicle vibrations.

The navigation sensor was accurately positioned after a series of calibration runs and rigidly bolted to the mounting plate on the vehicle floor. An electronic compass was purchased to accurately determine vehicle heading at the start of each pavement test section. The PosNav unit also has the ability to gyrocompass (i.e., compute its own heading relative to true north). Starting positions of test sections were determined from topographic maps.

A computer program was written by personnel from the department's Engineering and Scientific Data Center to communicate with the navigation sensor through RS 422 serial interface at 9600 baud. The software is capable of transferring sensor data at 20 samples per second and linearly interpolates the data to record 4-ft spatial samples, independent of vehicle speed. Details of other software features are given later in this report. Post processing of the vehicle data with a separate data reduction program produced a file with the required curve and grade information in a form required for submittal to the FHWA.

The collection of data required two technicians. The driver and operator worked together to identify measurement sites. Once the ends of the test section were identified, the route was traversed and the data were recorded.

In practice, one technician would operate the computer and the other would drive the vehicle. They began a day's run with a printed listing of the route by test section identification numbers. The list contained a description of the beginning of a section relative to some visible feature such as a county line, roadway feature, or mile marker. This list was prepared in advance from a database resident on the department's mainframe computer. As each test section was encountered along the route, the computer operator pressed a function key which caused the computer to place a marker record in the data file. The driver would also watch an independent electronic odometer, warning in advance of the end of a test section. This scheme worked very efficiently with few errors. The operators' experience with real-world data collecting and possible problems which needed to be solved on the spot was valuable. Some 960 sites were measured and the data processed in approximately four months.

At the end of each day's data collection, files would be archived and copied to floppy disks. At the end of the week, they were returned to the office for cataloging, archival storage and subsequent processing. Throughout the first part of the project, an effort was made to process the data as quickly as possible in order to identify any potential problems.

SOFTWARE OVERVIEW

A total of three programs were written to support data collection and reduction for the curve and grade project. The first program completed was a menu-driven data collection program, which is very simple to use. This program provides the vehicle operator some information about the status of the data collection process, so the operator can monitor the system for possible problems. The program consists of hardware interrupt-driven data communications routines and algorithms needed to reconstruct the system's status from data packets which were received from the PosNav unit.

A program was developed which provides extended commands to the PosNav for calibration and testing. This program had special privileges in terms of functions requested of the navigation unit. When calibration was completed, this program was removed from the vehicle's computer to safeguard the system.

While the vehicle was being used for data collection in the summer and early fall of 1992, the data reduction program was written. This program

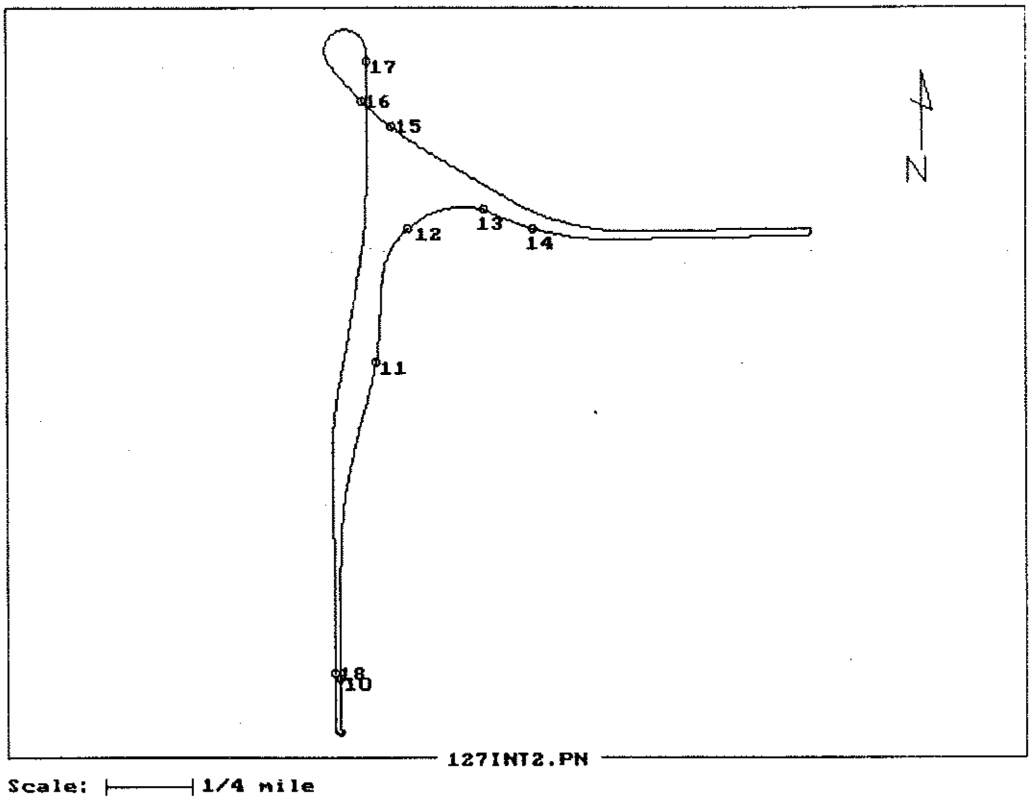

Figure 1. Roadway map generated by post processing software.

reads the raw data files, identifies appropriate sections of the route and applies appropriate mathematical filtering and reduction procedures. The resulting files were in a tape format as required by the FHWA. Details of this process will be described later in this section. Figure 1 shows an example of a roadway section obtained using the complete system.

The data collection program primarily handles communication with the PosNav unit and reconstructs positional information from the data received. The program also monitors the keyboard accepting operator commands to control data collection and recording. Buffered data are written to the computer's hard disk. Because of the relatively harsh environment for the computer operating in the van, the program was written to store data to a large memory buffer or floppy disk in case the hard disk failed on the road. A floppy disk backup of the entire system was prepared to assist in any on-the-road emergency. Fortunately, these options were not needed.

When data collection begins, the computer operator is prompted for the beginning longitude and latitude of the vehicle and the compass heading. These data are sent via the serial communications to the PosNav unit along with the necessary commands to initialize and control the unit. The route name and any identifying characteristics and comments are entered and stored in a comment record file. As a new test section is begun, the operator merely presses a function key which places a marker in the data file. These marker records correspond to sections listed on the computer printout, which was prepared earlier. Other function keys suspend and resume data recording while the vehicle is being driven a short distance to a new test section. This avoids re-initializing the system. Typically, about a dozen test sections are recorded in a single file. The operators were careful to keep file sizes manageable and safeguard against data loss.

All commands sent to the PosNav unit and all data received from it occur in eight word (16-bits per word) packets. For the mathematical filtering routines to work, this application needed data sampled at equal spatial intervals, close to four feet. At 60 MPH (88 ft/sec), this required retrieving data from the unit at its maximum rate of 20 eight-word packets per second. An interpolation procedure converts the sampled data to 4-ft intervals.

When operating, the PosNav is busy with its internal computations, continually updating its state. Even though the unit returns data packets 20 times per second, the position reported in a given packet may reflect the vehicles position a quarter or half second earlier. The packets are spatially and temporarily asynchronous. Therefore, each packet needs to be spatially stamped.

The remedy was simple. The unit has a provision for accepting an external odometer pulse, and the van already had been equipped with such an odometer. Even though processing in the PosNav unit may be running behind the vehicle's actual position, the unit samples all its sensors, including the odometer, instantaneously. The low order word of the odometer reading is included in the data packet. It doesn't matter when a particular data packet arrives at the computer, since the data packet contains information sampled effectively at one instant.

Due to the need for data packets twenty times per second and since the PosNav unit could only return eight 16-bit words, the unit was programmed to send six words of partial information. The full data items were reconstructed from these low order words. Two words of each packet are dedicated to the communication: the first word identifies the packet type and the last word is a checksum which helps guarantee the integrity of the data transmission.

For this project, the PosNav unit was re-programmed to return the following six 16-bit data words:

1. Latitude (low order 16 of 32 bits)
2. Longitude (low order 16 bits)
3. Heading (as an integer in tenths of a degree)
4. Odometer (signed integer, modulo 10,000)
5. Sine pitch angle (scaled integer)
6. Sine roll angle (scaled integer)

Throughout the data collection process, the entire system worked well and reliably. Of the 960 sites surveyed, fewer than twenty sections needed to be surveyed a second time due either to highway construction, or small errors in identifying the precise location of the beginning of a test section. Figure 2 is an example of a data report generated to examine system performance. Figure 3 shows the curve and grade processing log for three HPMS sections.

SIGNAL PROCESSING CONSIDERATIONS

For the remainder of this report, extensive use is made of a viewpoint adopted in sciences dealing with fluctuating signals. Whether the data are stock market trends or random radio noise from space, they can be treated in what is called the frequency domain. This is a viewpoint from which moving profilometers and vehicles are described by their response to frequencies induced by road profile. Descriptive units would be in cycles or radians per second. Profiles in this domain are seen as random signals with specific statistical properties. Units would be in cycles or radians per foot. Profiles

FILE: 127INT1.PN June 25, 1992
DATA: Interpolated raw data file.
Del Hdg* is the filtered change in heading
Pitch* is the filtered pitch

X-ft	Heading	Del Hdg	Pitch	Del Hdg*	Pitch*
0.00	0.0000	0.0000	-0.4125	0.0000	-0.0006
4.00	0.2250	0.2250	0.2936	0.0004	-0.0031
8.00	0.3517	0.1267	0.3335	0.0021	-0.0064
12.00	0.3332	-0.0185	0.3935	0.0062	-0.0069
16.00	0.3822	0.0490	0.3880	0.0122	-0.0011
20.00	0.3092	-0.0731	0.5348	0.0188	0.0130
24.00	0.1795	-0.1297	0.5182	0.0246	0.0364
28.00	0.0558	-0.1237	0.5019	0.0280	0.0692
32.00	359.9383	-0.1175	0.3563	0.0278	0.1098
36.00	359.8281	-0.1102	0.1389	0.0235	0.1552
40.00	359.6441	-0.1840	0.0164	0.0154	0.2004
44.00	359.2797	-0.3644	0.1973	0.0034	0.2404
48.00	359.0451	-0.2346	0.5260	-0.0130	0.2725
52.00	358.9279	-0.1172	0.6652	-0.0338	0.2979
56.00	358.7720	-0.1559	0.5812	-0.0572	0.3200
60.00	358.6207	-0.1512	0.4351	-0.0812	0.3415
64.00	358.3797	-0.2410	0.3977	-0.1043	0.3627
68.00	358.1640	-0.2157	0.4946	-0.1259	0.3828
72.00	357.9817	-0.1822	0.5420	-0.1457	0.4013
76.00	357.9000	-0.0817	0.4620	-0.1630	0.4183
80.00	357.8022	-0.0978	0.4188	-0.1770	0.4338
84.00	357.7760	-0.0262	0.5475	-0.1865	0.4472
88.00	357.6000	-0.1760	0.5810	-0.1912	0.4588
92.00	357.5650	-0.0350	0.4372	-0.1913	0.4691
96.00	357.4131	-0.1519	0.3503	-0.1874	0.4780
100.00	357.2505	-0.1626	0.3806	-0.1806	0.4843
104.00	357.1459	-0.1046	0.4121	-0.1720	0.4873
108.00	357.1000	-0.0459	0.3064	-0.1626	0.4866
112.00	357.1000	0.0000	0.1997	-0.1526	0.4819
116.00	357.0443	-0.0557	0.2734	-0.1415	0.4727
120.00	357.0533	0.0090	0.5023	-0.1295	0.4591
124.00	357.0503	-0.0030	0.6502	-0.1166	0.4435
128.00	356.9111	-0.1392	0.5832	-0.1032	0.4291
132.00	356.7614	-0.1497	0.4304	-0.0903	0.4189
136.00	356.6684	-0.0930	0.3423	-0.0793	0.4131
140.00	356.6223	-0.0461	0.3406	-0.0709	0.4104
144.00	356.7121	0.0898	0.3931	-0.0648	0.4092
148.00	356.8020	0.0899	0.4183	-0.0595	0.4086
152.00	357.0000	0.1980	0.4240	-0.0534	0.4082
156.00	357.0760	0.0760	0.3848	-0.0451	0.4081
160.00	357.1617	0.0856	0.3194	-0.0342	0.4080
164.00	357.2000	0.0383	0.2653	-0.0210	0.4072
168.00	357.2305	0.0305	0.2441	-0.0068	0.4046
172.00	357.3145	0.0839	0.2496	0.0074	0.3995
176.00	357.4000	0.0855	0.2349	0.0210	0.3914
180.00	357.4787	0.0787	0.3205	0.0336	0.3805
184.00	357.6182	0.1396	0.3844	0.0452	0.3677
188.00	357.7387	0.1205	0.4192	0.0558	0.3548
192.00	357.8178	0.0791	0.4154	0.0656	0.3434
196.00	357.9000	0.0822	0.3495	0.0745	0.3348
200.00	357.9000	0.0000	0.2902	0.0821	0.3292
204.00	357.9512	0.0512	0.2253	0.0877	0.3257
208.00	358.0279	0.0767	0.1738	0.0909	0.3232

Figure 2. Example of one raw data interpolation report.

```
                    HPMS Curve and Grade Processing Log

File:     D6629A.PN
HPMS Id: 1760230395110
6900 records processed.

     Curves by Degree of Curvature        Grades by Percent Grade
     _____________________________        _________________________
     Class        Number      Miles       Class      Number     Miles
     0.0 to  0.4    34        4.905       0.0 to  0.4    6      4.943
     0.5 to  1.4    33        1.307       0.5 to  2.4    6      1.269
     1.5 to  2.4     0        0.000       1.5 to  4.4    0      0.000
     2.5 to  3.4     0        0.000       2.5 to  6.4    0      0.000
     3.5 to  4.4     0        0.000       3.5 to  8.4    0      0.000
     4.5 to  5.4     0        0.000       8.5 greater    0      0.000
     5.5 to  6.9     0        0.000       _________________________
     7.0 to  8.4     0        0.000
     8.5 to 10.9     0        0.000
    11.0 to 13.9     0        0.000
    14.0 to 19.4     0        0.000
    19.5 to 27.9     0        0.000
    28.0 greater     0        0.000
    Total length              6.212
    ______________________________
File:     D6629A.PN
HPMS Id: 1760230400110
13469 records processed.

     Curves by Degree of Curvature        Grades by Percent Grade
     _____________________________        _________________________
     Class        Number      Miles       Class      Number     Miles
     0.0 to  0.4    16        4.602       0.0 to  0.4   18      1.610
     0.5 to  1.4    14        0.341       0.5 to  2.4   16      2.727
     1.5 to  2.4     1        0.246       1.5 to  4.4    2      0.852
     2.5 to  3.4     0        0.000       2.5 to  6.4    0      0.000
     3.5 to  4.4     0        0.000       3.5 to  8.4    0      0.000
     4.5 to  5.4     0        0.000       8.5 greater    0      0.000
     5.5 to  6.9     0        0.000       _________________________
     7.0 to  8.4     0        0.000
     8.5 to 10.9     0        0.000
    11.0 to 13.9     0        0.000
    14.0 to 19.4     0        0.000
    19.5 to 27.9     0        0.000
    28.0 greater     0        0.000
    Total length              5.189
    ______________________________
File:     D6629A.PN
HPMS Id: 1760230410110
20043 records processed.

     Curves by Degree of Curvature        Grades by Percent Grade
     _____________________________        _________________________
     Class        Number      Miles       Class      Number     Miles
     0.0 to  0.4    22        2.803       0.0 to  0.4    8      3.068
     0.5 to  1.4    19        0.511       0.5 to  2.4    6      1.383
     1.5 to  2.4     2        1.439       1.5 to  4.4    1      0.303
     2.5 to  3.4     0        0.000       2.5 to  6.4    0      0.000
     3.5 to  4.4     0        0.000       3.5 to  8.4    0      0.000
     4.5 to  5.4     0        0.000       8.5 greater    0      0.000
     5.5 to  6.9     0        0.000       _________________________
     7.0 to  8.4     0        0.000
     8.5 to 10.9     0        0.000
    11.0 to 13.9     0        0.000
    14.0 to 19.4     0        0.000
    19.5 to 27.9     0        0.000
    ______________________________
```

Figure 3.

can be analyzed in the frequency domain as explained in many texts on the subject. It will aid the reader to bear in mind the relationship between profile wavelength, vehicle speed and induced frequencies. For example, a 20-foot wave traversed at 60 mph (88 feet per second) will produce a 4.4 Hz signal while the same wave traversed at 30 mph induces a 2.2 Hz signal. Note that frequencies may be temporal (time based) or spatial (distance based). Bandwidth in the profile sense refers to the spatial bandwidth. That is, the range of spatial frequencies of interest.

Roadway Path

Some explanation of the PosNav unit's internal instrumentation is necessary to illuminate the following discussion. The unit contains two gyroscopes. One gyro is a dynamically tuned gyro (DTG) which is a two-axis rate sensor. The other gyro is a single axis rate detector. These are used to measure pitch, roll and yaw. In this discussion, the *x*-axis is fore and aft of the vehicle's travel and the *y*-axis is left and right. The DTG senses pitch and yaw and the less sophisticated single axis gyro measures roll rate. Two high quality accelerometers measure acceleration along the *x* and *y* axis. These provide correction for the gyros when axial or centripetal accelerations might otherwise be mistaken for pitch and yaw. The accelerometers also help determine motion along the *x* and *y* axis when used with an odometer signal that must be supplied from an external source.

While the *x* and *y* axis relate to the body of the vehicle (or PosNav unit), the unit does not directly provide *z*-axis or vertical information. A complete inertial system can provide accurate positions in all three axis, however, such a system is beyond the scope and requirements of this project. Possibly, vertical position may be determined from the sine of pitch attitude multiplied by distance traveled.

Roadway Elevation

To determine *z*-axis positions, certain constraints are inevitable. It is not possible to integrate small changes in elevation over arbitrarily long distances. Such a process, known as open loop integration, always leads to a positive or negative vertical runaway. This is true for even the most sophisticated inertial guidance systems. In practice, such integration is coupled with high pass filtration to limit the longest wave integrated. This process is called pseudo-integration and the result is given by the expression:

$$s = \frac{1}{p}\left[\frac{p^2}{p^2 + wp\sqrt{2} + w^2}\right]$$

where p is the differentiation operator (making $\frac{1}{p}$ an integration) and s is the signal output to input ratio. The filter breakpoint expressed in cycles per foot for road profile work is w. The expression describes a transfer function for integration combined with a second order, high pass Butterworth filter. The filter prevents integration of low frequency components below the breakpoint, w. Note that the filter order must be one higher than the number of integrations. The PosNav unit may permit w values out to many thousands of feet. That is, elevation changes corresponding to the lay-of-the-land may be retrievable. There are other ways to periodically correct the elevation measure using GPS or possibly a new class of ultra-precise barometric altimeters. This type of correction would be necessary only if extremely long waves were measured.

To further describe this expression, note that the left side of the equation is a ratio of output over input. A trivial system such as a piece of wire would provide a ratio of one, no matter what the input. Useful systems can be described by plotting the ratio over a large range of input frequencies. Such a graph is known as a Bode plot and it may be familiar to users of high fidelity audio equipment. (In that case a ratio of 1 is preferred.)

The first factor, $\frac{1}{p}$, describes the process of integration, which amplifies low frequencies. Since long term signal offsets are unavoidable in electronic equipment, they may be filtered out. Because the integration process provides one order of low frequency gain, it is necessary that the filter have two orders of attenuation. If the filter had only one order of attenuation, the gain of the integration would balance out to a constant or DC level in output. The extra order of attenuation removes this potential DC constant. Factor two on the right describes an appropriate filter.

The operator, p, known as the Heaviside operator is just a shorthand way of writing the process of differentiation. By convention, $1/p$, is the process in integration. The symbol, w is often used to express frequency in radians per second. For roadway profile analysis, this is often thought of as cycles or radians per foot.

If vertical displacement can be measured, a host of additional applications are possible. The most important of these is extending the measuring capacity of profile measuring devices based on the General Motors Rapid Travel Profilometer (RTP) concept. Profiles based upon the GM concept compute vertical displacement; but, only over a limited spatial bandwidth extending from a few inches to several hundred feet. Long wave, lay-of-the-land features cannot be measured.

In the GM concept, short wave features are measured by a vertical displacement sensor reading distance from vehicle body to ground. Thus, it also measures vehicle body bounce. An accelerometer also measures body bounce and long wave features. Body displacement is calculated by pseudo double integrating acceleration. The result is summed with vertical distance to cancel vehicle bounce and produce an elevation profile. By this process, the profile bandwidth is divided into two parts. The first part contains all wavelengths shorter than those determined by the vehicle bounce rate and speed. These are sensed by the vertical displacement sensor. Second, the accelerometer measures wavelengths longer than those determined by vehicle bounce and speed, but only up to a few hundred feet.

The PosNav instrument can be considered a third element in the RTP system that takes over at several hundred foot waves and extends these to many thousands of feet. In practice this would be accomplished by pseudo integrating the measured elevations derived from pitch and distance. This result would then be low pass filtered to remove all wavelengths shorter than the maximum wavelength passed by the RTP system. The RTP profile could then be summed with the PosNav profile to provide a composite, broadband profile. It should be noted that one might want to keep these signals separate, with their own scaling, because the broadband profile could have a very large dynamic range. This is to say, you couldn't see little bumps because of the big hills.

So far, this report has described use of the PosNav instrument for a curve and grade study requested by the FHWA. The next section will describe a few possible new applications for this technology.

POSSIBLE FUTURE PROJECTS

This section explores further research based on features of the instrument not covered so far. Its potential for cartographic use in conjunction with Global Position System (GPS) is enormous. The GPS system with portable receivers can provide high accuracy, however, collecting the quantities of data needed to reflect the curves and hills along a roadway with GPS is time consuming. Ideally, one could use GPS to get precise initial coordinates for the inertial PosNav system, then take full advantage of the PosNav for a high speed survey. A portable GPS receiver could be used when high precision starting coordinates are required. The State of Michigan is developing new geodetic monuments along major roadways in an effort to densify the geodetic reference system. Indirectly, GPS derived starting positions could be determined conveniently from these new monuments.

Ordinarily, it is not essential to measure elevation changes over long distances. These have very little effect on ride quality for instance. Recent interest in the lay-of-the-land profile stems from several areas of concern. These are accident litigations involving sight distance and accidents involving surface water pooling into bituminous pavement ruts. Another need is to inventory hills that may be unsafe or energy inefficient. As the Curve and Grade study mentioned above illustrates, many states may be asked to inventory hills by elevation as well as by slope. The PosNav extension to the GM RTP based systems would ensure standard elevation measures across all states. This would enable intelligent allocation of funds for competing projects. Also, broadband profiles of airport runways are essential to determine dynamic aircraft behavior during takeoff and landing.

In addition to long wave components, the PosNav instrument could permit measurements of superelevations and the true roll component generated by left and right wheel path elevations. Many of the GM RTP class of profilometers measure the profile in both the left and right wheel paths. Often, an instantaneous difference between these is derived to measure the short wave roll component. The long wave roll or superelevation is measured by a simple inclinometer. The roll component supplied by the PosNav unit is superior to that produced by simple inclinometers. This is because the instrument is not fooled by all the other forces that can affect an inclinometer. Its internal instrumentation reports only the true roll component. In summary, the PosNav unit, coupled with GM's RTP concept, could produce measurement of position in all six degrees of freedom, from very short to very long spatial wavelengths. In addition, its mapping ability would provide precise location of profile features.

Another application for the PosNav unit is inventorying roadway features.

Highway maintenance operations require accurate measurements of the number of lane miles of concrete and bituminous pavements, the location of signs, catch basins, location and length of guard rail. Each of these items can be easily identified using the PosNav unit. As the vehicle is driven on the highway, an operator with a specially designed keyboard can indicate the occurrence of each item to be inventoried. Subsequently, a straight line map can display the data. The information could also be placed into a Geographical Information System (GIS).

Inertial navigation systems have been linked with GPS to achieve high-accuracy results in navigation and kinematic positioning. By combining differential GPS with inertial navigation systems and mathematical models utilizing Kalman filtering, centimeter accuracies can be obtained. This technique can be used to speed up surveying times from hours to minutes and still maintain the required accuracy.

The PosNav is a unique device. Its long term stable reference and many other features suggest other areas of research. These might include such diverse uses as roadway grader guiding, paving machine control or monitoring, vehicle location and vehicle dynamic response measurements.

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