Measurement of the International Roughness Index (IRI) Using an Autonomous Robot (P3-AT)

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Abstract

In this paper, we test whether an autonomous robot can be used to measure the International Roughness Index (IRI), a description of pavement ride quality in terms of its longitudinal profile. A ready-made robot, the Pioneer P3-AT, was equipped with odometers, a laptop computer, CCD laser, and a SICK laser ranger finder to autonomously perform the collection of longitudinal profiles. ProVAL (Profile Viewing and AnaLysis) software was used to compute the IRI. The preliminary test was conducted indoors on an extremely smooth and uniform 50 m length of pavement. The average IRI (1.09 m/km) found using the P3-AT is robustly comparable to that of the commercial ARRB walking profilometer. This work is an initial step toward autonomous robotic pavement inspections. We also discuss the future integration of inertial navigation systems and global positioning systems (INS and GPS) in conjunction with the P3-AT for practical pavement inspections.

Keywords: Pavement, Smoothness, International Roughness Index (IRI), Autonomous Robot, ProVAL

1. Introduction

Road roughness, or smoothness, inspections are performed to monitor the pavement conditions in order to evaluate the ride quality of new and rehabilitated pavements. Roughness is closely related to vehicle operating costs, vehicle dynamics, and drainage. The American Society for Testing and Materials (ASTM) E 867 defines roughness as the deviations of a pavement surface from a true planer surface with characteristic dimensions. A pavement profile represents the vertical elevations of the pavement surface as a function of longitudinal distance along a prescribed path of travel (Wang, 2006). Both manual and automatic multi-function profiling systems are continuously being developed and marketed for improved performance.

In this study, we pioneer the use of an autonomous robot (the P3-AT) to perform roughness inspections for project-level pavement management purposes. The P3-AT is able to autonomously collect longitudinal profiles at prescribed sampling intervals and compute the International Roughness Index (IRI). It is anticipated that the robot will replace manually operated equipment for construction QC/QA purposes in the near future. A preliminary test on an extremely smooth and uniform 50 m pavement section shows that the average IRI (1.09 m/km) obtained by the P3-AT is comparable to commercial Australian Road Research Board (ARRB) walking profilometer. We also discuss the future integration of inertial navigation systems and global positioning systems (INS and GPS) in conjunction with the P3-AT for practical pavement inspections.

2. Literature Reviews

Pavement profiling systems started with straightedge devices in the early 1900s. Other simple profiling devices, profilographs, and response type road roughness measuring systems (RTRRMS) were developed in the late 1950s and 1960s. Between the late 1960s and 1980s, highway agencies primarily adopted the profilograph for measuring and controlling initial roughness of new construction pavement. The use of inertial profilometers in monitoring pavement condition increased in the 1980s and early 1990s (Wang, 2006). The aforementioned equipment can be divided into five categories (Perera and Kohn, 2002):

- Manual devices: rod and level surveys, straightedge, rolling straightedge (high-low detector), Dipstick, ARRB walking profilometer, etc.
- Profilographs: Rainhart profilograph, California profilograph, etc.
- RTRRMS: Bureau of Public Roads (BPR) roughometer, Mays Ride Meter (MRM), Portland Cement Association (PCA) ridemeter, etc.
- High-speed inertial profilometers: Automatic Road ANalyzer (ARAN) by Roadware Group Inc., Model T6600 Inertial Profilometer by K. J. Law Engineers Inc., etc.
- Lightweight profilometers: Model 6200 lightweight inertial surface analyzer (LISA) by Ames Engineering, Inc., CS8700 lightweight profiler by Surface Systems & Instruments, Dynatest/KJL 6400 lightweight profilometer by Dynatest Consulting, Inc., etc.

The high-speed inertial profilometer can be fitted to full-sized vehicles to measure the pavement profiles at traffic speed. Most lightweight profilometers currently commercially available integrate using the same hardware used in high-speed inertial models mounted on golf carts or small vehicles. ASTM E 950 defines inertial profilometers as Class 1 to Class 4 according to their sampling interval, vertical measurement resolution, precision, and bias. The commonly used modern devices for profiling such as rod and level, Dipstick, ARRB walking profilometer and most inertial profilometers and lightweight profilometers are all Class 1 devices (FHWA-LTPP Technical Support Services Contractor, 2004).

The high-speed inertial profilometer is commonly used to perform roughness inspections for network-level pavement management purposes, but other approaches (such as the California profilograph, ARRB walking profilometer, and lightweight profilometers) have been specifically developed for project-level pavement management purposes. Furthermore, although high-speed inertial profilometers dominate today's market, their application to construction acceptance testing for new or rehabilitated pavements remain limited due to their high cost and scheduling limitations – the short-length pavement overlay and the tests on rigid pavements, for instance, cannot be performed until after a few days of curing (Kelly et al., 2002). As such, most highway agencies use primarily manual methods for QC/QA purposes of new pavement construction and small-scale rehabilitation projects, with the high-speed inertial profilometer used for extended measurements over time (Baus and Hong, 1999).

Roughness indices are derived from profile data and correlated with road users' perceptions of ride quality to indicate the level of pavement roughness. These include the Profile Index (PI), International Roughness Index (IRI), Ride Number (RN), Michigan Ride Quality Index (RQI) and Truck Ride Index (TRI) (Sayers and Karamihas, 1996). Among them, IRI is the index most widely used for representing pavement roughness. ASTM E 1926 defines the standard procedure for computing the IRI from longitudinal profile measurements based upon a mathematical model referred to as a quarter-car model. The quarter-car is moved along the longitudinal profile at a simulation speed of 80 km/h and the suspension deflection calculated using the measured profile displacement and standard car structure parameters. The simulated suspension motion is accumulated and then divided by distance travelled to give an index with unit of slope (m/km), the IRI. Most highway agencies are using the IRI to evaluate new and rehabilitated pavement condition, and for construction QC/QA purposes (Wang, 2006). The IRI can be reported two ways:

- Single path IRI: Based on a quarter-car model run over a single profile.
- Traffic lane IRI: A composite result representing the roughness of a traffic lane. It is determined by averaging two individual, single path IRIs obtained separately in each wheel-path (at 0.75 m either side of the lane mid-track).

Some surveys of state highway agencies in the United States indicate that about 10 percent (4 of 34 respondents) use IRI to control initial roughness (Baus and Hong, 1999), while about 84 percent (31 of 37 respondents) use IRI to monitor pavement roughness over time (Ksaibati et al., 1999), making IRI the statistic of choice for roughness specifications. The proposed 2002 Design Guide under development by the National Cooperative Highway Research Program (NCHRP) also included IRI prediction models that are a function of initial IRI (IRI0) (Kelly et al., 2002; Baus and Hong, 1999).

The lightweight profilometer has been shown to obtain timely and accurate measurements of pavement profiles and to be significantly faster than profilographs (24 km/hr versus 5 km/hour). However, like the high-speed inertial profilometers, they require operators to perform repetitive, tedious, and time-consuming procedures, their awareness and knowledge of the profiling systems and influencing factors largely determining the efficiency of the measurement. The profilometer, for example, must be operated by experienced inspector at relatively constant speeds and the wheel-path must be consistent between measurements. (Mondal et al., 2000).

This study proposes using robots to complete project-level pavement roughness inspections, by autonomously collecting longitudinal profiles and computing the IRI, thus increasing mobility and accuracy, and minimizing time and labor commitments. With self-controlled and automatic motion, robots can reduce the variation and uncertainty of profile measurements and improve inspection reliability.

3. Autonomous Robot Preparation

In this section, we briefly introduce the preparation of the autonomous robot. An integrated set of vertical displacement sensors (CCD laser), odometers, SICK laser ranger finder, and control laptop are mounted on the P3-AT, which is manufactured by MobileRobots Inc (2008). The P3-AT, which can move up to 3 km/h, is capable of measuring longitudinal profiles using a CCD laser at 15 cm or smaller sampling intervals, from which the IRI can be simultaneously computed using laptop-based ProVAL software.

3.1 Autonomous Robot: Pioneer 3-AT (P3-AT)

Being powerful, easy-to-use, reliable and flexible, the P3-AT used in this study is a highly versatile all-terrain robotic platform particularly suited to pavement inspections. Figure 1 shows the P3-AT (MobileRobots Inc., 2008), equipped with a control laptop, onboard Pan-Tilt-Zoom (PTZ) camera system, Ethernet-based communications, a SICK laser and eight forward and eight rear sonars which sense obstacles from 15 cm to 7 m. The P3-AT's powerful motors and four robust wheels can reach speeds of 0.8 m/sec and carry a payload of up to 30 kg. It can climb steep 45% grades and sills of 9 cm and uses 100-tick encoders with inertial correction recommended for dead reckoning to compensate for skid steering. Its superior sensory system employs laser-based navigation options, integrated inertial correction to compensate for slippage, bumpers, a gripper, vision, stereo rangefinders, a compass and a rapidly growing suite of other options. The bare P3-AT base includes the Advanced Robotics Interface Application (ARIA) software enabling the user to (MobileRobots Inc., 2008):

- make the P3-AT move randomly;
- drive using key or joystick control;
- plan inspection paths with gradient navigation;
- display a pavement spatial map using sonar readings, laser readings or a combination of the two;
- localize using sonar or laser upgrade;
- communicate sensor and control information relating sonar, motor encoder, motor controls, user I/O, and battery charge data;
- test pavement inspection activities quickly with ARIA API (in C^{++});
- simulate pavement inspection behaviors offline with the simulator that accompanies each development environment.

3.2 Laser for Vertical Displacement Measurements: LK-G155

In order to conduct inspections on extremely smooth pavement (e.g. a new construction pavement), the resolution of the sensor signals must be very high. Laser sensors are best suited to this purpose. In this study, a LK-G155 (a CCD laser displacement sensor), as shown in Figure 1, is used to measure the vertical displacement from laser to pavement surface, at 15 cm sampling intervals while the P3-AT is in motion. It is mounted in front of the P3-AT and is situated 15 cm above the pavement. The sensor head specifications of LK-G155 are as follows (Keyence Corporation, 2008):

- Mounting mode: Specular reflection
- Reference distance: 147.5 mm
- Measuring range: ± 39 mm
- Spot diameter (at reference distance): Approximately 120 x 1700 μm
- Resolution: 0.5 μm
- Linearity: ±0.05% of F.S. (F.S. = ± 40 mm)
- Sampling frequency: 20/50/100/200/500/1000 μs (selectable from 6 levels)
- Weight (including the cable): Approximately 290 g

- Light source: Red semiconductor laser with 650 nm wavelength (visible light), Class II (FDA), 0.95 mW maximum output
- Temperature characteristics: 0.01% of F.S./°C (F.S. = ± 40 mm)
- Resistance to vibrations: 10 to 55 Hz, multiple amplitude 1.5 mm; two hours in each of X, Y, and Z plane
- LED display: Green in the centre, within the measurement area is orange lights, outside the measurement area is flashing orange.

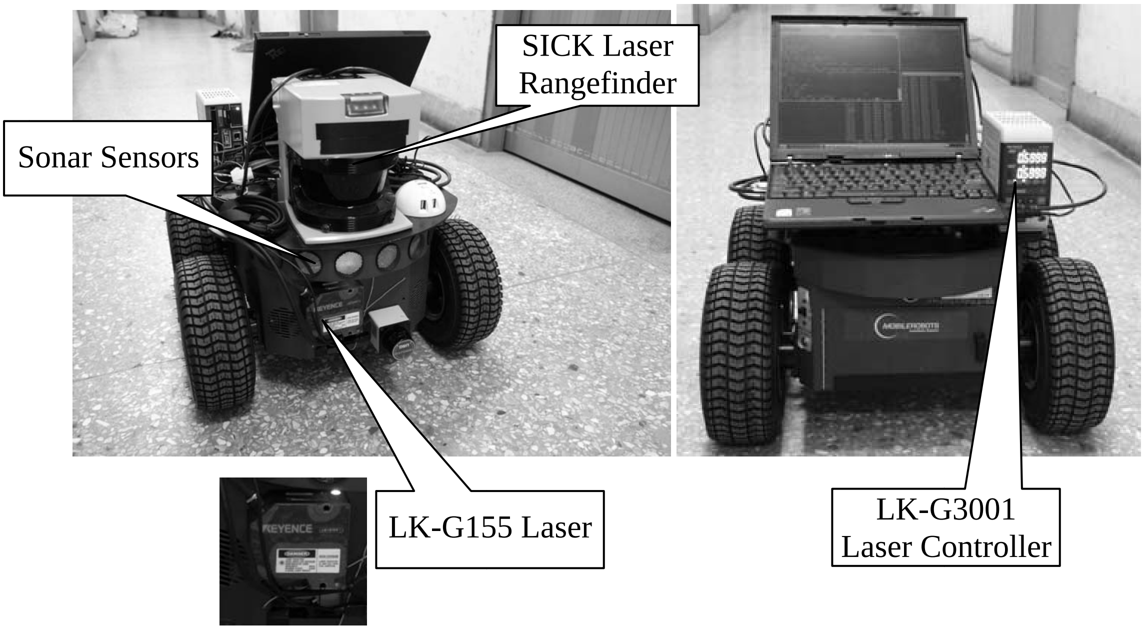


Figure 1 - P3-AT Robot equipped with LK-G155 Laser

Spot size is an important consideration. A small laser spot increases the detector's sensitivity to coarse pavement macro-textures, thus resulting in a profile including high frequency content not relevant to roughness. The LK-G155 uses the wide spot optical system that has high measurement stability. In order to avoid data fluctuations, diffused reflections caused by pavement surface irregularities are averaged with multiple samples to reduce the amount of texture noise at each point of the measured profile. Moreover, this issue does not present a problem because of the effective anti-aliasing process applied to the laser signals.

The digital vertical displacements measured by LK-G155 are displayed and controlled by LK-G3001 controller (as shown in Figure 1). The LK-G3001 controller can transmit the displacement measurements to the laptop via USB at a high-speed 50 kHz. The profile measurements can then be further imported into the ProVAL (Profile Viewing and AnaLysis) software to compute the IRI.

3.3 ProVAL (Profile Viewing and AnaLysis)

The ProVAL engineering software package, developed by the Transtec Group (2008), allows analysts to view and analyze pavement profiles in many different ways. It is easy to use and can perform various profile analyses, including profile editing, standard ride statistics (IRI, RN, etc.), profilograph simulation, rolling straightedge simulation and ASTM E 950 precision and bias. ProVAL is a product sponsored by the US Department of Transportation, Federal Highway Administration (FHWA) and the Long Term Pavement Performance Program (LTPP).

Version 2.73 was installed on the laptop. The LK-G3001 controller imports profile measurements obtained from the LK-G155 laser into ProVAL, which then analyzes IRI for each longitudinal profile as soon as one profile inspection has been finished. Analysts are then able to print a report of the original profiles and of any analyses performed.

4. Preliminary Roughness Inspection Test

In this section, we describe the preliminary indoor test and the comparison of measured IRIs between the P3-AT and an ARRB walking profilometer.

4.1 *Test Section and Test Plans*

A 50 m straight test path was designated on a smooth, uniform indoor test section, as shown in Figure 2. The test procedure was as follows:

- LK-G155 laser test: The precision and bias of the laser sensor was tested under a static situation before the preliminary test.
- Longitudinal distance test: This test was used to evaluate the precision and bias of the odometer and SICK laser ranger finder. Coupled with the odometer, the SICK laser ranger finder was used to ensure the P3-AT moves accurately along the test path and at a consistent and precise speed.
- Profiling of test path: The test path was used to compare profiles and IRIs between the P3-AT and commercial equipment. Repeated measurements of the IRI were found to evaluate the repeatability of the P3-AT. The ARRB walking profilometer was also used along the same path. The results from each method were then compared.

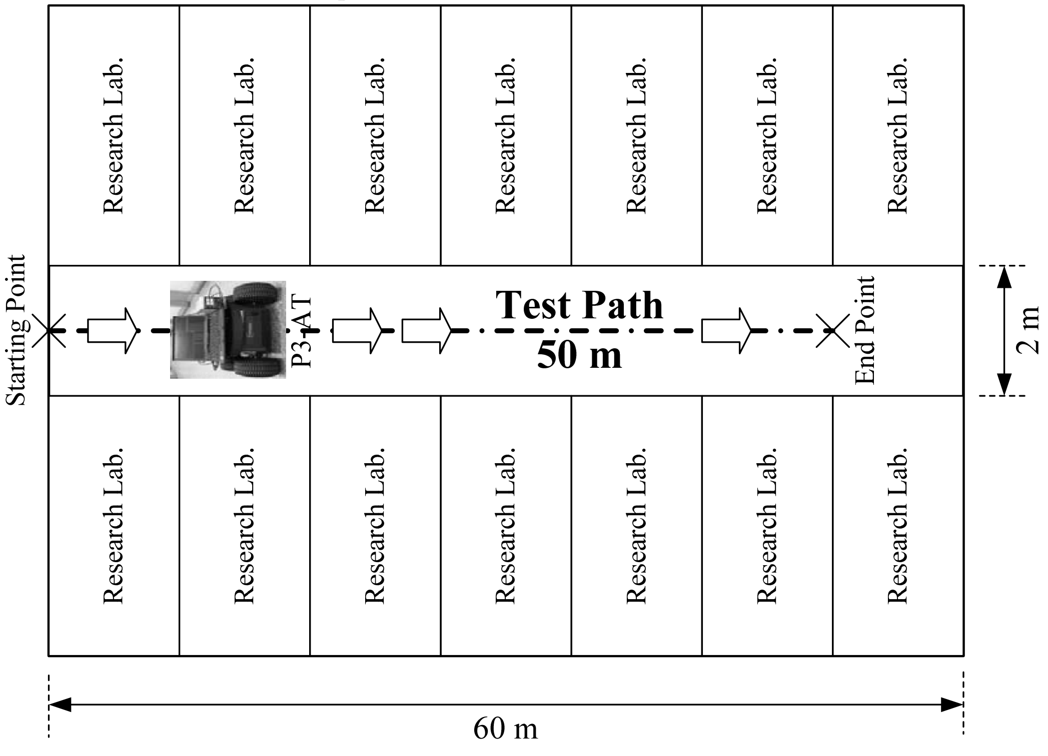
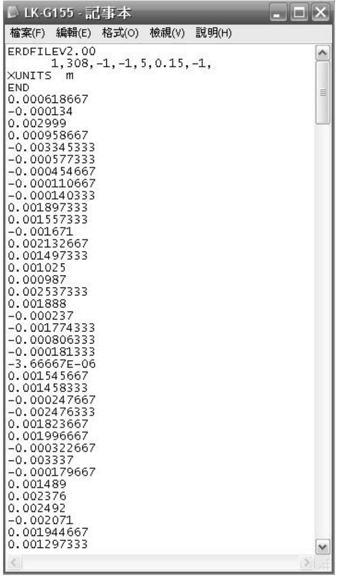


Figure 2 - Test section

4.2 *Test Procedures and Test Results*

The P3-AT, moving along the test path at a speed of up to 3 km/h, autonomously stops at each 15 cm sampling interval to measure the vertical displacement with the LK-G155 laser. In general practice, sampling intervals range from less than 25 mm to 380 mm. The P3-AT's speed has no effect on the result because the vertical displacement measurement is found when the unit is at rest. The odometer is used to determine the longitudinal distance. The SICK laser range finder is used to ensure the P3-AT follows the test path. No accelerometer is required on the P3-AT, usually needed to compensate for the vertical acceleration of the unit itself, because the test surface is uniformly smooth and level. The commercial device, the ARRB walking profilometer, was then used to obtain another computation of the IRI on the test path. The average IRI (1.09 m/km) from several runs on the test path shows that results from the P3-AT are comparable to the IRI (1.11 m/km) obtained from the ARRB. Figure 3 shows the vertical displacement measurement dataset, in *.ERD format, imported from LK-G3001 controller. Figure 4 displays the original profile of the imported file and the metric system of units has been selected, with distance in meter and elevation in millimeters. Figure 5 shows the effect of IRI filter (with 250 mm filter) on the original profile. Figure 6 shows the result of IRI computation (1.09 m/km).



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ERDFILEV2.00
      1,308,-1,-1,5,0.15,-1,
XUNITS  m
END
0.000618667
-0.000134
0.002999
0.000958667
-0.003345333
-0.000577333
-0.000454667
-0.000110667
-0.000140333
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0.001888
-0.000237
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-0.000181333
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0.001823667
0.001996667
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Figure 3 - The vertical displacement measurement dataset in *.ERD format

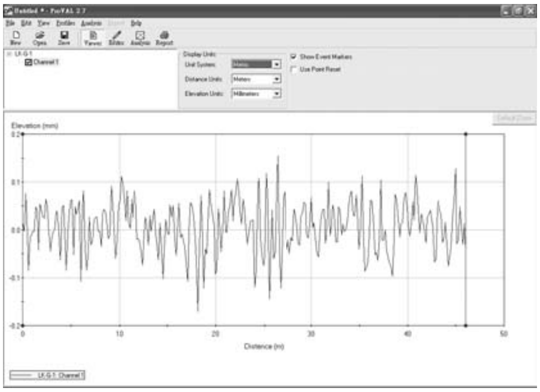


Figure 4 - The original profile

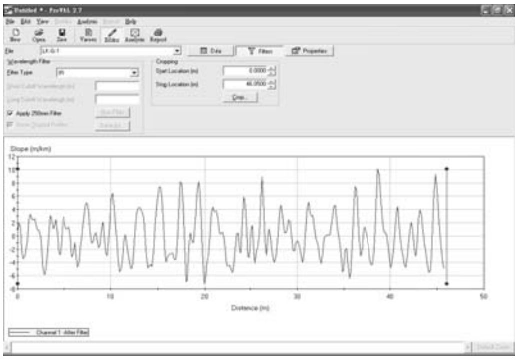
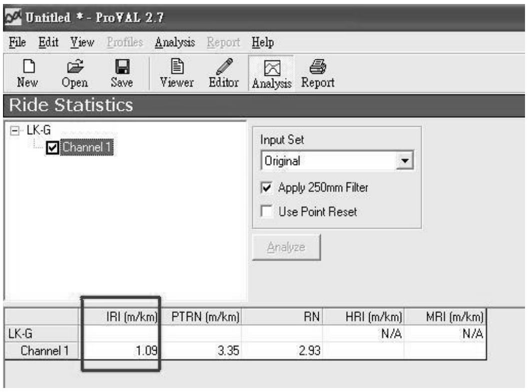


Figure 5 - The filtered profile by IRI filter (250 mm filter)



LK-G
☑ Channel 1

Input Set: Original

☑ Apply 250mm Filter

☐ Use Point Reset

	IRI (m/km)	PTRN (m/km)	RN	HRI (m/km)	MRI (m/km)
LK-G				N/A	N/A
Channel 1	1.09	3.35	2.93		

Figure 6 - The IRI computation (m/km)

5. Conclusions and Remarks

In the study, we propose using a P3-AT robot to perform roughness inspections for project-level pavement management purposes. The P3-AT can autonomously conduct the collection of longitudinal profiles using a 15 cm sampling interval and compute the International Roughness Index (IRI). It is anticipated that the use of an autonomous robot will replace manually operated or driven equipment for construction QC/QA purposes in the near future. The preliminary test on an extremely smooth 50 m test path shows that the average IRI (1.09 m/km) obtained by the P3-AT is comparable to a commercial ARRB walking profilometer (1.11 m/km). The inspection architecture of P3-AT has proven to be very reliable. In the future, the test path can be profiled with the P3-AT at different speeds to evaluate its effect on profiles and IRIs.

For the current inspection architecture, there is no accelerometer mounted on P3-AT since the test path is very level, the pavement surface is extremely smooth, and the vertical displacement measurement by the P3-AT occurs when the unit is at rest. An accelerometer could however be integrated with the P3-AT to facilitate non-level surfaces found in actual pavement inspections

For accurately positioning, the authors have previously successfully integrated a virtual reference station

(VRS) system to the P3-AT to reach centimeter-level positioning accuracy (Chang et al., 2008). We are currently working towards the design and implementation of an inertial navigation system (INS) using an inertial measurement unit (IMU) and GPS with the P3-AT. The INS is capable of providing continuous estimates of P3-AT's position and orientation. The IMU coupled with the proper mathematical algorithms, is capable of detecting accelerations and angular velocities and then translating those to the current position and orientation of the P3-AT. The detailed pavement information (e.g. grade, cross fall, etc.) can be derived by the use of INS. The innovation of both systems can be used to improve pavement roughness inspections when used in conjunction with the P3-AT.

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