VIRTUAL REFERENCE STATION (VRS)-BASED INTELLIGENT ROBOT (PIONEER 3-AT) TO ASSIST IN PAVEMENT INSPECTIONS

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Abstract

This study develops a framework for the application of a Pioneer 3-AT (P3-AT) autonomous robot integrated with two types of highly accurate Virtual Reference Station (VRS) technology. The tire pressure and the horizontal movement of the P3-AT were calibrated. The positioning accuracy of P3-AT was measured by VRS under both static and dynamic conditions at 25 cm to 20 m distances of movement. We saw a standard deviation in the static test of less than 0.03 m, and the root mean square (RMS) to be very close to the specified distance of movement. This research also conducted the use of P3-AT in positioning distresses on the pavement, the P3-AT's autonomous monitoring, and its ability to plot slabs on a rigid pavement in order to prove that VRS can indeed provide P3-AT with high-accuracy positioning data that is required when moving on the broad pavement, thus meeting the positioning requirements of pavement inspection.

KEYWORDS: Virtual Reference Station, Intelligent Robot, Pavement Inspection, Distress.

INTRODUCTION

The level of serviceability given to pavements is highly related to surface condition. In general, the surface conditions are monitored by periodically collecting the longitudinal evenness (roughness), transversal evenness (rutting) and distress information using manifold commercial equipment (Shahin, 2005). Traditional pavement inspections are generally conducted using manually operated instruments which are very labor-intensive. These inspections usually include repetitive and tedious procedures, and often require a large amount of time for post-analysis. This study integrates a Pioneer 3-AT (P3-AT) autonomous robot with a high-accuracy positioning system, the virtual reference station (VRS), to investigate whether, under static and dynamic states, the accuracy of positioning data provided by VRS to P3-AT is adequate enough for it to serve its role in pavement inspections.

VIRTUAL REFERENCE STATION (VRS) SYSTEM

RTK positioning in conjunction with GPS can reach a high accuracy (to the centimeter-level) and is one of the most widely used surveying techniques today. RTK has some problems such as the effect of the troposphere and ionosphere resulting in systematic errors in raw data, etc. Recently, the concept of the Virtual Reference Station (VRS), also called network RTK, is one of the more feasible approaches for relaying network correction information to the network RTK users (Euler et al., 2001). This approach does not require an actual physical reference station. Instead, it allows the user to access data of a non-existent virtual reference station at any location within the network coverage area and allows modeling the systematic errors to provide the possibility of an error reduction. An example of a VRS network operation is shown in Figure 1 (Trimble, 2005). Figure 2 shows the architecture for linking the control centre to the user receiver (Hu et al., 2002). The VRS approach is quite flexible; users can use their current receivers and software without any need for specific software to manage corrections from a series of reference stations. For accurately positioning the robot on pavements, a positioning system with high accuracy (to the nearest centimeter) is extremely necessary. In this study, Leica's GPS VRS system was equipped on a P3-AT. A HSDPA (high speed downlink packet access) broadband wireless modem (3.5 G) is utilized as the transmission device for positioning information. Two types of VRS systems were adopted. One was the VRS system developed by a private enterprise Control Signal Company Limited in Taiwan (CSCL, 2010), and the other was the real-time kinematic positioning system (e-GPS) from Taiwan National Land Surveying and Mapping Center (NLSC, 2009). A comparison of the two VRS systems is summarized in Table 1.

P3-AT CALIBRATION TESTS

Test Sites and Hardware Configuration

The study was carried out on one test site which was a flexible pavement in MingHsin University of Science & Technology in Taiwan (Figure 3). A Leica SR530 GPS receiver and an IBM X61 notebook was mounted on the platform of the P3-AT (Figure 4). The VRS software (SpiderNET) in the notebook connects to the control center through a HSDPA (3.5G) wireless network card using programs designed by using Microsoft Visual Programming Language (MVPL) (Microsoft, 2009) and sends back corrected data to the P3-AT in real time so that it can choose accurate autonomous movements.

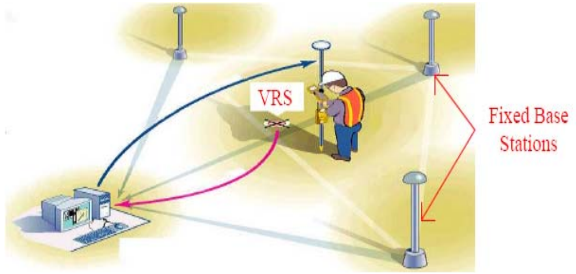

Figure 1: VRS Network Operation (Trimble, 2005)

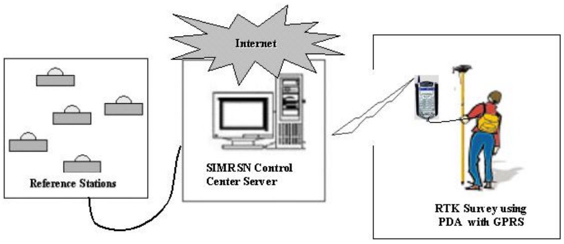

Figure 2: The Architecture of Internet-based VRS System via GPRS (Hu et al., 2002)

Table 1: The Comparison of the Two VRS Systems Adopted in This Study

Item / VRS System	Reference Stations	Range of Services	Organization	Cost	Convergence Time
e-GPS	76	Taiwan, Penghu Kinmen, Matsu	State enterprise	300 NTD/day	Relatively fast
CSCL	11	North Island	Private enterprise	Nil	Relatively slow

Figure 3: The Test Site in MingHsin University of Science & Technology (N 24°85'97.47", E 120°98'80.76")

Figure 4: P3-AT Robot Hardware Architecture

Tire Pressure Calibration Tests

The tire pressure was calibrated by commanding the P3-AT to autonomously move 500 cm in a horizontal direction using a MVPL program at 6 different tire pressures. The 50 psi is the upper limit for P3-AT's tire pressure and the actual distance travelled by the robot was then measured and compared against the specified value of 500 cm. The results in Table 2 show an error between 0.14 – 2.63%. At a tire pressure of 25 psi, the actual travel distance is the closest to the specified distance of 500 cm. We then set the tire pressure at 25 psi to carry out the remaining VRS positioning tests.

Table 2: P3-AT Tire Pressure Calibration Tests (cm)

Tire pressure / Number of tests	10	20	25	30	40	50
1	487.30	499.40	500.70	505.90	509.80	511.30
2	486.90	499.20	500.80	505.80	509.50	511.40
3	486.40	499.10	500.60	505.60	509.30	511.40
Average	486.87	499.23	500.70	505.77	509.53	511.37
Standard deviation	0.368	0.125	0.082	0.125	0.205	0.047
Difference with 500 cm	13.13	0.77	0.70	5.77	9.53	11.37
Error (%)	2.63	0.15	0.14	1.15	1.91	2.27

Horizontal Displacement Calibration Tests

Here the tire pressure of the P3-AT was set to 25 psi, and was controlled by MVPL program to autonomously move distances of 25 cm, 100 cm, 300 cm, 500 cm and 1000 cm on the test site. After the P3-AT had completed each move and had stopped, the actual distance travelled was measured. The results of the calibration tests are tabulated in Table 3. The results indicate that, under a fixed tire pressure of 25 psi, the actual travel distances are very close to specified distances. Therefore, it is concluded that the P3-AT can move according to specified distances correctly in the tests conducted from here on.

TESTING THE VRS-BASED P3-AT

After completing the horizontal displacement calibration tests, we went on to carry out a series of tests designed as shown in Table 4 below using CSCL and e-GPS VRS systems.

Static Testing

The P3-AT was made to move autonomously 5 specified distances of 0.25 m, 1 m, 3 m, 5 m and 10 m on the test site stopping after each move. The difference between the real travel distance which was calculated from its X (Easting), Y (Northing) coordinates (Taiwan Grid) provided by VRS before and after the P3-AT's movement and the specified distance was assessed. It is worth noting that, if possible, the VRS positioning data collected in static tests should be received after the positioning accuracy is within 1 cm according to the GPS receiver. Since the accuracy of positioning may experience minor fluctuations due to a number of factors, positioning data within an accuracy of 3 cm was considered acceptable in the current study. Table 5 presents the root mean squares (RMS) and standard deviations of measured travel distances. A sample plot of 15 measurements for the 0.25 m test using the e-GPS system is given in Figure 5.

Table 3: P3-AT Displacement Calibration Tests

Distance (cm) / Test Number	25	100	300	500	1000
1	25.90	100.50	300.40	500.10	1000.60
2	25.50	100.90	300.90	500.00	1000.60
3	25.00	100.30	300.80	500.60	1000.70
4	24.90	99.90	299.90	499.90	1000.30
5	25.70	100.50	300.00	500.40	1000.60
6	25.60	100.60	300.30	500.00	1000.20
7	25.10	99.90	300.20	500.30	1000.00
8	25.00	100.00	300.30	500.30	999.90
9	25.80	100.60	300.10	500.70	999.80
10	25.90	100.40	300.40	500.50	1000.60
Average	25.44	100.36	300.33	500.28	1000.33
Standard deviation	0.38	0.32	0.30	0.26	0.32
Difference with specified distance	0.44	0.36	0.33	0.28	0.33
Error (%)	1.76	0.36	0.11	0.06	0.03

Table 4: Experimental Design

Test site	VRS system	State	Horizontal displacement (m)
Flexible pavement	Control Signal Company Limited	Static	0.25、1、3、5、10
		Dynamic	3、5、10、20
	NLSC	Static	0.25、1、3、5、10
		Dynamic	3、5、10、20

From the results in Table 5, the VRS-based P3-AT performed with actual travel distance standard deviations of less than 0.03 m and the root mean squares are close to the specified distances in static tests regardless of VRS systems used. This confirms that the VRS system is able to provide a P3-AT with high degree of accuracy in its positioning information.

Table 5: Results of Static Tests

Test site and VRS system	Specified displacement (m)	Root mean square tests	Standard deviation of 15 tests (m)
Flexible pavement CSCL	0.25	0.249	0.011
	1	1.001	0.008
	3	2.996	0.018
	5	4.997	0.008
	10	9.993	0.016
Flexible pavement e-GPS	0.25	0.245	0.010
	1	1.002	0.017
	3	2.998	0.011
	5	4.992	0.020
	10	9.997	0.015

Dynamic Testing

In dynamic testing, positioning data provided by the VRS were recorded non-stop by MVPL programs when the P3-AT travelled four specified distances: 3m, 5m, 10m and 20m. The positioning path of the P3-AT can be plotted by adding together its displacements every second from the start to the finish. An example (one of three tests) is given in Figure 6 where the test site was used with the CSCL VRS system robot running the 5 m test. Figure 6 shows that it takes about 10 seconds for the P3-AT to travel the 5 m. In the first two seconds it is accelerating. After this, it enters a constant speed phase for 3 seconds. It travels with a maximum speed of 2.7 km/hr (approx. 0.7m/s). It then decelerates in the last 2 seconds. Due to the fact that the P3-AT goes through a cycle of starting up, accelerating, constant speed and decelerating, the shape positioning path appears to produce a slight S curve. The reproducible error of the three tests is 0.014 m. Table 6 summarizes the reproducible errors. The results show that the VRS based P3-AT exhibits a reproducible error of less than 0.03 m in dynamic tests regardless of VRS systems. The results prove that VRS system has the ability to provide P3-ATs with correct positioning information to move around.

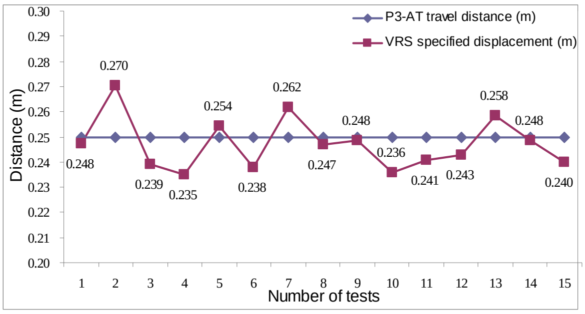

Figure 5: Results from Static VRS positioning tests (15 tests): e-GPS system, 0.25 m displacement

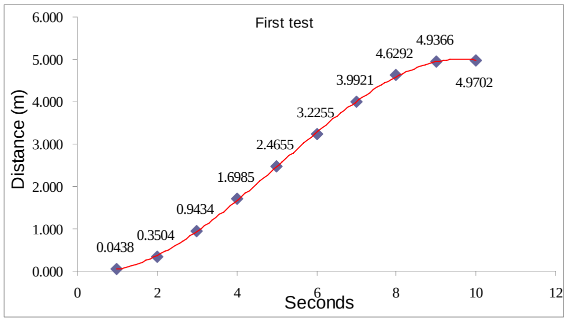

Figure 6: Results from Dynamic VRS positioning tests (one of three tests): CSCL VRS system and a 5 m Positioning Path

Table 6: Reproducible Error in the Results of Dynamic Tests

Test site and VRS system	Distances (m)	Reproducible error of three tests (m)
Flexible pavement CSCL	3	0.005
	5	0.014
	10	0.006
	20	0.006
Flexible pavement e-GPS	3	0.008
	5	0.010
	10	0.009
	20	0.029

PAVEMENT INSPECTIONS USING THE P3-AT

The X, Y coordinates (Taiwan Grid) of seven existing distresses (including potholes, manholes, alligator cracking and patching etc.) on the test site were obtained by use of a static positioning method, which is the most accurate approach for positioning purposes. Note that considering the requirements of distress photos taken by the P3-AT, the coordinates were obtained at an approximate distance of 3 m to the existing distresses. The coordinates and types of the seven distresses are summarized in Table 7 while locations of the site are marked on Figure 7 as well. The P3-AT started from distress point 1 on Figure 7 and autonomously moved on to the next target in the order according to the positioning data delivered through VRS. The P3-AT then used its PTZ Camera to take photos of the distresses. From the coordinates in Table 7, it is noticed that P3-AT does almost stop at the specified position with the error within 0.03 m. Figure 8 shows photos of distress number 1, 4 and 5 taken by the P3-AT. This test can be applied to inspections of historic distresses within specified areas or regions with potential hazards. Regularly scheduled autonomous inspections by robots can be conducted to assist pavement engineers so that they can acquire a better understanding of the current situations at any time mitigating the pressure on manual inspections.

Table 7: Distresses on the Site

Distress number	Distress condition	Taiwan Grid		Coordinates of P3-AT		
		X (mE)	Y (mN)	X (mE)	Y (mN)	Distance to targets (m)
1	pothole + alligator cracking	248738.038	2750255.672	248738.043	2750255.648	0.02
2	rectangular manhole	248800.946	2750295.591	248800.968	2750295.599	0.02
3	pothole + alligator cracking	248795.146	2750324.048	248795.142	2750324.035	0.01
4	square manhole	248779.276	2750305.713	248779.251	2750305.699	0.02
5	alligator cracking	248767.908	2750317.509	248767.899	2750317.499	0.01
6	rectangular manhole	248764.296	2750329.395	248764.301	2750329.417	0.02
7	pothole + alligator cracking	248765.448	2750338.671	248765.468	2750338.683	0.02

Figure 7: Schematic Diagrams Indicating Locations of Distresses on Test Site

Moreover, in this study, the P3-AT was also operated manually to travel along the joints of 6 m x 5 m rigid pavement slabs. The X, Y coordinates of the corners of slabs were recorded as shown in Table 8 through VRS. These coordinates were employed to produce the drawing in Figure 9 with points that mark the corners of slab. By calculating the corner coordinates of the slab, it is found that the size of the slab is extremely close to 6 m x 5 m. This demonstrates the remarkably high accuracy of VRS's positioning capability in its performance of pavement engineering related plotting.

Figure 8: Distress Photographs Taken by P3-AT (Point 1, 4 and 5)

Table 8: Rigid Pavement Slabs Recorded by the P3-AT through VRS

Point number	X (mE)	Y (mN)	Distance between points (m)
1	248664.356	2750401.119	
2	248658.343	2750401.715	1-2 (6.04)
3	248658.842	2750406.749	2-3 (5.06)
4	248664.872	2750406.151	3-4 (6.06) / 1-4 (5.06)
5	248665.445	2750411.213	4-5 (5.09)
6	248659.393	2750411.784	5-6 (6.08) / 3-6 (5.06)
7	248659.944	2750416.818	6-7 (5.06)
8	248665.956	2750416.223	7-8 (6.04) / 5-8 (5.04)
9	248666.467	2750421.233	8-9 (5.04)
10	248660.471	2750421.852	9-10 (6.03) / 7-10 (5.06)

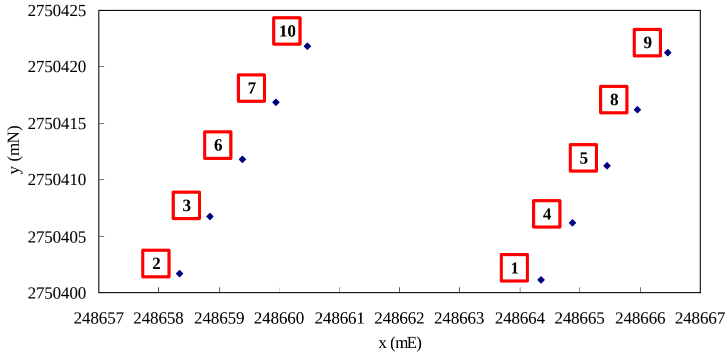

Figure 9: P3-AT Positions Rigid Pavement Slabs through VRS

CONCLUSIONS

This study puts forward the idea and framework of using mobile robots in pavement inspections. The two network-based and highly accurate VRS systems – the VRS by the Taiwan Control Signal Company Limited and the e-GPS (a real-time kinematic positioning system) from Taiwan's NLSC – were integrated on the platform of a P3-AT robot. Through the control of MVPL programs, after the completion of P3-AT's tire pressure tests and horizontal displacement calibration tests, the VRS's ability to provide the P3-AT with accurate positioning information was tested under both static and dynamic conditions whilst it traveled varying distances between 25 cm to 20 m. The standard deviation results of the static tests were all less than 0.03 m, and the RMS of the actual distances were all very close to the specified distances. Moreover, VRS can also direct the P3-AT along an accurate moving path under dynamic condition. This study deployed a P3-AT to locate distresses on the testing pavement, to conduct autonomous automatic monitoring and to plot rigid pavement slabs in order to prove that VRS technology can indeed provide a P3-AT with the highly accurate positioning data required whilst it moves around a specified area on pavements. The results show that the P3-AT is able to meet the positioning requirements in pavement inspection works.

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