（2）Crack are more likely to appear at these sections with soft soil underground and insufficient subgrade strength. The rheology in the soft soil underground, along with repeated compaction of traffic load over time, generates uneven settlement in the subgrade. This uneven settlement leads to structure destruction and cracks of the pavement. In the case of insufficient subgrade strength, the repeated action of traffic load cause tensile fatigue damage in the main stress layer of the pavement structure which leads to the transverse cracks in the pavement.

Table3. Comparison of cracks between soft soil section and non-soft soil section.

Section	Year	Number of track		Average crack space(m)	
FG expressway（soft soil1,6.73km）	2003	FG：0	GF：0	FG：——	GF：——
	2004	FG：19	GF：14	FG：880.5	GF：1195
	2006	FG：88	GF：76	FG：190.1	GF：220.1
	2007	FG：120	GF：102	FG：139.4	GF：164.0
FG expressway（non-soft soil,65.8km）	2003	FG：4	GF：4	FG：15500	GF：15500
	2004	FG：15	GF：7	FG：4133.3	GF：8857.1
	2006	FG：293	GF：160	FG：211.6	GF：387.5
	2007	FG：436	GF：389	FG：150.9	GF：169.2
YJ expressway（soft soil,21.3km）	2004	NT：4	TN：2	NT：5325	TN：10650
	2005	NT：33	TN：20	NT：645.5	TN：1065
	2006	NT：34	TN：30	NT：626.5	TN：710.0
	2007	NT：63	TN：77	NT：338.1	TN：276.6
YJ expressway（non-soft soil,45.3km）	2004	NT：5	TN：4	NT：9060	TN：11325
	2005	NT：18	TN：18	NT：2516.7	TN：2516.7
	2006	NT：32	TN：36	NT：1415.6	TN：1258.3
	2007	NT：38	TN：37	NT：1192.1	TN：1224.3

Note: Cracks in the table do not include those within 10m from constructs.

After the construction of semi-rigid base, all the five expressways appear to crack with average spacing of 20m. It can't be denied that cracks existed in the subgrade do not necessarily reflect to the pavement. But this situation would take place under the condition of low strength and small modulus subgrade.

(3) Temperature variation is a vital factor that contributes to cracks. Twelve samples were drilled to analyze in December, 2004, and all the cracks appeared to be small on the top and large on the bottom. When the percent of overload vehicles arrived at 100%, the integrated tensile stress on the bottom layer reached 3.27MPa and the cleavage strength ranged from 2.5MPa to 3.0 MPa at 0 centigrade. From which it can be seen that the bottom layer seems more likely to be destructed under the condition of low temperature and overload vehicles. Actually, from the substantive theoretical calculations in the subject that this paper relies on, that temperature stress is dominant in the pavement structure stress. On the other hand, survey that conducted on all the five expressways indicates that pavement transverse crack emerged primarily in winter.

(4) Traffic load is another factor that contributes to the pavement crack. Firstly, all the five expressways suggest that the number of cracks in the driving lane is much more than that in passing lane and parking lane. Secondly, pavement crack appears to be more in these sections with heavy traffic vehicles ; Thirdly, between the down direction and up direction at the same section, pavement crack varies due to different traffic load and proportion of heavy load. Cracks appear to be more at sections that has larger proportion of overload.

Table4. Influence of Traffic load to pavement crack.

Expressway name	Year	Average space of pavement transverse crack(m)		Note
FG expressway	2007	FG:100.9	GF:106.9	Traffic load and proportion of heavy load :FG>GF
YJ expressway	2007	NT:396.9	TN:403.2	Traffic load and proportion of heavy load :NT>TN
NJ airport expressway	2006	NG:47.1	GN:61.8	Traffic load and proportion of heavy load :NG>GN
LX expressway phaseII	2006	XL:545.9	LX:870.7	Traffic load and proportion of heavy load :XL>LX
NSX expressway	2006	NS:522.6	SN:440.5	Traffic load and proportion of heavy load :SN>NS

(5) Proper choice of mixture constitutes will contribute to relieve the severity of crack. Lime fly-ash aggregate base and cement stabilized aggregate base were ever widely used in Jiangsu provinces. As presented before, cracks seem to be more severe in

these sections with lime fly-ash aggregate base than sections with cement stabilized aggregate base. This signifies base mixture has an effect to the formation of cracks.

(6) Insufficient strength of pavement structure exerts a negative effect. When stiffness and strength of pavement structure (including surface course and base course) is insufficient, cracks are easily occurred under the repetitive action of traffic load. For example, cracks on partial sections of FG expressway, NJ airport expressway, and NSX expressway appear in pairs, and the interval of two parallel cracks is less than five meters. This is mainly due to the stiffness and integrity of the pavement structure suffered from the emergence of cracks, which result in new fracture failure near original cracks under the condition of dynamic load.

(7) Construction quality and construction timeline are both critical factors for crack prevention. Reflective cracks are detected on several sections due to the variation of construction quality. Moreover, the construction climate also exerts an influence on the life span and using character of pavement, as well as the construction quality. This paper shows that the influential factors and their influential extent on semi-rigid base reflective cracks never come to the same case when the construction is executed on different location and different time, by different construction team. Different place refers to the circumstances such as the temperature, traffic load, the strength of road structure subgrade varying from one location to another. Different time indicates the influence of different construction time. While the quality and proficiency of construction team determines the construction quality.

Therefore, since the various influential reasons exist in different terrain, it is reasonable to analyze the factors under the situation.

DEVELOPMENT RULES OF PAVEMENTTRANSVERSE CRACK (INCLUDING REFLECTIVE CRACK)

The results of the survey also reveal the following laws of pavement transverse cracks of expressways by the in-depth survey and analysis of operation condition.

(1)The appearances of cracks from expressway pavements have peak period but differs from one expressway to another. This shows that different pavement may experience a large scale of cracks unexpected under various working environment. These differences of environment conditions include geographic location, climatic condition, structure strength, subgrade strength, traffic flow and so forth. The same conclusion will be drawn even in the locations that measures have been taken for reflective cracks prevention. For instance, seven methods were applied in the test sections of FG expressway to deter the occurrence of reflective cracks. However, after opening to traffic for six years, many cracks are found in these test sections. The emergence of these cracks happens at a different time for the same road section, which is mainly dependent on the environment conditions.

(2) By the time sequence, the cracks initially arise near structures, and then comes to soil subgrade and finally the non-soft underground sections (partly overlaps may occur among the three steps). When the construction of pavement is finished, the road structures are supposed to keep at the same elevation with road section. However, the

material property differs from road structures, soft soil sections and non-soft soil sections. Furthermore, variations of material property and temperature as time goes on, together with the traffic load, are all contributing to the uneven settlement cracks near the road structures. The soft soil sections, non-soft soil sections and the joints between them are other locations that may come to crack. It should be pointed out that cracks in the non-soft soil sections is a type of fatigue crack that mainly caused by the variations of traffic load and temperature.

Cracking Prevention Strategy Recommendation

Based on the survey that conducted on the five expressways, several recommendation are given in this paper in order to prevent the reflective cracks.

(1) Anti-reflective cracks measures that can be used in the process of pavement structure design. First, it would be better to reduce the number of the road structures to an extreme. Second, different structure proposal can be used in road design when there is a great difference of traffic volume between two traveling directions. Third, distinct structure design can be used from soft underground section to non-soft underground section. Fourth, in the transitional parts between soft underground section and non-soft underground section, propel transient mode should be taken in the pavement structure design and underground treatment for the purpose of reducing uneven settlement. Sufficient compaction of the pavement near the section of pavement structures is also encouraged, which could increase the density of the pavement material and the strength overall. Finally, new road structure project is supposed to be studied and put into practice, such as rigid-base asphalt pavement. Actually, a study related to long life pavement structure at YJ expressway revealed that three types of pavement structures (D, E1, E2, see in Table 5) have relatively low cracks ratio despite of the relatively high traffic volume. These three pavement structures, which can be seen as long life pavement structure, are also suitable in preventing reflective cracks. The study provides a good way in selecting pavement structure with its ability to t prevent the reflective cracks.

(2)

Table5.Three types of pavement structures of YJ expressway.

D	E1	E2
4cm SMA-13 6cm CDAC-20 8cm CDAC-25 18cm ATB-25 9cm FDAC-10 16cm graded aggregate 15cm lime-fly ash stabilized soil subbase 80cm lime stabilized soil subgrade	4cm SMA-13 6cm CDAC-20 26cm CRCP 1cm asphalt sand sealed layer 20cm cement stabilized macadam 20cm lime-fly ash stabilized soil subbase 80cm lime stabilized soil subgrade	6cm SMA-13 24cm CRCP 1cm asphalt sand sealed layer 26cm cement stabilized macadam 20cm lime-fly ash stabilized soil subbase 80cm lime stabilized soil subgrade

Note:
SMA-13: Stone mastic asphalt pavement with the Nominal maximum aggregate size 13mm;
CDAC-20: Coarse aggregate asphalt concrete with the Nominal maximum aggregate size 20mm;
FDAC-10: Fine aggregate asphalt concrete with the Nominal maximum aggregate size 10mm;
CRCP: continuously reinforced concrete pavement;
ATB: Asphalt treated base.

(2) The proper pavement material should be used to reduce the number of cracks . Considering the influence of temperature variation, two points should be taken into account in the process of pavement material selecting. On one hand, temperature variation among different areas ought to be taken into consideration during the process of pavement structure design. On the other hand, in order to reduce the large effect of temperature on cracks, materials that are not sensitive to temperature are expected to be taken into prior consideration.
(3) The appropriate preventive measures should be taken to reduce the number of cracks. The measures used in preventing reflective cracks are supposed to on the basis of mechanical theory. When taking different preventive measures, design target that adopted should better lie on the long-term service life and pavement performance instead of demanding initial effectiveness.
(4) Proper pavement construction season and high construction quality will result in relatively less cracks. Construction during unfavorable season should be avoided which is critical to avert the development of cracks. Moreover, the construction quality of road structures should be strictly controlled to reduce the variation of pavement structure mechanical and material control parameters between laboratory and field detections. Finally, proper measures should be adopted to protect the base after the construction of semi-rigid base, which will definitely benefit to diminish early-stage shrinkage cracks or cracks in winter.
(5) Road maintenance is critical in preventing the growth of reflective cracks. The treatment of the existing cracks of asphalt pavement in Jiangsu province mainly consists of notch and filling with modified asphalt. However, this technology carries with it some drawbacks. It requires good bond behavior between crack filling material and pavement. Properties such as ductibility and temperature stability are also essential for the crack filling material. Therefore, this kind of technology is nothing but an expedient measure.

CONCLUSIONS

In summary, the following conclusions can be made:
(1) The main influence factors of road transverse cracks (including reflective crack) are summarized in this paper. It should be noted, however, that the influencing extent of these factors varies from construction team, construction sections and construction time. Pavement designers are expected to analyze the characters of locations where road located, find the most adverse factor and tackle it with proper measures.

(2) Cracks of asphalt pavement using semi-rigid base have a peak period.
(3) In sequence cracks initially arise near structures. The next comes to soil subgrade and eventually the non-soft underground sections (partly overlaps may occur among the three steps).
(4) Pavement transverse cracks (including reflective crack) emerge mainly in winter.
(5) Density of pavement transverse crack (including reflective crack) in soft soil sections is higher than these non-soft soil sections.
(6) Taking different preventive measures is an effective way to reduce the number of pavement transverse crack (including reflective crack) and retard their development.

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The Use of a VRS-Based Pioneer 3-AT Robot in Assisting Pavement Inspections

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ABSTRACT: This study proposes the idea of using robots in pavement inspections and 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 two testing sites constituted in the study were 60 km apart, one of which was a rigid pavement and the other, a flexible pavement. The tire pressure and the horizontal movement of the P3-AT were calibrated. The accuracy of positioning data provided by VRS to the P3-AT was investigated 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. The results show that VRS can provide the P3-AT with accurate positioning data regardless of pavement types and VRS systems. This study also demonstrated 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.

INTRODUCTION

The surface conditions of pavements 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. Considering the advanced developments and capabilities of robots, this study proposes the idea of using robots in pavement inspections for some specified areas (such as an airport) and particular purposes (such as the QC/QA control). A Pioneer 3-AT (P3-AT) autonomous robot was integrated with a high-accuracy positioning technology, the virtual reference station (VRS), in the study to examine the feasibility of pavement inspection robot. The inspection tasks were demonstrated using the P3-AT to verify that the accuracy of positioning data provided by VRS to P3-AT is adequate enough for pavement inspections.

THE FRAMEWORK FOR PAVEMENT INSPECTIONS WITH AN AUTONOMOUS ROBOT

The general framework for a pavement inspection system (PIS) is configured as shown in Figure 1(a). The conveyer (such as a vehicle) carries various inspection instruments and is controlled by an inspector to collect pavement data. An autonomous robot consists of three parts including a sensor unit, an actuator unit, and a logic unit (Kilner et al. 2002), as shown in Figure 1(b). The sensor unit works using instruments, such as an ultrasonic, a laser range finder, image capturing equipment, and an odometer in the PIS. The actuator unit (Arimoto 1990) is responsible for the robot's motions and works as a conveyer in the PIS. The logic unit has computational power, which is similar to data analyses modules in the PIS. One autonomous robot framework for pavement inspections is proposed as in Figure 1(c). The sensor unit of the robot is combined with pavement inspection instruments and mounted on the robotic platform. By integrating the results from the logic unit and pavement data analyses, the robot is capable of intelligently planning its future behavior.

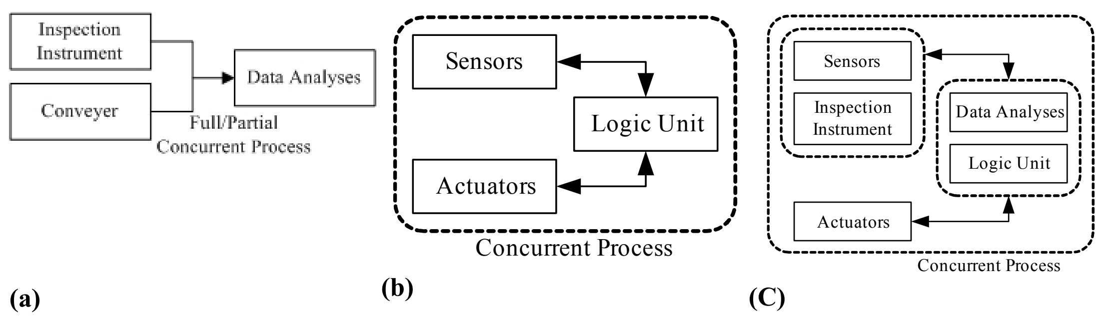

FIG. 1. The systematic framework: (a) present PIS; (b) autonomous robot; (c) autonomous robot framework for pavement inspections.

VIRTUAL REFERENCE STATION (VRS) SYSTEM

For accurately positioning the robot on pavements, a positioning system with high accuracy (to the nearest centimeter) is extremely necessary. The concept of the virtual reference station (VRS), also called network real-time kinematic (RTK), is one of the more feasible approaches to overcome the limitations of standard RTK positioning in conjunction with global positioning systems (GPS) (Martin et al. 2009, Rolbiecki and Lyle 2008, Wei et al. 2006). This approach 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 2 (Trimble

2005). Figure 3 shows the architecture for linking the control centre to the user receiver (Hu et al. 2002). In this study, Leica's GPS VRS system was equipped on a P3-AT robot. 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 developed by the Taiwan Control Signal Company Limited (CSCL 2010), and the other was the Virtual Base Station Real-Time Kinematic (VBS-RTK), also called e-GPS, from Taiwan National Land Surveying and Mapping Center (NLSC 2009). A comparison of the two VRS systems is summarized in Table 1.

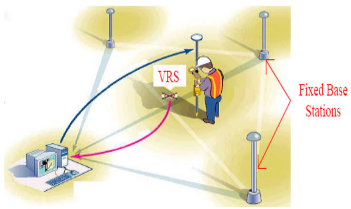

FIG. 2. VRS network operation (Trimble, 2005).

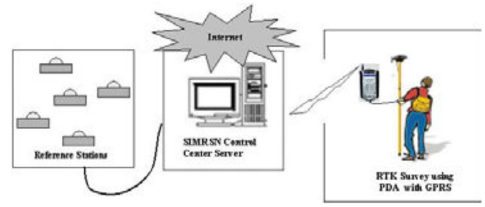

FIG. 3. The architecture of VRS system via GPRS (Hu et al. 2002).

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

Item / VRS System	Reference Stations	Range of Services	Owner	Payment	Convergence Time
e-GPS	76	Taiwan	nation	USD 10/day	Relatively fast
CSCL	11	North Taiwan	private enterprise	Nil	Relatively slow

P3-AT HARDWARE CONFIGURATION AND CALIBRATION TESTS

The P3-AT (Figure 4) is manufactured by MobileRobots Inc. and is equipped with an onboard Pan-Tilt-Zoom (PTZ) camera system, SICK laser, eight front and eight rear sonars (MobileRobots Inc. 2010). The Microsoft Visual Programming Language (MVPL) in Microsoft® Robotics Developer Studio (MSRDS) (Microsoft Corporation 2010) was used to program the P3-AT operation, as shown in Figure 5. A Leica SR530 GPS receiver and an IBM X61 notebook was mounted on the P3-AT in this study. The VRS software (SpiderNET) in the notebook connects to the control center through a 3.5 G HSDPA using programs designed in MVPL and sends back corrected data to the P3-AT in real time so that it can possess accurate autonomous movements.

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 (10, 20, 25, 30, 40, 50 psi). The 50 psi is the upper limit for P3-AT's tire pressure. The actual distance travelled by the robot was then measured and compared against the specified value of 500 cm. At a tire pressure of 25 psi, the actual travel distance is the closest to the specified distance of 500 cm.

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, 100, 300, 500 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 indicate that, under a fixed tire pressure of 25 psi, the actual travel distances are very close to specified distances regardless of rigid pavement and flexible pavement. Therefore, it is concluded that the P3-AT can move according to specified distances correctly in the tests afterwards.

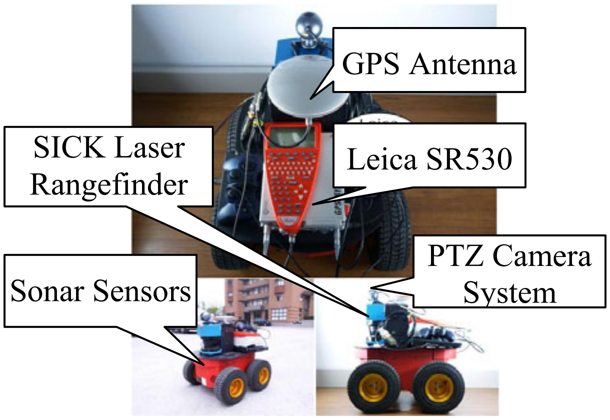

FIG. 4. The MobileRobots P3-AT hardware architecture.

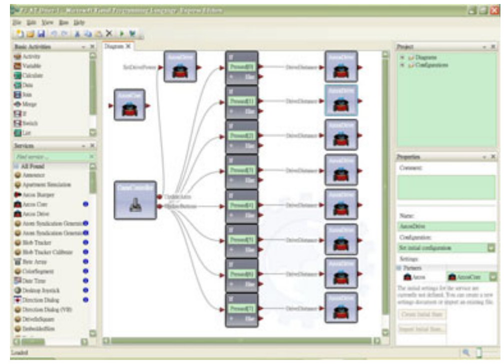

FIG. 5. The MVPL in MSRDS for P3-AT's control.

TESTING THE VRS-BASED P3-AT

Test Sites

The study was carried out on two test sites, as shown in Table 2. One of which was a flexible pavement in MingHsin University of Science & Technology (MUST) (Figure 6(a)) and the other was a rigid pavement in National Taiwan University (NTU) (Figure 6(b)). The experimental design for testing the accuracy of P3-AT's positioning provided by VRS is shown in Table 3. By choosing this two test sites, the following could be investigated:

- VRS qualities at different locations: The two sites are 60 km (36.93 miles) apart which far exceeds the 10 km's optimum working range of RTK.
- Differences in terrain: mesa (MUST) vs. basin (NTU)
- Differences in pavement type: flexible pavement (MUST) vs. rigid pavement (NTU)
- Differences in the two kinds of VRS system: CSCL vs. e-GPS

Table 2. A Comparison of Test Sites in MUST and NTU

Item / Site	Location	Terrain	Pavement Type	CSCL	e-GPS	Latitude and Longitude
MUST	Hsinchu	Mesa	Flexible	Receivable	Receivable	N 24°85'97.47" E 120°98'80.76"
NTU	Taipei	Basin	Rigid	Receivable	Receivable	N 25°01'80.41" E 121°54'71.15"

Static Testing

The P3-AT was made to move autonomously 5 specified distances of 0.25, 1, 3, 5 and 10 on both the rigid and flexible pavement stopping after each move. Fifteen measurements were taken for every distance travelled. 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 the VRS positioning data in static