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# A real-time monitoring system for lift-thickness control in highway construction

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ABSTRACT

Monitoring and controlling lift-thickness are critical in pavement construction, because lift-thickness can affect the durability and long-term performance of pavement. Existing methods for measuring lift-thickness are not sufficient due to four limitations. First, the reliability of manual measurements is questionable, since manual measurements can only be conducted at sparse points instead of entire pavement surface. Second, the accuracy of lift-thickness measurement is not satisfactory. For instance, the string-line method and balance beam system are unable to achieve millimeter-level accuracy. Third, current techniques cannot indicate the accurate positions of weak areas where the lift-thickness is not compliant with construction standards. Fourth, the agency and supervisor cannot monitor lift-thickness remotely in real time with current techniques. To overcome the above limitations, this study created a novel system that integrates inclinometer, robotic total station, laser ranging sensors, and wireless communication technologies to monitor lift-thickness during highway construction. The elevations of datum plane and the layer being paved can be accurately obtained using this system. Lift-thickness then is measured in real-time as the difference between the elevations. Visualization of weak areas, warning messages, and monitoring reports are synchronized among the operator, contractor, supervisor and agency, guiding them to adjust operations and to ensure paving quality. Field applications demonstrated that this newly created system could monitor lift-thickness in an automatic, accurate, continuous, and real-time manner. In addition, the operator, contractor, supervisor and agency could access the information of construction quality simultaneously; and thus work closely to resolve quality issues in time. This system facilitates an integrated quality control mode that is suitable for the construction industry.



## 1. Introduction

Monitoring lift-thickness is a critical quality control practice in pavement construction, because lift-thickness can affect the durability and long-term performance of pavement. Well-controlled lift-thickness allows desirable density levels to be achieved more efficiently [1,2]. Non-compliance of lift-thickness with construction standards leads to accelerated pavement deterioration.

Existing methods for measuring lift-thickness are not sufficient due to four limitations.

(1) Manual measurement and visual inspection are unproductive and error-prone. According to the Chinese specification [3], field inspectors are required to measure lift-thickness at random points using a steel rule. This method, although simple and cost-effective, is unreliable and can easily result in non-uniform lifts because of limited samples collected and various disturbances to inspectors in construction sites.
(2) The accuracy of lift-thickness measurement is not satisfactory. For instance, the string-line method [4–6] and the balance beam system [7] cannot achieve millimeter-level accuracy. Moreover, the lift-thickness between control points of string lines is difficult to control. In balance beam system, the lift-thickness can only be accurately measured when the elevations of the front and rear ends of beam at datum plane are consistent. However, this condition is difficult to maintain during pavement construction.
(3) Current practice is not capable of indicating the weak areas where the lift-thickness is not compliant with construction standards. This is because most existing techniques are not equipped with accurate real-time positioning systems. Lack of positioning information renders quality assessment and subsequent reworking inefficient and ineffective.
(4) The agency and supervisor cannot monitor lift-thickness remotely in real time with current technologies, which has seriously hampered the quality management in construction. In China, the agency and supervisor are the main entities to monitor and

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control lift-thickness in pavement construction, because most often the contractor and machine operator are not incentivized to do so. Without real-time feedbacks, it would be too late for the supervisor and agency to identify a defect and to request the contractor to correct it.

There is a critical need to address the aforementioned limitations. This study aims to create an automatic, accurate, continuous, and real-time system for monitoring lift-thickness in highway construction. This system provides rich information regarding lift-thickness for all the stakeholders involved in pavement construction, which helps the agency and supervisor identify weak areas and assists contractor and operator in adjusting operation and reworking on the defects.

## 2. Related studies

A number of pilot studies have been conducted to monitor and control lift-thickness in highway construction. Makio et al. [8] invented a device to automate the control of pavement thickness and the leveling machine during construction. Yon [9] devised an apparatus for automatically controlling operation of a slip-form paver to maintain a constant mold position relative to a string line while changing the cross slope of the mold. Peyret et al. [10] used real time kinematic (RTK) global positioning system (GPS) to locate the paver. Hence, the elevations of the spreading of sub-base and base layer can be controlled to comply with the altitudes and cross-slopes prescribed by the design. Walters and Jaselskis [11,12] and Cable et al. [13] proposed to integrate laser scanner and RTK GPS to measure and monitor lift-thickness during pavement construction. Laser is used to scan the surface of the base prior to paving and the surface after paving. Consequently, lift-thickness at any point can be estimated as the difference between the elevations before and after paving. In addition, the thickness variance can be calculated and the areas where the thickness is below requirement can be identified. This method is capable of monitoring and controlling lift-thickness continuously and automatically. However, one basic limitation with this method is the unsatisfactory accuracy of GPS. RTK GPS can only achieve centimeter-level accuracy. The vertical accuracy is especially suspicious. In China, the lift-thickness for each layer varies from 3 cm to 15 cm. The tolerance is usually 10% of the lift-thickness. Hence, GPS is not well suited for lift-thickness monitoring and control. Leica Geosystems [14] utilized multiple intelligent total stations to locate and track the slip-form paver during highway construction, which enables the automatic control of lift-thickness. However, multiple prisms are required to be set up manually, which is not convenient in construction sites.

Non-destructive methods are also used to measure pavement thickness. For instance, Nazarian et al. [15] used the spectral analysis of surface waves (SASW) method to determine the thickness of pavement. Glemena [16] utilized impact-echo method to measure the thickness of new concrete pavements. Grote et al. [17] and Al-Qadi et al. [18] used ground penetrating radar (GPR) to measure the layer thickness of pavement. Grove et al. [19] determined the thickness of concrete pavement in a nondestructive manner using magnetic pulse induction. Guralnick et al. [20] utilized image-processing algorithms to obtain the profile of pavement surface automatically, and to analyze the pavement surface quantitatively. However, these technologies are primarily used to evaluate highways after paving. It is difficult to apply them directly to measure lift-thickness during pavement construction.

This research integrates robotic total station (RTS), laser ranging sensors, Zigbee communication, and general packet radio service (GPRS) to create a real-time system for monitoring and controlling lift-thickness in high-grade highway construction. These technologies have been widely used to facilitate the automation of construction activities. Laser ranging technique estimates the distance based on the two-way time of light traveling from the device to the surface of an object and back to the device. The rationales of using laser ranging sensor lie in its high accuracy and short sampling time [21,22]. Robotic total station has a higher accuracy and precision than GPS for locating and tracking objects in construction sites [23–25]. Yakar et al. [26] built digital elevation models based on the data collected by robotic total station instruments. Shen et al. [27] located, tracked, and measured the orientation of tunnel boring machine in tunnel construction using robotic total station.

## 3. Methodology

In this study, a real-time lift-thickness monitoring system is devised to address the aforementioned limitations in current practice. This system consists of four main components: elevation data collection module, database and application servers, real-time monitoring client, and warning device, as illustrated in Fig. 1.

This system utilizes robotic total station (RTS) to continuously track the position of a platform-cart that connects and moves simultaneously with the paver. Laser ranging sensors mounted on the platform-cart can capture the distance to the road surface. General packet radio service (GPRS) is employed to communicate the collected data to the database and server. These data are processed to obtain the elevation of the layer being constructed and the datum plane of pavement. The lift-thickness of the entire pavement surface is estimated based on the digital elevation models and monitored remotely via the client. Warning messages will be issued to the client and the portable android device (PAD) in the field, if lift-thickness is not compliant with construction standards. This enables a feedback control mechanism of lift-thickness to ensure paving quality.

### 3.1. Monitoring method

Fig. 2 illustrates the procedure of monitoring lift-thickness in construction sites. There are four steps as detailed below.

(1) Monitoring preparation
The equipment needs to be configured in the construction site. The equipment includes robotic total station, prism mounted on the platform-car, laser ranging sensor, inclinometer, integrated controller, PAD, GPRS, and data transfer unit. The communications between the equipment should be tested.

(2) Datum plane establishment
Prior to monitoring, a triangular irregular network (TIN) model should be built for the datum plane. First, the datum plane is established based on surface coordinates and its attributes are determined. Thereafter, the platform-cart is set up in the construction site and its parameters are tuned. Data acquisition starts if command is sent to activate the datum plane; the collected data are then used to establish the elevation model of datum plane.

(3) Lift thickness monitoring.
In this step, the attributes of the layer being paved are first determined. The controlling standard of lift-thickness is then set by users. Subsequently, the platform-cart is set up and its parameters are tuned. Lift-thickness monitoring starts if command is sent to activate the paving process.

(4) Results reporting
Supervisors use the monitoring client to inspect lift-thickness during the paving process. Real-time monitoring results are generated, which include visualization and textual reports of the lift-thickness through the pavement cross section and along the paving trajectory.

### 3.2. Real-time road elevation measurement

#### 3.2.1. Data collection

Life-thickness is estimated as the difference between the elevation of the road surface being constructed and the elevation of the datum