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A THERMAL-BASED TECHNOLOGY FOR ROLLER PATH TRACKING AND MAPPING IN PAVEMENT COMPACTION OPERATIONS

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ABSTRACT

Compaction is one of the most important phases in construction of asphalt concrete (AC) pavements, as it directly affects the density and thereby the performance of pavements. This paper proposed a thermal-based compaction technology for real-time roller path tracking and mapping in pavement compaction operations, based on which roller operators can better control their compaction quality. In the proposed method, the incremental change of a roller position in a short interval was decomposed into two motion components (i.e., the change in heading direction and the linear translation). The global position of the roller was then recovered by chaining the frame-by-frame motion in terms of their changes. Two sets of experimental data from different pavement construction sites were used to test the performance of the proposed technology. The results showed that the developed technology is a promising alternative to the current GPS-based intelligent compaction (IC) in pavement compaction operations.

1 INTRODUCTION

Compaction is considered as the last and possibly the most important phase in quality control associated with constructing asphalt pavements (Yoon et al. 2018). Both under rolling and over rolling can lead to poor performance of a pavement, so proper rolling is critical to providing the desired performance and intended service life of the pavement. In order to achieve a proper rolling, a common practice is that the trained operators operate the roller over a designed rolling pattern including the predetermined number of roller passes, the starting and the end point of each pass, and the total number of coverages. However, human errors inevitably involve in the roller operations and consequently lead to a deviation between the executed routine and the planned pattern (Chang et al. 2011). This deviation has a high possibility to cause some improper-compacted longitudinal areas that will degrade quickly within a short period.

Intelligent compaction (IC) is an emerging technology that can overcome the above limitations and be used to improve compaction quality performance (Mooney et al. 2010; Gallivan et al. 2011; Savan et al. 2016; Imran et al. 2018). Generally, IC refers to an improved process that uses rollers equipped with a measurement system that consists of a highly accurate global positioning system (GPS), accelerometers, infrared thermometers, and an onboard computer reporting system. Since IC shows several superiorities over the conventional compact process in quality control and documentation recording, the recent two decades have witnessed an increasing amount of felid applications of IC technology in pavement constructions (Liu et al. 2019). Nevertheless, there still exist some drawbacks associated with implementation of the IC technology, which make the contractors and the highway agencies hesitate to adopt this technology. The first one is the high equipment cost. Generally, retrofitting an existing roller with an IC system will cost about $100,000, in which the GPS has a large portion of shares (Savan et al. 2016). The cost is untrivial to contractors and oftentimes will increase the construction estimation. The second one is the restrained applicability of the GPS-enabled technology. In case that the radio line of sight between the GPS and the base station is disturbed, which is the often case in mountain and rural areas or the roller distance to the base station exceeds two miles, the precision of the GPS receiver will degrade drastically. Consequently, the system requires effort on the ground to relocate and reset the reference station once it is out of reach. These hurdles impede GPS-based IC been extensively applied in the field, and a low-cost alternative would be desirable.

Inspired by the principle of visual odometry (Campbell et al. 2004; Scaramuzza and Siegwart 2008; Yang et al. 2019), this paper proposed a thermal-based technology as an economical alternative to GPS-based IC for roller path tracking and mapping. The proposed technology can not only provide the location of the roller in real time but also generate a color-coded map that helps operator count the number of passes. The main benefits of choosing the thermal (IR) camera instead of a regular camera are that 1) the IR camera can eliminate the unfavorable factors in pavement construction environments such as smog and water vapor; and 2) the IR camera can detect the clear boundary information of pavement due to the temperature difference between the hot mix asphalt pavement mat and the environment background, which is valuable information upon which the heading direction estimation can be built as explained later.

The remainder of this paper was organized in five sections, i.e., algorithm development, system setup, performance validation, discussion, and conclusion and future work. In the first section, the algorithm development was presented in which the focus was on recovering the global position of the roller by chaining the frame-by-frame motion. In the second section, the hardware setup for this technology was illustrated. In the third section, two experiments in different pavement construction sites were conducted to test the performance of the proposed technology. In the fourth section, discussion was made on the limitations of the developed technology. Finally, conclusions and future work were presented.

2 ALGORITHM FOR ROLLER TRACKING AND MAPPING

The overview of the algorithm development for the roller tracking and mapping is presented as follows. At a selected interval between two consecutive frames, the roller's motion is decomposed into two motion components – the change of heading direction and the linear translation. To estimate the change of heading direction, a geometric model of projective transformation is established and the relationship between the change of heading direction and the location of the vanishing point is utilized. To estimate the linear translation of the roller on the pavement surface, the flow vector in the image plane is first obtained with the help of optical flow technique (Bouguet 2005), and then the translation component of the roller is determined by projecting the flow vector onto the ground plane using the projective relationship between the image plane and the ground plane. Finally, by combining these two motion components, the global estimate of roller position is recovered by chaining frame-by-frame change of the roller positions. The details of the algorithm are described in the following sub-sections.

2.1 The geometric model of projective transformation

The geometric model of projective transformation employed in this proposed technology is depicted in Figure 1. π_I and π_G correspond to the image plane and the ground plane, respectively. O_i is the principal point of the image plane, which can be determined by camera calibration. O_c is the center of projection (COP) of the camera. V is the intersection of two imaged boundaries in the image plane. Since the left boundary is parallel to the right boundary in the ground plane, V is also called vanishing point. Under this condition, φ corresponds to the deviation angle of the roller driving direction with respect to the road direction. θ is the angle between the optical axis and the ground plane. f is the focal length. Line PV and line PO_i are parallel to the x-axis and the y-axis of the image plane, respectively.

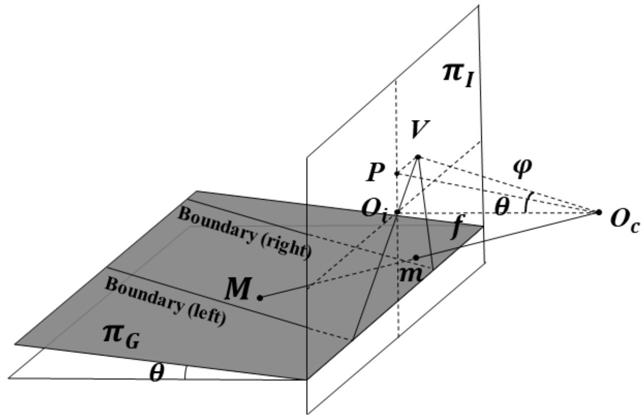


Figure 1: The geometric model of projective transformation.

Given an object point $\boldsymbol{M}$ on the ground plane, projection of this point through the camera lens will lead to its corresponding point $\boldsymbol{m}$ on the image plane. Their relationship can be expressed as:

$$s\boldsymbol{m} = \boldsymbol{HM} \tag{1}$$

where $\boldsymbol{m} = [x \quad y \quad 1]^T$; $\boldsymbol{M} = [X \quad Y \quad 1]^T$; s is a scale factor; and $\boldsymbol{H}$ represents the transformation relationship between the image plane and the ground plane. Since $\boldsymbol{H}$ is defined up to scale, namely there are actually eight independent ratios amongst it, this projection matrix can be determined by at least four-point correspondences in a general condition with help of the DLT method (Zhou et al., 2020).

2.2 Estimating the change of heading direction of roller

To estimate the change of heading direction of roller, i.e., φ in Figure 1, we leverage the location information of vanishing point in the image plane. According to Jung and Kelber (2005), the vanishing point of two parallel road boundaries that are near the vehicle location can be easily obtained from the boundary information in the near region of the image plane next to the vehicle, considering that the boundary in this region can be approximately considered as a linear model. Figure 2 illustrates this strategy, in which the image plane is divided into two parts, i.e., the distant region and the near region, and the boundary in the near region can be further used to derive the vanishing point in this selected frame. To this end, the parameters of both straight boundaries (left and right) in the near region will be identified with the help of Hough transform, and the corresponding boundary models will be established as such. Then, the location of the vanishing point can be found in the intersection of two established linear models in the image plane, as shown in Figure 2 (point V). Once the coordinates of vanishing point are known, according to the geometric relationship presented in Figure 1, the change of heading direction of roller with respect to the road direction in a selected frame can be obtained as:

$$\varphi = atan\left(\frac{x_v - x_i}{\sqrt{f^2 + (y_v - y_i)^2}}\right) \tag{2}$$

where $\mathrm{atan}(\cdot)$ is the inverse trigonometric function; (x_v, y_v) is the coordinates of the vanishing point; and (x_i, y_i) is the coordinates of the principal point O_i.

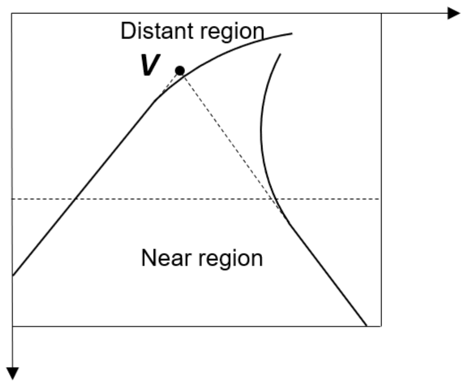


Figure 2: The delimitation of the near and distant region.

It is worth mentioning that the definition of the heading direction in our method is somewhat different from the traditional definition in visual odometry or SLAM. In our method, the heading direction of the roller is significantly connected with the road direction by taking the road direction as the reference direction. Namely, there is no change in heading direction while the roller is precisely driving along the road center regardless of either a straight road or a curved road; the change of heading direction only happens when the driving direction deviates from the road direction. In the case of roller tracking and mapping, it is essential that we concentrate on the local position of the roller relative to the layout of the pavement rather than the global position in the environment. As a result, the developed method for estimating the heading direction is reasonable and pragmatic.

2.3 Estimating the translation of roller

To estimate the translation of roller, we first extract visual features in thermal images by applying Fast (features from accelerated segment test) corner detector. In consideration of the low context in thermal images, we use a low corner threshold (0.0005) and specify a small distance (10×10 pixels) between features. This helps uniformly detect features across thermal images. Then, we obtain the flow vector from two consecutive frames by applying the optical flow technique. In order to eliminate the external elements from the background such as moving vehicles and people that will lead to disruptive components in the flow vector, only components extracted from the near region are utilized for further analysis. Next, the flow vector is back projected onto the ground plane with the help of the projection matrix between the image plane and the ground plane. By doing so, the motion vector can be established, in which each component corresponds to the actual translation of the roller within the short interval between two consecutive frames. In an ideal condition, the components in the motion vector are identical displacement. However, due to the measurement error and the side-effect of disruptive components in the flow vector caused by setting a low corner threshold, the motion vector can be perturbed. To eliminate the unfavorable effect, this study averages the translation components in the motion vector, and the mean value serves as the translation of the roller in the proposed method.

2.4 Estimating the position of roller

After obtaining the changes of the heading direction and the linear translation of the roller from two consecutive frames, the position of the roller on the ground plane in the current frame can be derived based on its location in the previous frame. Finally, the global position of the roller can be determined by cumulating the frame-by-frame motion.

3 SYSTEM SETUP

Figure 3 shows an illustration of the whole platform employed in our developed technology, which consists of an infrared camera, a digital video recorder, a display screen and a laptop. The infrared camera is an inexpensive IR camera (FLIR PathFindIR) with a resolution of 704×480 pixels. The maximum FOV of camera are 24^o and 18^o in the horizontal and vertical direction, respectively. The maximum frame rate is 30 fps. The focal length is 19 mm. The IR camera is mounted on the top of the roller with the help of a triple suction cup camera mount, which is in corresponding to the center of rotation of the roller in order to precisely record the motion of roller. In addition, the x-axis of the image plane is manually aligned to the horizontal direction of the ground plane. The thermal video stream data captured from the IR camera are continuously transferred to the digital video recorder – Safety Vision DVR Model SVR 4100, which is wirelessly linked to a laptop for further data process in a real-time manner. Then a color-coded plot that contains the location of the roller and the number of roller passes is back transmitted and displayed on the display screen in front of the operator.

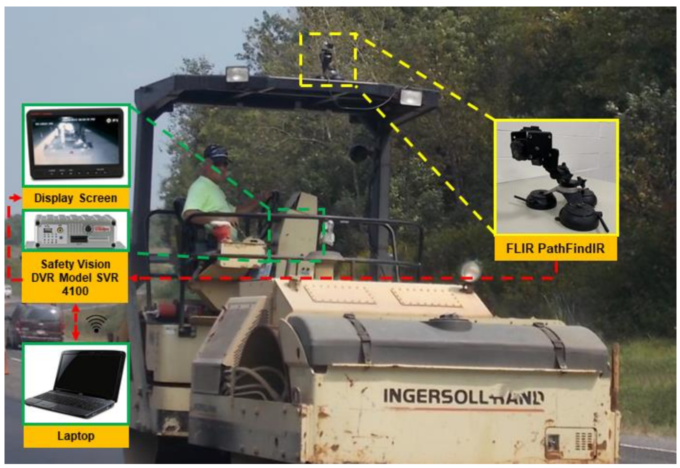


Figure 3: System setup.

4 PERFORMANCE VALIDATION

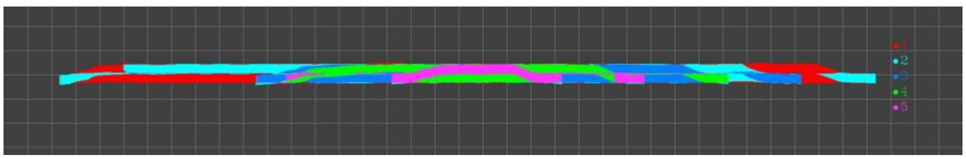
Two field experiments were conducted in different pavement construction sites to initially evaluate the performance of the developed technology for roller path tracking and mapping. The detailed information is listed in Table 1. In order to eliminate the effect of lens distortion, the IR camera was intentionally calibrated before each task. After the calibration, the IR camera worked uninterruptedly at a frame rate of 15 fps. The camera parameters in each task are summarized in Table 2. By testing the developed technology, the roller positions and the rolling paths in two different construction scenarios were obtained in real time. The resulting all-passes and color-coded data are presented in Figure 4, in which the different color corresponds to the different number of passes. Intuitively, two satisfactory rolling paths were obtained from the developed technology except for a small portion located on the left side of the rolling pattern, as annotated by a dashed box in Figure 4 (b). After checking the raw thermal data, this abnormal phenomenon mainly occurred when the roller was reaching the end of the layout of the pavement, namely the boundary information disappeared in the FOV of the camera. Consequently, the motion component, i.e., the heading direction, was invalid during this period. In the time when the IR camera can continuously capture the boundary, the roller tracking process remains stable and satisfactory. It visually helps verify the validity of this developed technology to some extent.

Table 1: Summary of field demonstrations.

Site	Location	Date	Materials/Construction	Test duration
1	I-68E MP 24	09/10/2019	HMA new construction	13 min
2	US 50W, WV	10/14/2019	HMA new construction	5 min

Table 2: Camera internal parameters.

Site	Principal point (pixel)		Focal length (mm)
	x_i	y_i	
1	349.266	245.263	19.125
2	348.589	246.158	19.231



(a) I-68E MP 24

(b) US 50W, WV

Figure 4: Color-coded pass coverage and counts.

In the two pavement construction sites, the pavements were separated into two lanes for compaction. According to the designed rolling pattern, the roller operator was required to drive straightly along one working lane and turn to the other lane when the operator was planning to change the movement from a back-or-forth rolling motion. The rolling operation kept up with such paving operation pattern until a required number of roller passes had been achieved. Under this situation, it was expected that there are a proper number of roller passes that are uniformly along with the mat. To examine this, a proof mapping containing only a randomly selected pass-coverage layer (first layer) from the first pavement construction site was extracted (as shown in Figure 5). By checking the experimental parameters, it shows that the drum width of the roller was 1990 mm and the width of the pavement was about 4000 mm. In combination with the designed rolling pattern, the performance of our developed technology could be verified from the result in Figure 5, in which the roller passes recorded from the one cycle of back-and-forth operation are distinctive and close proximity to each other.

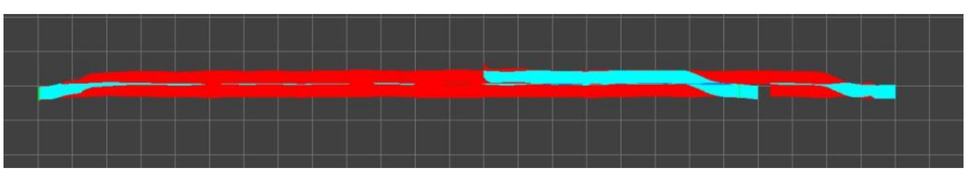
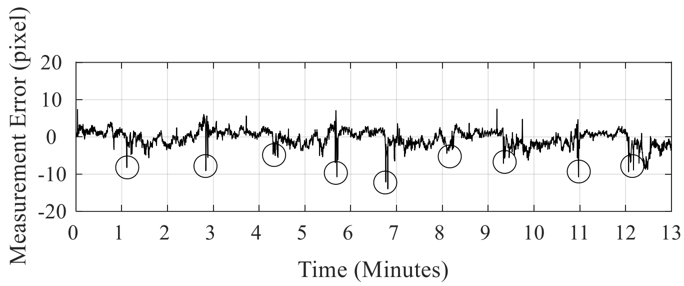


Figure 5: A typical proof-mapping from the first pavement construction.

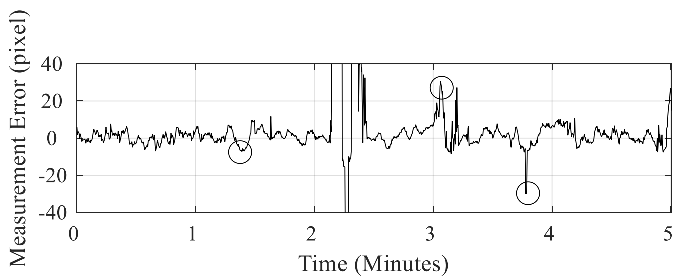
To further verify the performance of the proposed technology, the accuracy of the estimated heading direction was examined. It is due to that, in comparison with the frame-to-frame translation estimation, the change of the heading direction has more weights in influencing the accuracy of roller position estimation. Even trivial errors in the heading direction estimate may lead to a large cumulative position error especially after a long period of operations. However, it is oftentimes difficult to test the accuracy of the heading direction since the heading direction keeps changing as the roller moves. In addition, there are also not available motion data from other control units installed in the roller that can be considered as reference. Note the fact that the heading direction is inversely identified from the location of the vanishing point. It hence can turn to examine the accuracy of the location of the vanishing point. For roller operation in pavement construction, it is practically reasonable to assume a locally planar pavement model in the vicinity of the roller. Under this assumption, the vanishing point that corresponds to two parallel boundaries is fixed in a special line in the image plane, which is called vanishing line (Szeliski 2011). It is evident that the vanishing line is parallel to the x-axis of the image plane in our case, since the x-axis of the image plane is aligned to the horizontal direction of the ground plane after installing the experimental instruments. Therefore, the ordinate of the vanishing point in the image plane is supposed to be fixed. The drift of the ordinate of the vanishing point is attributed to the measurement error induced from the proposed algorithm. Figure 6 plots the changes of the ordinate of the vanishing point identified from the entire compaction process in two different construction scenarios. As it can be seen, the trend of drift randomly fluctuates around zero, evidencing that the accuracy of the location of the vanishing point identified from the proposed algorithm. It is also worth noting that the ordinate of the vanishing point suddenly jumps at some point within a special period (labeled with circle in Figure 6). After checking the raw thermal videos, these sudden jumps occurred when the roller was turning direction or changing the movement from a back-or-forth rolling motion. During that time, the angle between the optical axis and the ground plane has a fluctuation due to the effect from movement suspension; therefore, the position of the corresponding vanishing line changes (Hamme et al. 2011). To quantify the drift error, the numerical statistics are reported in Table 3 and Figure 7. The abnormal data in the second experiment has been removed since it does not belong to the system error of the proposed technology. As shown in Table 3, the ordinate measurement error of the vanishing point falls within a range of ± 4.300 pixels in site 1 and ± 4.360 in site 2 with a 99.5% confidence interval. Assuming a homogeneity of the measurement errors distributed in the image plane, meaning that the measurement errors along the x-axis and y-axis are homogeneous or identical, a maximum heading direction measurement error of ± 0.071 degree ± 0.073 degree can be obtained by conversion using Equation 1, which is acceptable in field applications of roller tracking and mapping. In addition, taking a reference to Figure 7, the abscissa measurement error of the vanishing point also obeys a Gaussian distribution due to the homogeneity. Therefore, the heading direction error induced from the proposed algorithm will be attuned by itself while the roller keeps moving. All in all, the performance of the proposed algorithm in the heading direction estimate is satisfactory.

Table 3: Statistics of ordinate measurement error.

Site	Mean Absolute Deviation (pixel)	Standard deviation (pixel)	Range (pixel)	99.5% confidence interval (pixel)
1	3.346	4.301	-29.319~19.818	-4.298~4.300
2	3.917	4.231	-29.831~30.658	-4.359~4.360

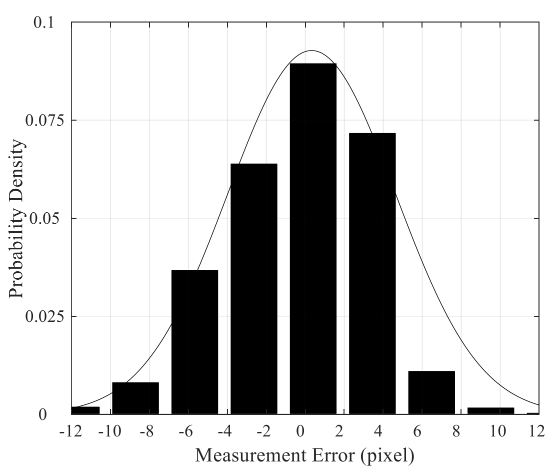


(a) I-68E MP 24

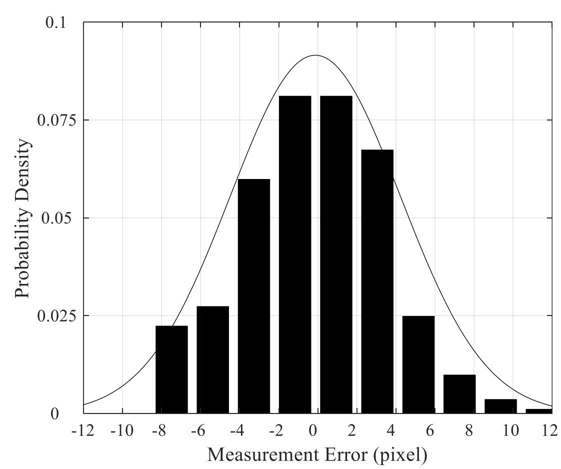


(b) US 50W, WV

Figure 6: The ordinate measurement error of the vanishing point.



(a) I-68E MP 24



(b) US 50W, WV

Figure 7: The distribution of ordinate measurement error.

5 DISCUSSION

The satisfactory performance of the developed thermal-based technology shows that it is a promising alternative to GPS-based IC technology, whose main advantages are attributed to its low cost and user-friendly operations. However, there are still some challenges that need to be tackled in order to further improve the performance and applicability of the developed technology in pavement construction. The first challenge is to ensure the developed technology compatible with different types of rollers. The proposed algorithm relied upon an assumption that the orientation of the IR camera is fixed in the entire rolling task. It is true when using the static roller but has yet to be investigated in case of using the roller with a dynamic drum. The inherent variability of dynamic roller makes the coupled IR camera oscillate, and the projective relationship between the image plane and the ground plane may changes accordingly. To combat this challenge, some equipment such as camera vibration isolators or camera gimbal stabilizers can be adopted to offset the adverse influence from the camera vibration. The second challenge is to improve the accuracy of roller motion estimation. As stated earlier, the roller's position in the current frame is completely based on that in the previous frame, implying that a cumulative translation error may exist after a long time of operations. This challenge can be resolved by periodically feeding the actual roller's position into the algorithm and the cumulative translation error can be effectively compensated so as to improve the accuracy of roller position estimation. It may be realized by setting up some traffic cones, which are often used to create temporary separation in road construction, along the pavement with known geometric displacement. Using these traffic cones as the reference locations, the roller position relative to the origin position can be determined when the IR camera captures certain traffic cone, and then the obtained roller's position from the traffic cone can be used as the benchmark for error compensation.

6 CONCLUSION AND FUTURE WORK

In this research, the authors developed a thermal-based technology for roller path tracking and mapping. The performance of the developed technology was preliminarily evaluated through two field experiments conducted in different pavement construction sites. Qualitative and quantitative validation results, i.e., the color-coded plots and the accuracy of the heading direction estimate, demonstrated that the proposed technology is a promising alternative to GPS-based intelligent compaction. However, more comprehensive evaluation is still needed, including the accuracy assessment of the translation estimate as well as performance testing of the global position of the roller estimated from the developed technology.

In future, lab experiments will be designed to systematically evaluate the performance of the developed technology. A miniature, self-heated pavement model and a roller model will be constructed in the lab in order to simulate in-situ conditions of pavement constructions. Under lab conditions, the real-time position of the roller model can be easily and precisely obtained by setting the ground references or estimating the roller positions from well-established high-precision sensors such as LiDAR or Total Station. Once mature in lab, the proposed technology will be further tested in fields by working with paving companies that the authors have partnered with. This will further validate the performance of the technology for improvement and possible field deployment of the proposed technology.

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REFERENCES

Bouguet, J.Y. 2005. "Pyramidal Implementation of the Lucas Kanade Feature Tracker Description of the Algorithm". *Trends in Microbiology* 13(11):505–509.

Campbell, J., R. Sukthankar and I. Nourbakhsh. 2004. "Techniques for Evaluating Optical Flow for Visual Odometry in Extreme Terrain". In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS),* September 28th-October 2nd, Sendai, Japan, 4:3704–3711.

Chang, G.K., Q. Xu, J. Rutledge, R.D. Horan, L. Michael, D.J. White, and P.K. Vennapusa. 2011. "FHWA-IF-12-002: Accelerated Implementation of Intelligent Compaction Technology for Embankment Subgrade Soils, Aggregate Base, and Asphalt Pavement Materials". Final Report, FHWA.

Yang X., T.L. Xue, H.C. Luo and J.B. Guo. 2019. "Fast and Accurate Visual Odometry from a Monocular Camera". *Frontiers of Computer Science* 13:1326-1336.

Gallivan, V.L., G. K. Chang, and R. D. Horan. 2011. "Practical Implementation of Intelligent Compaction Technology in Hot Mix Asphalt Pavements". In *Proceedings of the Association of Asphalt Paving Technologists 2011*, March 27th-30th, Tampa, FL, 1–31.

Imran, S.A., M. Barman, S. Commuri, M. Zaman, and M. Nazari. 2018. "Artificial Neural Network-Based Intelligent Compaction Analyzer for Real-Time Estimation of Subgrade Quality". *International Journal of Geomechanics* 18(6):1–14.

Jung, C.R., and C. R. Kelber. 2005. "A Lane Departure Warning System Using Lateral Offset with Uncalibrated Camera". In *Proceedings of IEEE Conference on Intelligent Transportation Systems*, September 16th, Vienna, Austria, 348–353.

Liu, D.H., Y.L. Wang, J.J. Chen, and Y.L. Zhang. 2019. "Intelligent Compaction Practice and Development: A Bibliometric Analysis". *Engineering, Construction and Architectural Management* 27(5):1213-1232.

Mooney, M., R. Rinehart, N. Facas, O. Musimbi, D. J. White, and P. Vennapusa. 2010. "Intelligent Soil Compaction Systems". Final Report NCHRP 21-09, National Cooperative Highway Research Program, Washington, DC, USA.

Savan, C.M., K.W. Ng and K. Ksaibati. 2016. "Benefit-Cost Analysis and Application of Intelligent Compaction for Transportation". *Transportation Geotechnics* 9:57–68.

Szeliski, R. 2011. *Computer Vision Algorithms and Applications*. New York: Springer London Dordrecht Heidelberg.

Scaramuzza, D. and R. Siegwart. 2008. "Appearance-Guided Monocular Omnidirectional Visual Odometry for Outdoor Ground Vehicles". *IEEE Transactions on Robotics* 24(5):1015-1026.

Hamme, D.V., P. Veelaert and W. Philips. 2011. "Robust Visual Odometry Using Uncertainty Models". In *Proceedings of Advanced Concepts for Intelligent Vision Systems*, August 22th-25th, Ghent, Belgium, 6915:1–12.

Yoon, S., M. Hastak and J. Lee. 2018. "Suitability of Intelligent Compaction for Asphalt Pavement Quality Control and Quality Assurance". *Journal of Construction Engineering and Management* 144(4):04018006.

Zhou, H.F., L.J. Lu, Z.Y. Li, and Y.Q. Ni. 2020. "Exploration of Temperature Effect on Videogrammetric Technique for Displacement Monitoring". *Smart Structures and Systems* 25(2):135–153.

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