Cellular-phone-based system for transportation engineering applications

Article *in* AEJ - Alexandria Engineering Journal · February 2020

DOI: 10.1016/j.aej.2020.01.040

Mohammed Taleb Obaidat
Jordan University of Science and Technology; Jadara University

ARTICLE IN PRESS

Alexandria Engineering Journal (2020) **xxx**, xxx–xxx

HOSTED BY

ELSEVIER

Alexandria University

Alexandria Engineering Journal

www.elsevier.com/locate/aej
www.sciencedirect.com

ORIGINAL ARTICLE

Cellular-phone-based system for transportation engineering applications

Mohammed Taleb Obaidat [a,b,*]

[a] *Jadara University, President, Civil Engineering Department, College of Engineering, Jordan*
[b] *Jordan University of Science and Technology (JUST), CE Dept., College of Eng., P.O. Box 3030, Irbid, Jordan*

Received 9 January 2020; revised 20 January 2020; accepted 23 January 2020

KEYWORDS

Computational methods;
Cellular phones;
Transportation engineering;
Traffic monitoring;
Road geometry;
Road inventory

Abstract Cellular phones cameras technological development as a hand-held electronic instrument with almost everybody nowadays will open the door to their potential usage as viable mensuration instruments. These extracted measurements would have the advantages of being inexpensive and portable ones.

As a hand-held tool and wide availability, cellular phones equipped with digital cameras is anticipated to give them the potential of in-situ real-time measurements as well as the usage for documentation purposes. However, the accuracy potential of the extracted measurements affected by the small image domain, small field of view, and camera configuration. Further, the usage of high resolution cellular phones cameras is anticipated to overcome these challenges.

The potential of cellular phones' cameras in metrology using normal-based setup was investigated. In this research work, the captured images were used to extract some of traffic monitoring parameters as well as road inventory, vehicle classification and intersections. Cellular phones cameras' resolutions that ranged from 2 to 12 Megapixels were investigated in this domain despite their fixed focus lenses and smaller sensors that would limit their performance in poor lighting.

Findings of research show that the potential of using high-resolution cellular phones in traffic parameters mapping, vehicle classification and road geometric features is promising. In fact, increasing the phone's camera resolution up to 12 Megapixels would consistently give high potential computational accuracy results for all studied parameters. Road intersection shows measurements of average errors ranging between 13% and 21% for camera resolution ranging between 8.0 Mega Pixels to 0.3 Mega Pixels. Further, speed profile could easily be generated with high accuracy potential.

A CAD drawing of the mapped intersection scene was also generated. However, the computational accuracy potential degraded rapidly when changing camera resolution in case of vehicle classification study due to shutter speed problem and mapping vehicles while in motion.

The promising conclusions of this technology is anticipated to open the door -for the first time usage- of cellular phones in the domain of transportation engineering computing in order to extract

* Corresponding author at: Jadara University; President; Currently: in leave from Jordan University of Science and Technology (JUST), Civil Engineering Department, College of Engineering, Jordan.
E-mail addresses: mobaidat@jadara.edu.jo, mobaidat@just.edu.jo.

Peer review under responsibility of Faculty of Engineering, Alexandria University.

https://doi.org/10.1016/j.aej.2020.01.040

Please cite this article in press as: M.T. Obaidat, Cellular-phone-based system for transportation engineering applications, Alexandria Eng. J. (2020), https://doi.org/10.1016/j.aej.2020.01.040

viable and accurate traffic and geometrical parameters. Thus, this method of gauging and computation would also be extended in order to produce surface measurements for any civil engineering application in the domains of transportation, structural, geotechnical and environmental engineering in a practical and new trend technology. It is anticipated that with the technology booming of new cellular phones production of higher resolution, mensuration accuracy would reach close values to real dimensions.

1. Introduction and literature review

Charged-Coupled –Devices (CCD) cameras were extensively used in traffic parameters mensuration last two decades. Despite their high accuracy potential in this domain and other domains in surface measurement tasks, their big sizes, availability and current technology trend are considered as main restrictions of their availability with everyone [1–5]. However, the trend of technology nowadays is tending toward the usage of cellular phones equipped with digital cameras that are considerably available with almost everybody and having small sizes that can be hand-held, light-weight and available in the pockets of almost all people [6].

Although cellular or mobile phones are mainly used for communications and data transfer tasks, and their usage while driving have dangerous impact on traffic accidents and crashes, the cameras they equipped with can be used for different measurement and documentation tasks.

Amidst the availability, variety, capability, booming and high competition of cellular phones companies it is anticipated to use the cameras of mobile phones as webcams for mensuration purposes. Almost everybody is using still and video images of cellular phones cameras for documentation and data-transfer, however, rare or may be none used it for measurements purposes.

[7–11] used cell-phone-based platform for biomedical device development and education applications. In their research work, they found that cell-phones are suitable for applications of medically relevant problems using the microscopic approach.

[12] measured distance with mobile phones using single-camera stereo vision. They showed good potential accuracy for mobile phones.

On the other hand, CCD-traffic enforcement camera (in the forms of red light camera, road safety camera, road rule camera, photo radar, photo enforcement, speed camera, safety camera, and bus lane camera) is used nowadays to automate ticketing enforcement process. It has been used as stationary cameras to detect traffic regulation violations, including speed measurement and other tasks.

[13,14] used mobile phones equipped with video cameras to study real-time urban road traffic classification and displacement. They measured good performance and low computing complexity vehicle's speed from mobile images with the aid of odometer and/or Global Positioning Systems (GPS) [15–17].

In this research work, the potential accuracy of cellular phones cameras of different resolutions on measuring different transportation, traffic and geometrical parameters were mainly investigated using the normal-based camera configuration. The studied parameters included: (1) traffic monitoring parameters including queue length and speed; (2) Vehicle's classification; and (3) Geometrical inventory parameters such as road width and intersection inventory. The accuracy of measured parameters was compared to classical methods. Still mobile phones images of different resolutions were used to study their potential in extracting traffic parameters characteristics and road inventory of intersections located in Amman-Jordan.

2. Significance of work

The followings represent this research significance:

1. The usage of cellular phones cameras to extract traffic and geometrical parameters is considered as a new era and initiative in the domain of metrology. In fact, it might be the first time usage according to the principal investigator knowledge.
2. Cellular phones cameras were used as data acquisition systems and mensuration technology.
3. The project outcomes open the door widely for using digital cellular phones cameras technology in different academic and engineering applications in research as well as deployment applications that require extraction of surface measurements.

3. Used cellular phones

The used cellular phones brands and resolutions were limited to available smart phones during the study period through the academic year 2013/2014. They were limited to Galaxy brands product of Samsung Company which are the most common used brands. The followings resolutions in Mega Pixels were used to investigate the goals of this research work to extract the geometry of an intersection: 0.3, 0.9, 2.0, 4.0, 6.0 and 8.0. However, resolutions of 2.0, 3.0, 3.2 and 8.0 Mega Pixels were used for vehicles classifications task. Whereas, resolutions of 2.4, 3.2, 3.6, 4.5, 5.5, 6.5, 8 and 12.0 Mega Pixels were selected for vehicles' speeds study in order to effectively find the speed of vehicles because of its accuracy potentials and sensitivity.

4. Camera setup and data acquisition system

Hand-held normal-based camera setup was used for all studied cases to reach the objectives of this research work in order to construct road intersection, find vehicles' speed profile and vehicles' classifications. Captured images were collected when

Please cite this article in press as: M.T. Obaidat, Cellular-phone-based system for transportation engineering applications, Alexandria Eng. J. (2020), https://doi.org/10.1016/j.aej.2020.01.040

the cellular phones were held in the hand of the users and facing the objects being mapped. The optical axes of the cameras were nearly kept perpendicular to the mapped objects in order to produce uniform scale of the image at least at the middle of the images. This would produce highly accurate extracted information from images. Multi users standing next to each other's and each of them is holding a camera with different resolution to map the studied objects at the same time in order to study the potential effect of camera resolution on measured and extracted information from images.

All scenes of the studied objects were mapped at noon time to avoid shadow effect on radial and decentering distortion of images and to assure natural sun light without using lighting facility.

5. Methodology

The following methodology was used in this research work:

1. Cellular phones of different resolutions ranging from 2 to 12 megapixels were used.
2. Road intersection scenes were mapped through cellular phones.
3. Normal-based images were used to map traffic scenes during motion and queuing.
4. Normal-based images were also been used to map intersection scenes for the purpose of intersection inventory.
5. Traffic images were used to compute vehicle speeds, queue lengths, vehicle classification and speed profiles.
6. Intersection scenes images were used to draw geometrical features of the intersection.
7. Ten research assistants holding cellular phones of different resolutions mapped traffic and intersection scenes at the same time.
8. Image analysis and computation were done assuming uniform-scale for normal-based images.
9. Comparison between cellular phones image-method analysis and classical measurement method were investigated.
10. Field as well as office work and the outcomes of this investigation are presented in this report.

6. Locations and safety considerations

The following precautions were taken into consideration in order to assure safety of humans doing data collections and their credibility:

1. The snap-shots of images were taken at selected intersections in Amman-Jordan using hand-held cellular phones of different resolutions. The traffic study was done at the main arterial road in front of Jordan University in Amman. While, the intersection study was done at one of the minor intersections of Al-Madena Al-Monawara street in Amman. However, the traffic classification study was done at the Arterial road in front of Jordan University, while mapping was done from overpass pedestrian bridge to assure sufficient field of view; that was located in front of Addustour News Paper in Amman, Jordan
2. Image analysis and computational procedures were done at the office using image analysis software and Android's programs equipped with Cellular Phones.
3. Research assistants took safety precautions into consideration while mapping the traffic and geometrical scenes. Official permissions were taken from traffic police department for this purpose.

7. Data collection

7.1. Road intersection study

The main purpose of this task was to map an intersection site scene using normal-photography configuration by cellular phones with different resolutions using the previously mentioned scheme of methodology.

Fig. 1 shows the mapped intersection with different resolutions of smart cellular phones ranging from 0.3 Mega Pixels to 8.0 Mega Pixels.

7.2. Vehicle classification study

Vehicle classification study was done in order to determine the effect of camera resolution on the extracted image measurements for vehicles' lengths while they are in motion. Data were collected from the top of Al-Ddoustor pedestrian bridge in Amman in spring time noon time in order to avoid the shadow effect on image distortion.

A sample of forty vehicles was mapped at different resolutions. A distance of about 1.455 m between two yellow spots cat eyes were measured on the street for the purpose of scale computation. The images were normal with the optical axe in order to assure uniformity of the image scale. The length of the mapped vehicles then measured in pixels and converted to actual length after multiplying its length in pixels with the scale factor. The measured lengths were then compared to AASHTO vehicles classification in order to categorize and compare them with the visual or actual vehicles types.

The scale equation that represents the mathematical model used in this research is:

$$\text{Image Scale} = (\text{Image domain measurement}/\text{Real object measurement}) \quad (1)$$

Fig. 2 shows sample of the mapped vehicles.

7.3. Vehicle speed study

The movements of vehicles for the field of view of the cameras were filmed using cellular phones with different resolutions, where each phone was hand-held by different person. For the purpose of speeds computations the following resolutions were used: 2.4, 3.2, 3.6, 4.5, 5.5, 6.5, 8 and 12.0 Mega Pixels. However, for the purpose of speed profile only four resolutions, 3.2, 4.5, 5.5 and 12.0 Mega Pixels were used for the field of view of the cellular phones cameras.

Fig. 3 shows sample image for mapped vehicle while in motion next to agriculture College Bridge at University of Jordan Campus in Amman.

Please cite this article in press as: M.T. Obaidat, Cellular-phone-based system for transportation engineering applications, Alexandria Eng. J. (2020), https://doi.org/10.1016/j.aej.2020.01.040

0.3 Mega Pixels 8.0 Mega Pixels

Fig. 1 Mapped Intersection Scene with Different Resolutions.

Fig. 2 Sample of the mapped vehicles.

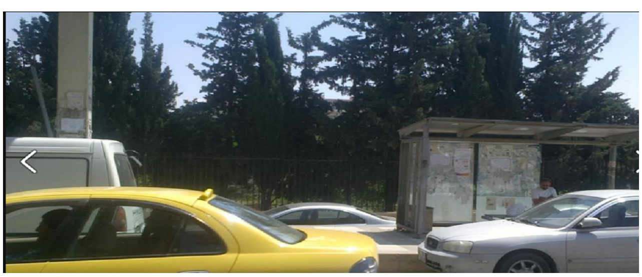

Fig. 3 A sample screen–shot for a vehicle while in motion.

8. Results and discussion

8.1. Road intersection study

The collected images were analyzed in order to study the potential accuracy of extracted quantitative values using cellular phones. The widths of the major and minor approach streets at the mapped intersection using different resolutions were measured using two methods: (1) The manual convention method using a tape; and (2) The image processing method having images of cellular phones at different resolutions.

Table 1 shows the comparison between the two methods. The percentage of the average error using the conventional method as a base-line method varied between 13% and 21%.

Fig. 4 shows the measured percentage errors when using cellular phones digital images for both minor and major streets of the intersection as well as their associated average errors. Clearly, the percentage errors increase consistently when decreasing cellular phones camera resolutions. The least error occurs at camera of 8.0 Mega Pixel resolutions of a percentage error approach 13%. Of course, the potential error will decrease with the production of cellular phones cameras of higher resolution such as 12 Mega Pixel or 16 Mega Pixel or even more in the upcoming time.

Comparison between conventional method and digital cellular phone method is shown in Fig. 5 for both minor and major streets, where percentage errors of the extracted measurements clearly shown. Again, the error decreases when resolution increases.

From the previous figures, it is clear that as the resolution of the camera increases the accuracy of the extracted quantitative measurements increases, whereas, the error decreases. This gives an indication how important is the type and resolution of the camera used for mapping. Of course, the cost of cellular phone increases when resolution increases as indication that accuracy costs money.

The snapped images for the mapped intersection may also be used in order to generate AutoCAD (CAD) drawings. Fig. 6 shows a CAD drawing for the mapped intersection using a resolution of 8 Mega Pixels. All measurements at the CAD generated intersection were extracted from the cellular phone image using a constant scale. Line length at the middle of the image was measured to compute the uniform scale.

8.2. Vehicle classification study

The forty mapped images were transferred into an image processing program in order to measure the vehicles length in pixels. The measured lengths of vehicles then were multiplied by scale factor in order to compute the length of each measured

Please cite this article in press as: M.T. Obaidat, Cellular-phone-based system for transportation engineering applications, Alexandria Eng. J. (2020), https://doi.org/10.1016/j.aej.2020.01.040

Table 1 Extracted quantitative measurements from conventional and cellular phones images.

Camera Resolution	Actual width of Street (A) in meters	Width of street (A) from image in meters	Street (A) Measured Error (%)	Actual width of Street (B) in meters	Width of street (B) from image in meters	Street (B) Measured Error (%)	Average Error (%)
8.0 Mpix	9.5	8.1655	14%	16.2	14.42	11%	13%
6.0 Mpix	9.5	8	15.70%	16.2	14	13.50%	15%
4.0 Mpix	9.5	7.6	20%	16.2	13.77	15%	18%
2.0 Mpix	9.5	7.5	21%	16.2	13.5	17%	19%
0.9 Mpix	9.5	7.44	21.68%	16.2	13.2	18.50%	20%
0.3 Mpix	9.5	7.425	22%	16.2	13	20%	21%

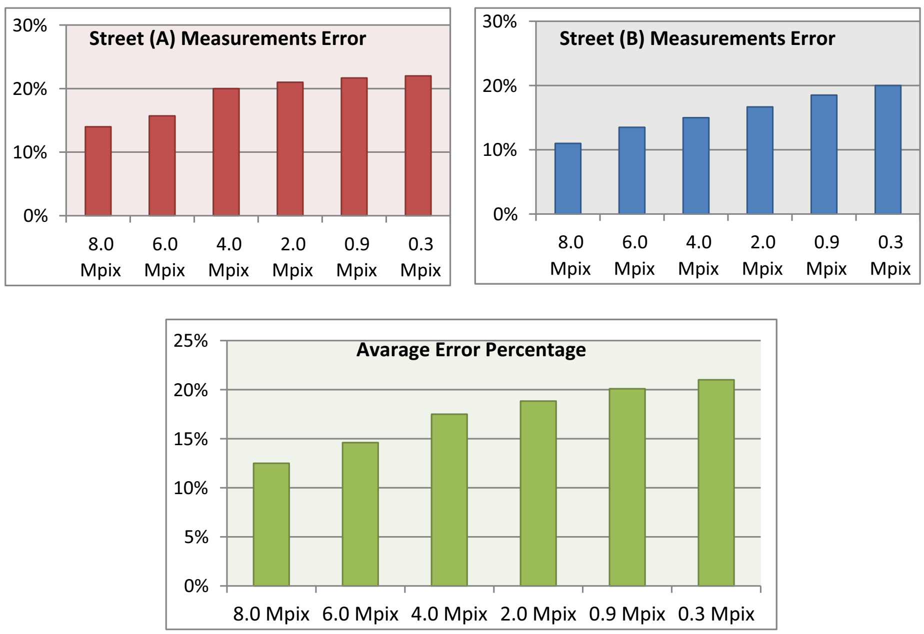

Fig. 4 Minor Street and major street errors as well as the average errors.

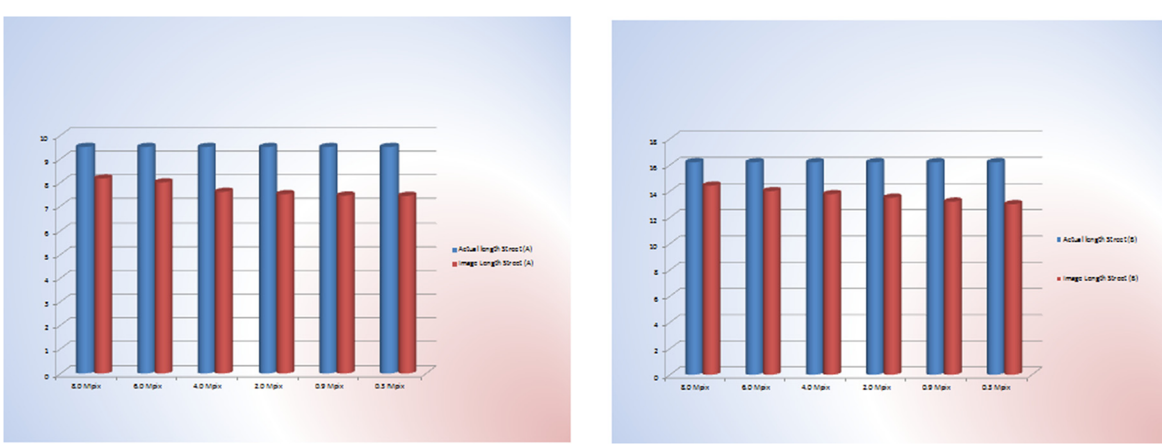

Fig. 5 Comparison between manual and cellular phones digital imaging measurements.

vehicle. On the other hand, the vehicle type and model were visualized and manually recorded for the purpose of comparison.

Of course, the accuracy of the measured vehicles' lengths was affected by many factors such as: distortion, parallax, tilt angle of optical axe, vehicles speed, phone camera setting,

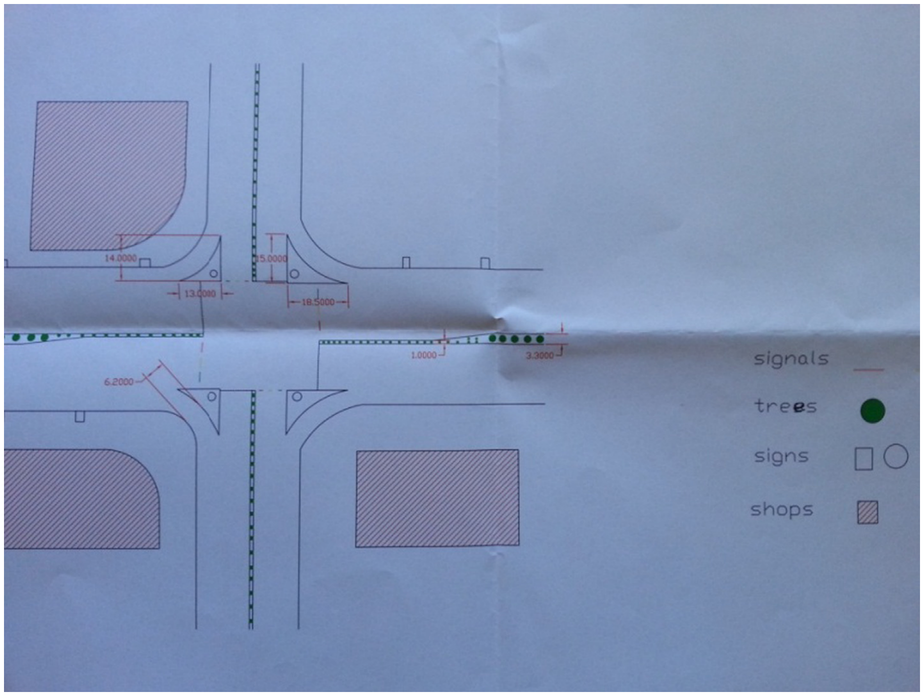

Fig. 6 Generated CAD drawing using cellular phone images.

shutter speed, color and texture of mapped scene, image scale, normality degree of camera, field-of-view of the used camera, and resolution of used camera.

Comparison between the measured lengths and widths from the mapped images with AASHTO specifications for vehicle's classification shows clearly that as the resolution increased the potential of accurate measurement would be better and matched to lengths and widths. The mapped vehicles were in the category of passenger vehicles. Another clear observation is that sometimes discrepancies between lengths or widths findings are not consistent. In fact, errors sometimes reached 25% of the measured length or even more. Reason behind that was the shutter speed that was not synchronized with vehicle speed while it is in motion. This task would be not an easy task to control the used cellular phone cameras as long as they have small field of view and small scale images as well.

8.3. Vehicle speed study

Ten vehicles were used in speed profile study, whereas, thirty vehicles were used for speed study. Table 2 shows sample computed speed values in m/sec for ten vehicles for 3.2 Mega Pixels and the computed speed profile data at distances of zero and five meters at different image resolutions. The conversion factor from m/sec to km/hr is multiplying by 3.6.

The following procedures and scheme were used in order to compute the speed:

1. Mark equal distances of five meters each on the longitudinal direction of the street; i.e. the path of vehicles.
2. Select the mapped scene, where cameras' having their optical axes perpendicular to the mapped vehicles.
3. Capture video images for moving vehicles at different resolutions.
4. Use program "speedometer" from the "Play Store" of "Android" Galaxy Note II Cellular Phone in order to compute speed at any location for the moved vehicle.
5. Plot the speed profile of the moving vehicles at different resolutions.

Fig. 7 shows the average computed speeds in m/sec versus moved distances (Speed Profile) for the four studied resolutions. Again, resolution of 12.0 Mega Pixels had the highest accuracy compared with actual speeds measured using conventional method. Clearly, increasing the camera resolution would give better accuracy for speed and speed profile vehicle tracking.

9. Summary and conclusions

Mobile phones with different image resolutions were successfully used in performing some surface measurement tasks for traffic parameters, vehicle classification and road geometry features. The used methodology in this domain according to the author is recent and will open a new era in metrology using cellular phones as data acquisition systems. It is anticipated that the developed mensuration scheme will open the door for many practical traffic and transportation engineering applications.

Smart cellular phones with resolutions ranging between 0.3 and 12.0 Mega Pixels were used in this investigation for the purpose of extracting useful information. Specific tasks included extracting of road intersection geometry, semi-automatic classification of vehicles, and speed and speed profile computation for vehicles while in motion. Normal-based

Please cite this article in press as: M.T. Obaidat, Cellular-phone-based system for transportation engineering applications, Alexandria Eng. J. (2020), https://doi.org/10.1016/j.aej.2020.01.040

Table 2 Computed speed values (m/sec) different distances while in motion.

Vehicle Number	Speed (0–5 m)	Speed (5–10 m)	Speed (10–15 m)	Speed (15–20 m)	Speed (20–25 m)
1	10.0	8.3	4.5	4.5	3.6
2	7.1	7.1	5.6	5.0	2.5
3	8.3	7.1	7.1	3.3	3.3
4	7.1	7.1	6.3	5.0	2.5
5	10.0	10.0	7.1	5.6	3.3
6	10.0	10.0	7.1	5.0	2.6
7	7.1	5.0	3.3	2.5	2.0
8	3.3	2.5	2.3	2.3	1.7
9	10.0	8.3	8.3	5.6	3.3
10	6.3	5.6	5.0	3.8	3.6

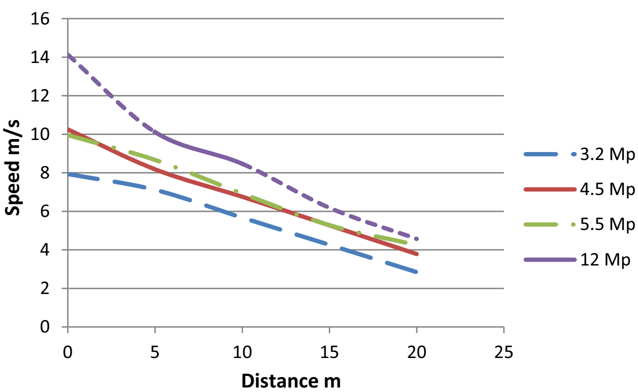

Fig. 7 Speed profile for different cellular phones camera resolution.

and hand-held camera setup was used in the study to assure uniformity and consistency of image scale.

A cellular-phones-based measurement scheme was developed specifically for the purpose of this research work. It consisted of image-captures, image-analysis, comparison with conventional measurements, and potential accuracy.

Research results and outcomes were promising though it contained high percentage of errors for tasks while traffic was in motion. Research work achieved the objectives anticipated to be reached. The following conclusions and findings were the most significant outcomes:

1. Computer-vision cellular phones cameras are promising and suitable for mensuration tasks in the domains of traffic, vehicles and road features.
2. The potential accuracy of cellular phones cameras in measuring traffic parameters and road inventory are compatible with conventional methods with mean errors ranging between 10% and 20% depending on image resolution and image stability.
3. The percentage of mean errors decreased consistently when increasing camera resolution for all measuring tasks and research objectives.
4. AutoCAD systems could be integrated with the used scheme of this research work in order to extract CAD maps of intersection scenes.
5. Vehicle classification task showed compatible results with AASHTO policy with some fluctuated errors while vehicles were in motion.
6. Speed profiles of moving vehicles were generated for different image resolutions. Of course, accuracy of measured speeds was compatible with actual conventional methods when resolution reached 12.0 Mega Pixels and more.
7. The findings of this research work will open the door for the usage of cellular/mobile phones cameras image-based for civil engineering measurements applications.

10. Recommendations

Despite the promising applications and findings of this research work, the following recommendations would enhance the performance of using cellular phones for traffic and roads metrology:

1. Strengthening the usage of cellular phones in Transportation Engineering, traffic monitoring, road geometry, and road inventory.
2. Investigating the potential accuracy of using higher resolution and other types of smart phones.
3. Widening the usage of mobile phones cameras to include domains of pedestrian parameters, behavioral response, other traffic parameters, and spatial mapping of traffic safety.
4. Suggesting prototype usage of cellular phones in traffic patrol systems.
5. Opening the door for other research work usage of cellular phones images in different domains.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The author wishes to express his gratitude and thanks to Jordan University of Science and Technology (JUST) for supporting his sabbatical leave that he spent at The University of Jordan-Amman during the academic year 2013/2014.

References

[1] S.F. El-Hakim, A.W. Burner, R.R. Real, Video technology and real-time photogrammetry, in: Non-Topographic Photogrammetry, 2nd ed., Am. Soc. Of Photogrammetry and Remote Sensing, Falls Church, Va., 1989, pp. 279–304.
[2] K.W. Wong, G.W. Anthony, M. Lew, GPS-guided vision systems for real-time surveying, J. Surv. Eng., ASCE 115 (2) (1989) 243–251.
[3] M.T. Obaidat, K.W. Wong, Geometric calibration of CCD camera using planar object, J. Surv. Eng., ASCE 122 (3) (1996) 97–113.
[4] M.T. Obaidat, H. Al-Masaeid, Video system to monitor archeological sites using ground-based photogrammetry, ASCE (J. Surv. Eng.) 124 (1) (1998) 3–25.
[5] K.B. Atkinson (Ed.), Close Range Photogrammetry and Machine Vision, Whittles Publishing, 2001.
[6] M.T. Obaidat, K.A. Ghuzlan, M.M. Alawneh, Analysis of volumetric properties of bituminous mixtures using cellular phones and image processing techniques, Can. J. Civ. Eng. 44 (9) (2017) 715–726, https://doi.org/10.1139/cjce-2017-0085.
[7] Z.J. Smith, K. Chu, A.R. Espenson, M. Rahimzadeh, A. Gryshuk, et al, Cell-phone-based platform for biomedical device development and education applications, PLoS One 6 (3) (2011) e17150, https://doi.org/10.1371/journal.pone.0017150.
[8] J. Wang, T. Ibrahim, D. Howe, Prediction and measurement of iron loss in a short stroke, single-phase, tubular permanent magnet machine, IEEE Trans. Magn. 46 (6) (2010) 1315–1318.
[9] D. Tseng, O. Mudanyali, C. Oztoprak, S.O. Isikman, I. Sencan, et al, Lensfree microscopy on a cellphone, Lab Chip 10 (2010) 1787–1792, https://doi.org/10.1562/0031-8655(2001)0730178IVFSON2.0.CO2, Find this article online.
[10] A.K. Ellerbee, S.T. Phillips, A.C. Siegel, K.A. Mirica, A.W. Martinez, P. Striehl, N. Jain, M. Prentiss, G.M. Whitesides, Quantifying colorimetric assaysin paper-based microfluidic devices by measuring the transmission of light through paper, Anal. Chem. 81 (2009) 8447–17452.
[11] D.N. Breslauer, R.N. Maamari, N.A. Switz, W.A. Lam, D.A. Fletcher, Mobile phone based clinical microscopy for global health applications, PLoS One 4 (2009) e6320, Find this article online.
[12] C. Holzmann, M. Hochgatterer, Measuring distance with mobile phones using single-camera stereo vision, in: Distributed Computing Systems Workshops (ICDCSW), 2012 32nd International Conference on 18-21 June 2012, (2012), pp. 88–93.
[13] A. Lapeyronnie, C. Parisot, J. Meessen, X. Desurmont, J.-F. Delaigle, Real-time road traffic classification using mobile video cameras, in: Proc. SPIE6811, Real-Time Image Processing 2008, 681108 (February 26, 2008), 2008, https://dx.doi.org/10.1117/12.766313.
[14] M.T. Obaidat, M.F. Attom, Computer vision-based technique to measure displacement in selected soil tests, ASTM, Geotechnical Test. J. 21 (1) (1998) 31–37.
[15] M. Hashemi, H.A. Karimi, A weight-based map-matching algorithm for vehicle navigation in complex urban networks, Int. J. Intell. Transp. Syst. Res. 20 (2016) 573–590.
[16] J.I. Engel, J. Martin, R. Barco, A low-complexity vision-based system for real-time traffic monitoring, IEEE Trans. Intell. Transp. Syst. 18 (2016) 1–10.
[17] G.R. Jagadeesh, T. Srikanthan, Heuristic optimizations for high-speed low-latency online map matching with probabilistic sequence models, in: Proceedings of the 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), Rio de Janeiro, Brazil, 1–4 November 2016, 2016, pp. 2565–2570.