Comparison of Handheld devices for 3D Reconstruction in Construction

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Abstract –

Generation and quality of as built models influence the subsequent applications such as progress monitoring, quality control, and deviation detection. The quality of any 3D reconstructed model heavily depends on the raw inputs and the post processing involved. While laser and LiDAR-based scanning are widely prevalent, lower cost equipment and sensors are increasingly becoming adaptable for 3D reconstruction. This study tests the feasibility of using IR-based scanning tablets and passive stereo vision cameras to acquire data from a construction environment based on the type of applications (such as progress monitoring, deviation detection) on a construction site. Two different off the shelf technologies: Tango tablet and ZED camera are tested during this research for developing as-built models using 3D reconstruction. The devices are compared on the basis of metrics such as preparation time for each scan, calibration of the scanner and total scanning time for determining the ease of scanning process, accuracy of generated point clouds. Also, the influence of external factors such as scanning parameters, ambient lighting, and characteristics of the object being scanned, and angle/orientation of scanner with respect to the object are studied.

Keywords –

3D Reconstruction; as-built modelling; stereo vision; infrared depth sensors

1 Introduction

Population growth, developing economy and urbanization are putting pressures on our infrastructure networks and assets. In order to meet these demands, it is necessary that we view infrastructure not just as a physical asset but also its digital twin through which all the all the associated data and information can be revealed[1]. The advent of new technologies such as BIM, Virtual/Augmented Reality, Cloud computing, IoT etc. are already transforming the way we built infrastructure. But the construction industry still lacks the culture of performance defined by outcomes instead of outputs. However, new forms of project delivery which enables more rapid and agile forms of management are being tested[2]. These agile forms of management require the progress and productivity data to be monitored in real-time for swift decision making and corrective action. This requires the need for an automated progress monitoring system in place of conventional manual progress monitoring which is slow and inaccurate[3].

One of the most popular methods of automated progress monitoring is using 3D scanning devices to create a 3D mesh of the structure/object and then comparing it with a design model to assess the progress of the construction [4]. Most common ways of acquiring a 3D mesh are by using a laser scanner which gives you a dense point cloud. However, a laser scanner is an expensive equipment and requires high skills for operation. Also, the data from the scanner is quite large and requires high-end computing devices as well as longer time to process[5]. Another popular method for as build 3D point cloud acquisition is photogrammetry. It uses multiple photographs or consecutive frames from a video to create a 3D point cloud. Equipment needed for this method are normal 'point and shoot' cameras with a good resolution. Although photogrammetry is inexpensive on the equipment side, it takes significant time to process the data and recreate the point cloud. Often, the photographs (data) wouldn't have enough overlap or quality resulting in incomplete or distorted point clouds. This brings us to the third set of devices which are called range cameras.

Range cameras are devices which give a depth value for every captured pixel. There are different techniques and sensors for computing the depth such as Time of Flight sensors and stereo vision technologies, structured light, etc. Recently, range cameras have started to come into the consumer market making it affordable. The reduced costs enable construction personnel to take ownership of these technologies and to experiment, using them to improve the construction progress monitoring practices. In addition, most of these devices are handheld and require minimal skill levels to operate. However, quality of the raw data from the devices needs to be evaluated for effective utilization Low quality raw data would result in higher post processing time and would require computers with high computation capability. While low quality raw data can be improved by better processing techniques, this would contradict the use of low cost devices which are time efficient. Therefore, it is essential to benchmark the quality of data and the ease of the scanning process for these devices. Hence, it is necessary that we test these technologies in construction site conditions to understand its performance in the above conditions.

The current paper aims at testing the capability of two commercially available devices (which use range imaging for depth estimation) based on the metrics such as accuracy of the scan, scanning times, the influence of lighting conditions and influence of object material. The devices tested are Google Tango tablet and ZED camera. The Tango tablet is an Android development level tablet that uses Infrared technology coupled with an RGB camera to capture depth. ZED camera is a stereoscopic RGB camera that uses stereo vision camera sensors and algorithms to reconstruct 3D scenes from stereo images [15].

The paper is divided into five sections. Section 2 gives a brief description of the works in the area related to benchmarking devices for point cloud generation. Section 3 gives an outline of the methodology used and details on the case study. Section 4 presents the results from the tests with discussion on the implication of the results and Section 5 provides the conclusions from the current study.

2 Past Work

This section gives a brief outline of the work done in the past to benchmark consumer level range cameras. It should be noted that the performance of the device is the combined performance of the sensing hardware and the software algorithms for 3D point cloud generation and optimization. There are studies which have determined the capability of off shelve software to model under construction structures through systematic studies [5]. Also, there are studies which determine the performance of the device as such [6].

Out of the two range cameras that the current paper is focusing on, ZED camera is new to the research community and has not been explored much. However, there are studies which evaluate the performance of 3D reconstruction using stereo cameras. Chung and Kim (2015) presented a 3D reconstruction algorithm for stereo cameras and tested it on a construction site. They have reported that stereo camera integrated with their MSD based 3D reconstruction algorithms provides good performance with low computational time for autonomous control applications[7]. There have been studies which compared structure from motion (similar to stereo cameras technology) with laser scanning[8].It is reported that the structure from motion algorithms is less accurate than point clouds generated from laser scans. However, image based data acquisition increases opportunities for as built visualizations. Zennaro et al (2013) have evaluated another stereo camera Kinect for its 3D reconstruction capabilities. They reported the devices to be less accurate than 3D scanners, yet able to reconstruct with reasonable accuracies[9].

Google Tango's interior scanning accuracy was tested by Froehlich and Azhar [10].They have reported that the scans can be beneficial in time and cost savings in 3D data acquisitions but the scan was not of high quality. Kalyan et al have compared Tango tablet with other methods of 3D reconstruction such as Photogrammetry and laser scanning focusing on construction quality assessment. The study concluded that the dimensional accuracy of Tango tablet. Tango limits itself from the applications for quality assessment. However, the device outperformed other methods in terms of cost and user convenience[11].Although the device was reported to be less accurate, there are studies which stress that the accuracy of the device can be improved through passing the outputs through algorithms such as RANSAC, shape detection, least square plane fitting etc. [12].

In short, there are studies which have benchmarked stereo vision and infra-red based range cameras. Most of the studies have benchmarked these cameras to be less accurate than the laser scanners. However, the cost factor, consumer availability and ease of use make these cameras to have easier adoption. It should be noted that most of the studies are being performed in controlled conditions. It is necessary that experiments are performed on a live physical construction site to understand the performance of these off the shelve devices in object cluttered, dynamic fast changing and harsh environment. Hence, the current study aims at evaluating the performance of ZED camera and Tango tablet on a live construction environment.

2.1 ZED Camera

ZED camera is a stereoscopic passive RGB camera that uses stereo vision camera sensors and algorithms to reconstruct 3D scenes from stereo images (as shown in Figure 1). It comes with software SDKs which can be used to calibrate and create 3D reconstruction using the stereo image inputs. The camera can record up to 2K resolution, has wide angle lenses. The maximum depth perception is 20m [18]. The ZED explorer is the primary software which can be used to record a video in .svo format (Stereolab's format) which is then processed by ZED Fusion package to create disparity maps from stereo images and create a 3D point cloud. Each frame from the video is converted to point cloud and registered

Figure 1 ZED camera

successively using visual odometry, enabling the creation point cloud represented in 3D space [18]. Although the same process can be done in real time using ZED fusion, the algorithm doesn't work efficiently and has the possibility of crashing or may result in a distorted point cloud. However, this glitch may be resolved in the future SDK updates.

2.2 Tango tablet

Tango table is an Android development level tablet that uses Infrared technology coupled with an RGB camera to capture depth (as shown in Figure 2). The tablet consists of a motion tracking camera, 3D depth sensor, Accelerometer, Barometer, Compass, GPS, and Gyroscope [15]. The infrared-based tablet uses Time of Flight (ToF) to detect the depth of the objects being scanned. It incorporates SLAM for mapping its location

Figure 2 Project Tango Development Kit

to create point cloud representation of the object in 3D space. The tablet Tango tablet's Constructor app was used for scanning. It directly generates the 3D point cloud and the meshed surfaces which are available for upload and export in ".obj" format for further processing. The device self-calibrates when the app starts, after which the user can use it for capturing scenes [15].

3 Case Study and Methodology

The experiments to test the device's performance were conducted in a residential Construction site. Periodic site visits were conducted at different project times to capture

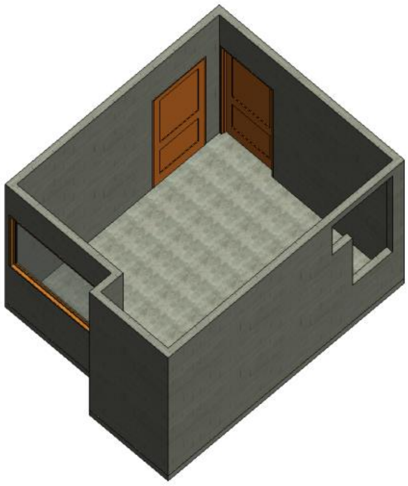

Figure 3 BIM model of the room considered for Case Study

various stages of construction. Four different stages of construction were scanned which are elaborated in table 1. The elements tested for scanning included masonry walls, concrete floors, columns, beams, and finished walls, tiled floors, windows, and doors. The raw point cloud generated from both the devices are shown in Figure 4 and Figure 5 for case 2. The original BIM for this case is shown in Figure 3.

Table 1 Description of Case studies

Case No.	Construction Stage Completed	Stage Description
1	Frame	Columns, Beams, Floor, Ceiling completed
2	Frame + Sill Level Masonry	Columns, Beams, Floor, Ceiling, Masonry till sill level completed
3	Frame + Masonry	Columns, beams, floor, ceiling, masonry till lintel level completed
4	Full Room	Fully constructed room including plaster, paint, tile finishing, windows, doors, etc.

3.1 Data collection using ZED and Tango

The feasibility of using ZED camera for 3D reconstruction application has been recommended in[6].

Figure 4 Raw meshed point cloud of Case 3 from ZED

But, the detailed study on the performance of the device, especially from a construction point of view is necessary to assess its usage in the field [16] [17]. The ZED camera was used at 720 resolution and frame rate of 60FPS since it was the highest resolution supported by ZED Fusion. The ZED Fusion Application included in the SDK package can be used in real-time to simultaneously scan and register point clouds of an area.

The Tango tablet is an IR device based on Time of Flight (ToF) for depth perception. It uses Inertial Measurement Unit (IMU) and visual odometry to successively register each depth scene. The Tango

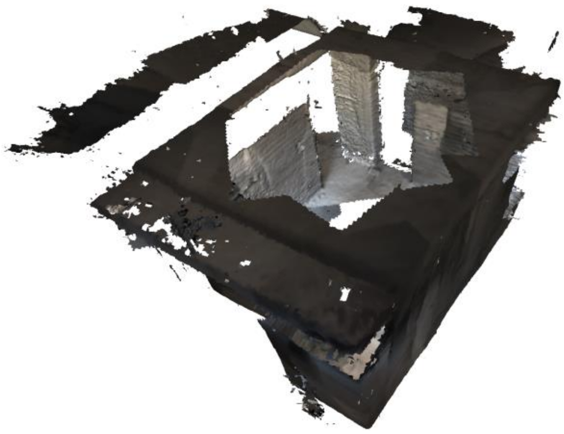

Figure 5 Raw Meshed point cloud of Case 3 from Tango

Constructor App from Google Play Store was used to scan and generate point clouds of the scenes.

3.1.1 Accuracy of Scan

The interior building dimensions are extracted from the scans manually and compared to manual survey dimensions to assess their accuracy and potential for verifying as-built conditions. The methodology by Sung and Kim on a similar work is adopted for this test [7][16]. The lengths of the major dimensions in each scan are measured in the scan data using MeshLab.

The as-built dimensions of three rooms which were scanned is measured using Leica Laser disto, an off-the-shelf laser surveying device which had a range of 0.05 – 150m and accuracy of 1mm. The deviation between scan values and actual values is evaluated using the absolute difference between the two measurements. The results of the Accuracy tests are tabulated in table 2. Tango has an average error of 3.08% while ZED has 7.80% as the dimensional error. Since these values are quite high for an object of dimensions 3m, the output of these devices cannot be directly used for monitoring dimensional quality analysis in construction.

3.1.2 Scanning Path, Speed of Scan and Angle of Scan

A clockwise scanning direction was chosen for both the devices. The scanning path is directly influenced by

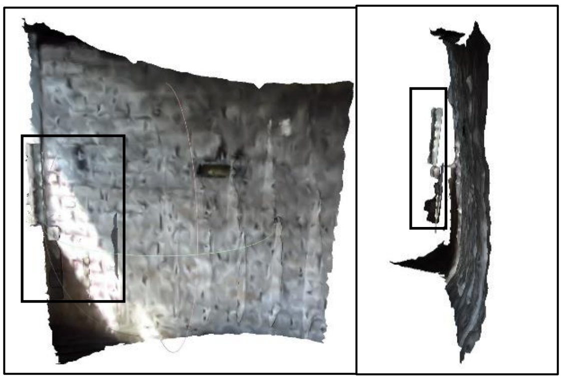

Figure 6: Effect of Rescanning using ZED Camera

the field of view of the device, and the maximum range of the device. ZED's horizontal Field of View is 61°. Based on its horizontal FOV, the vertical FOV is calculated as 93° (approx.) using the formula given below [15].

$$FOV\ V = \ (2\arctan(\frac{0.5 * height}{Fy})$$

$$FOV\ H = \ (2\arctan(\frac{0.5 * width}{Fx})$$

Where Fx and Fy are Focal lengths, and width and height denote the image dimension on the sensor.

Table 2 Dimensional Accuracy Analysis

Scan Description	Original Dimenions (m)	As-Built Dimensions From Tango(m)	AS-Built Dimensions from ZED (m)	Absolute Error for Tango(m)	Absolute Error for ZED(m)
Case 1: Component 1	5.8	5.74	5.31	0.06	0.49
Case 1: Component 2	4	3.96	3.85	0.04	0.15
Case 1: Component 3	3.05	3.07	2.75	0.02	0.30
Case 1: Component 4	3.05	3.08	2.77	0.03	0.28
Case 2: Component 1	3.5	3.41	3.18	0.09	0.32
Case 2: Component 2	4	3.92	3.72	0.08	0.28
Case 2: Component 3	3.05	3.1	2.92	0.05	0.12
Case 2: Component 4	3.05	3.12	3.03	0.12	0.02
Case 3: Component 1	4.3	4.56	3.63	0.26	0.67
Case 3: Component 2	3.5	3.41	3.10	0.09	0.40
Case 3: Component 3	3.05	2.91	2.87	0.14	0.18
Case 4: Component 1	4.3	3.97	3.81	0.33	0.49
Case 4: Component 2	3.5	3.35	3.16	0.15	0.34
Case 4: Component 3	3.05	2.95	2.95	0.13	0.10
Average				**0.11**	**0.30**
Standard Deviation				**0.08**	**0.18**
Maximum				**0.33**	**0.67**
% Error				**3.08%**	**7.80%**

Since ZED's horizontal FOV is significantly larger than its vertical FOV and its maximum range is 20m, the ZED camera was rotated 90° horizontally. This enabled to capture more a larger area vertically and capture the floor and the ceiling in one frame. The rate of movement of ZED camera for scanning was limited to 0.2m/s-0.5m/s. The increase in this speed caused the stereo camera to lose track of its localization, causing drift errors.

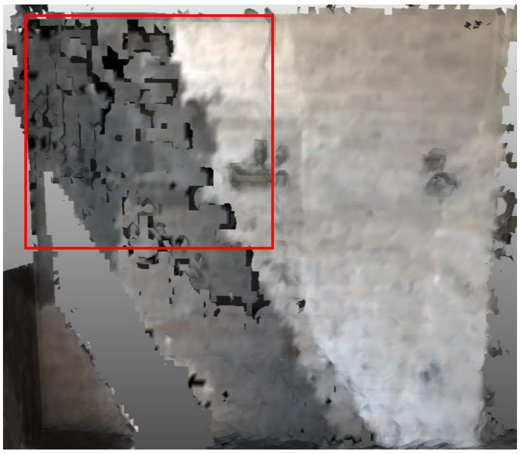

Figure 7 Effect of Rescanning using Tango

Tango has a vertical FOV of 38° and a horizontal FOV of 68°. Because of the limited range of Tango (4m), adopting a 90° horizontal flip did not cover more scan area. While scanning construction elements such as walls and floors, the device is rotated clockwise, in a circular motion, to capture both the ceiling and floor. Backtracking in the scanning path (i.e., rescanning an area) sometimes results in the introduction of new surface of the object which does not coincide with the existing surface. An example is shown in Figure 7. ZED camera also has problems with rescanning if the scan velocity is too high as shown in Figure 6. The effect of rescanning an area in ZED is minimal, compared to tango.

The speed of using the device to scan scenes has an indirect influence on the quality of the point clouds generated. It was observed that moving the devices too fast resulted in localization errors, and some areas were not captured. The IMU can, for example, be affected by the inconstant or sudden movement of the tablet holder, thus small positioning errors are accumulated as the scanning process goes [12]. To determine the range of the angular velocity of using these devices, a series of trial and error experiments were performed to observe the threshold beyond which localization errors occurred. ZED and its SDK performed with minimal localization errors when the capture speed was in the range of 0.1-0.5m/s. Tango could significantly scan faster, performing better when the capture speed was in the range 0.5-1.0m/s.

When scanning a scene, the location of the camera and the FOV influences the area captured. Both ZED and Tango did not exhibit any difference in capturing data in different angles.

3.1.3 Mobility and Time efficiency

One of the most determining factors in the adoption of a technology for construction is its ease of use and the time it takes to use it. A construction environment is complex and unstructured; often multiple scans are required to capture one single floor. Hence, light weight devices and devices which can withstand long durations of use are preferred as they offer more mobility. In fact, the above reasons are the main factors which led to the increase in adoption of low cost range cameras for construction environments. The ZED camera weighs 160 grams, making it very light to carry and use. But to scan an area, the camera needs to be connected by an USB cable to a computer which runs the SDK. Thus, the user needs to carry a computer in order to use the device on site.

Tango, on the other hand, is a tablet which weighs 370g. The point cloud is generated by the Constructor App can be viewed in real time on the tablet, making it much more user-friendly. In order to determine the time

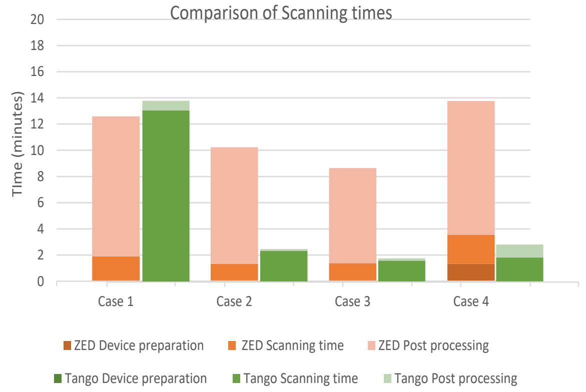

Figure 8 Comparison of Scanning Times for ZED and Tango

efficiency of the device, the time required for preparation, scanning, and data processing are measured for the four cases. The results are shown in Figure 8.

Due to inherent range and FOV limitations of the Tango tablet, the scanning time is much longer for larger areas. Prolonged use of the Tango tablet results in heating of device and crashing of either the scanning app/sensor/ OS. This results in loss of scan data which cannot be retrieved even upon restarting the device.

ZED on the other hand, with its long range capacity, can easily scan both small and larger areas without experiencing sensor malfunction. But, as seen from Figure 8, the post-processing time of ZED is higher than Tango tablet for all cases.

3.1.4 Influence of Lighting Conditions

ZED camera's SDK ZED Fusion takes rectified stereo image as input and computes the disparity map. Given a video file (in .svo format), the SDK uses an optimized stereo algorithm to register the point clouds of consecutive frames, resulting in a 3D reconstruction of the scanned space. There is a marked difference in the performance of the device in low light (5lux-20lux) and high light conditions (150lux-250lux). Stereo reconstruction algorithms depend on accurate correspondences which in turn relies on unique features

Figure 9 Effect of Excess Lighting on quality of Scan from Tango

in the stereo images. Unique features are better identified with better lighting conditions. So, lighting indirectly influences the quality of the stereo-based 3D reconstruction.

Tango uses Infrared to detect the depth of the scene. As a result, any object directly illuminated by sunlight or artificial lighting was not captured. Figure 9 shows the area not detected due to excessive bright light (the same area was detected by ZED which is shown in Figure 6). Objects which had illumination less than 4lux were either not detected by a tango or the resulting reconstruction was distorted.

The effect of lighting on scenes comprising of the indoor as-built environment was studied by [8], which also reported similar effects.

3.1.5 Influence of Object Material on Scan Quality

The device was tested on common construction scenes encompassing concrete elements, masonry, reinforcement, finishing, and joineries. Objects such as reinforcements were not modelled at all since they were too small to be captured. When scanning reflective or transparent surfaces such as glass joineries, the point cloud generated using ZED camera gives a distorted surface. The possible reasons for this include improper computation of depth by the stereo algorithm in the SDK due to different reflections in multiple frames. On the other hand, the Tango tablet does not detect any transparent surface or objects that reflect light. Thus, for case 4, glass windows, and glass doors were not detected.

4 Summary of Results and Discussion

Both the devices were evaluated by testing them on the construction site on the following criterions:

- Mobility and Time Efficiency
- Accuracy: Precision and reliability of the resulting point cloud
- Scanning Methodology: Including path adopted and speed of scanning
- Influence of Lighting Conditions
- Influence of Object Materials

Both the two devices, Google Tango and ZED Camera tested scored well on the mobility and time efficiency. The devices were light in weight and easy to set up. Both devices don't require the user to have special skill set to operate. This allows the construction personnel to take ownership of this device without much effort. However, ZED camera should be connected to a computer while scanning. Unlike Tango tablet, ZED camera required to be connected to a computer while it captures the reality mesh. This limits the usability of ZED camera to an extent such as drone surveying.

It was observed that both these devices could capture the reality mesh with reasonable accuracy. The average error for Tango was 3.2% while that of ZED camera was 8.28%. Although these values benchmark these devices below Laser scanners, ease of use, mobility and commercial availability gives an edge for these devices over the laser scanners.

Although Tango tablet scored better in accuracy when compared to ZED camera, operational issues such as overheating, increased time for scanning etc. reduces the usability of Tango tablet. For example, while scanning Case 1, the device was continuously used for 20 minutes leading to overheating, battery drain and subsequently crashed. The crashing is a result of both overheating and the size of data. A 20-minute scan generates a huge file size, and the hardware is unable to progress further, causing the application to crash, and the data is lost before it can be saved. But, in order to assess the progress of a building under construction, multiple areas will have to be captured. A preemptive way to avoid losing data is to split large areas into smaller scans, thereby limiting the scanning time and avoiding overheating. But, such splitting will force the user to manually register the scan segments to each other to get the full 3D model, thus reducing the level of automation in progress monitoring and as-built generation workflows. The combination of Tango's range, FOV, scanning time and battery capacity makes it difficult to be adopted for continuous capture of the entire area under construction. Also, the device's performance in outdoor environments may not capture as well as indoor environments because of infrared radiations due to sunlight. Thus, it is more suitable for scanning smaller indoor areas and for applications that require fairly accurate models.

ZED camera, on the other hand, has better performance indoors provided sufficient lighting. It also works in outdoor environments, with the same range capabilities as indoors. Owing to its larger range and FOV, it is possible for the ZED camera to scan more area in lesser time. In addition to the real-time reality mesh capture, the ZED SDK offers the opportunity to save the *.svo files and process later. Hence, even if the device fails during the data capture, data isn't lost. Also, this makes ZED camera independent of the processing capability of the hardware subject to conditions such as availability of CUDA graphics processing. One can use a low-end laptop for data capture and then transfer files to a workstation with high-end computing capabilities for processing. This increases the reliability of ZED camera over Tango. Although ZED has these advantages over Tango, ZED has accuracy limitations, which can limit its usage to progress monitoring, and AR/MR Visualizations, but the creation of as-built models and using them for quality check might not be viable for all environments.

A major limitation observed in both these devices is their inability to detect glass/ transparent surfaces, making it difficult to automatically detect windows, doors and other similar surfaces. Workarounds for these have been explored in literature before. Whether the same heuristics and algorithms perform similarly for data from these devices needs to be explored.

5 Conclusion

This paper presented an evaluation of two devices which use two different technologies: a stereo vision based ZED camera and IR based Tango tablet in construction environments to generate as-built models. Most of the performance evaluation studies for Range camera devices have benchmarked these cameras to be less accurate than the laser scanners [10] [11]. However, the cost factor, consumer availability and ease of use make these cameras easier to be adopted in construction applications. This study explores the type of experiments needed to be performed to evaluate the applicability of these devices in construction environments which are dynamic and complex.

This study focuses on the preliminary tests performed using these devices to establish benchmarks for using them successfully for capturing a live construction site. But, their true capabilities need to be benchmarked in a controlled environment so that the best practices for using them can be established. In order to assess if these devices and their benchmarks are adequate for specific applications in construction such as progress monitoring remains to be explored. If the resulting accuracy of progress monitoring using these devices is comparable to conventional technologies such as lasers, then these low cost devices have the potential to make a tangible difference in construction project monitoring and control.

References

[1] A. Kemp *et al.*, “State Of The Nation 2017 : Digital Transformation,” London, 2017.

[2] R. Levitt, “Towards project management 2.0,” *Eng. Proj. Organ. J.*, vol. 1, no. 3, pp. 197–210, 2011.

[3] I. N. Davidson and M. J. Skibniewski, “Simulation of Automated Data Collection in Buildings,” *J. Comput. Civ. Eng.*, vol. 9, no. 1, pp. 9–20, 1995.

[4] T. Omar and M. L. Nehdi, “Data acquisition technologies for construction progress tracking,” *Autom. Constr.*, vol. 70, pp. 143–155, Oct. 2016.

[5] A. Bhatla, S. Y. Choe, O. Fierro, and F. Leite, “Evaluation of accuracy of as-built 3D modeling from photos taken by handheld digital cameras,” *Autom. Constr.*, vol. 28, no. December 2012, pp. 116–127, 2012.

[6] M. Aijas and A. Sharma, “Google Tango tablet,” in *Proceedings of International Conference on Advanced Computing (ICAC-2016)*, 2016, pp. 29–34.

[7] C. Sung and P. Y. Kim, “3D terrain reconstruction of construction sites using a stereo camera,” *Autom. Constr.*, vol. 64, pp. 65–77, 2016.

[8] M. Golparvar-Fard, J. Bohn, J. Teizer, S. Savarese, and F. Peña-Mora, “Evaluation of image-based modeling and laser scanning accuracy for emerging automated performance monitoring techniques,” *Autom. Constr.*, vol. 20, no. 8, pp. 1143–1155, 2011.

[9] S. Zennaro *et al.*, “Performance Evaluation of the 1st and 2nd Generation Kinect For Multimedia Applications,” *Multimed. Expo (ICME), 2015 IEEE Int. Conf.*, pp. 1–6, 2013.

[10] M. Froehlich and S. Azhar, “Handheld Simultaneous Localization and Mapping Devices for 3D Scanning,” no. Isarc, 2016.

[11] T. S. Kalyan, P. A. Zadeh, S. Staub-French, and T. M. Froese, “Construction Quality Assessment Using 3D as-built Models Generated with Tango tablet,” *Procedia Eng.*, vol. 145, pp. 1416–1423, 2016.

[12] A. A. Diakité and S. Zlatanova, “First Experiments With the Tango Tablet for Indoor Scanning,” *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci. Vol. III-4*, no. September, pp. 67–72, 2016.

[13] A. Burbano, M. Vasiliu, and S. Bouaziz, “3D Cameras Benchmark for Human Tracking in Hybrid Distributed Smart Camera Networks,” *Proc. 10th Int. Conf. Distrib. Smart Camera*, pp. 76–83, 2016.

[14] N. Li, “Imaged-based verification of as-built documentation of operational buildings,” *Autom. Constr.*, vol. 21, no. January 2012, pp. 161–171, 2012.

[15] Google. Project Tango. Online: https://developers.google.com/tango/hardware/tablet, Accessed: 15/02/2017.

[16] T. Schops, T. Sattler, C. Hane, and M. Pollefeys, “Large-scale outdoor 3D reconstruction on a mobile device,” *Computer Vision and Image Understanding*, vol. 157, pp-151-166.

[17] Runceanu et al., “Indoor Point Cloud Segmentation for Automatic Object Interpretation”, *Scientific-technical anniversary of the DGPF*, Wurzburg 2017, Accessed:03-05-2017.

[18] STEREOLABS, ZED Stereo Camera.Online: https://www.stereolabs.com/developers/ , Accessed: 03/02/2017.