Developing a Workflow for Cloud-based Inspection of Temporary Structures in Construction

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Abstract –

Temporary structures are used during construction and removed after construction. It is necessary to inspect these structures in terms of quality and stability in an automated manner. However, the storage and sharing of inspection data of temporary structures is a problem because most of them have not been included in Building Information Modelling. A cloud-based platform provides a possibility to improve the workflow of data collection and sharing the real-time information with different stakeholders. Hence, to address these issues, this paper aims to develop a workflow to monitor the temporary objects and share them through a cloud accessible to multiple users for safety management.

There is a need to measure the structure heights especially scaffolds during construction. However, traditional inspection methods like tape measurement and recording 2D images on site are tedious practices and sometimes not possible. This paper applied advanced 3D, 360 and action cameras for data collection. Two case studies have been selected. The accuracy of measurement and performance of the proposed workflow were evaluated. First, the initial results of this ongoing study show that implementing the proposed workflow is highly efficient. Second, the comparison of the results with the current practice demonstrates that the workflow can be used for estimating area and quality of certain objects in medium sized buildings. Third, the initial field experimentations reflect that the accuracy of this method depends on the complexity of sites. In conclusion, the developed workflow provides a new opportunity to site engineers to record objects and share information with head offices for further processes and updating information models off site.

Keywords –

3D building modelling; Photo modelling; cloud-based construction data analysis; virtual inspection; Temporary structure; Safety management

1 Introduction

According to “Safe work Australia” report from 2014 to 2015, construction is the third highest industry in serious incidents with 12,575 serious claims [1]. Thus, safety monitoring should be the first priority in construction. As a part of safety monitoring, checking quality of temporary structures is indispensable. For example, construction fencing should be fixed in order to not hurt people in windy and rainy days. However, Engineers usually ignore quality inspection of temporary structures because they will be removed after construction. This may result in serious incidents. For instance, scaffolding has collapsed on the playground of a primary school in Cardiff and frightened children due to lack of safety monitoring [2]. Hence, temporary structures should be checked constantly to ensure the safety in construction [3].

Although 3D-based safety monitoring and quality inspection is applied in construction, it cannot be used for temporary structure in most cases. This is because 3D information of temporary structures is always lack and not included in 3D Building Information Modelling (BIM). Moreover, data collection and transmission is an important task in safety monitoring of temporary structures. Conventional visualization collection methods for data collection are 2D image collection and taking periodical notes in situ. It is usually time-consuming to give data from one partner to another with these methods, and data loss can easily happen if no effective data recording and management method is provided. Thus, it is necessary to provide a feasible and cost saving 3D-based approach for information transferring and inspection of temporary structures.

Cloud computing provides a possibility of automated storing and sharing data of temporary structure conveniently and quickly. It is a type of technology using communication devices such as tablets, laptops and mobile photos to transfer information [4]. Receivers can know the updated information immediately via cloud computing. Related research has been operated. For instance, Matthews, et al. [5]

proposed a new process of progress management based on cloud-based BIM platform for real-time monitoring of a reinforced concrete structure. In this method, the contractor's site engineers can report the process daily using iPad. The project planners and other industry partners can see this real-time progress based on cloud-based BIM in office. Zou, et al. [6] developed a cloud-based information and communication system for safety management in infrastructure. They wrote a web page to connect a Google Drive for data storage shared to all partners. Although these research projects can improve communication and collaboration of different partners of construction projects, few of these visualization methods record temporary structures.

Virtual Reality (VR) provides better understanding of space to clients and contractors which can enhance collaboration such as revising design together [7]. For example, Paes, et al. [7] improved understanding of architectural components by designing an 3D immersive environment, and testers preferred to understand information in VR compared with 2D drawings. Hence, this paper will add VR technology to enhance information understanding for individuals who have no access to real construction sites.

Several digital cameras are applied in construction and civil engineering. 3D, 360 and action cameras are three types of digital cameras. 3D camera provides depth of image, which can create 3D scenes via structure light with stereo sensing or time-of-light sensing [8]. Traditional stereo cameras have two or more lenses to obtain 3D images. Time-of-light cameras project electromagnetic or other wave and record the time from projection to sensor received the reflected wave. 360 camera, also known as omnidirectional camera, is the camera having a field of view that covers approximately the entire sphere. It can be used in building engineering [9] and help to build surveillance system in construction site [10]. Action camera is designed for recording action process with low-cost, portable and high-resolution features.

This paper aims to present a workflow of recording temporary objects using advanced cameras and share the data in a cloud accessible to multiple users. It intends to utilize and evaluate visualisation technologies and investigate their applications in construction. It first introduces background of inspection of temporary structures. Second, the workflow with related methods is presented. Thereafter, challenges and opportunities of technologies are discussed from a practical sense.

2 Methodology

This paper presents a novel workflow for temporary structure inspection including data collection by advanced cameras and process and storage on cloud to make it available for multiple users.

Using advanced cameras, the developed workflow was employed to assist in real time communication for safety management. The whole workflow includes four main steps shown in Figure 1. First, collecting data with advanced cameras. Second, creating 3D models and 2D pano images. Third, inspecting the temporary structures including measuring dimension and adding markers. Finally, displaying scenes in a cloud-based platform with VR headset. Details are introduced as follows.

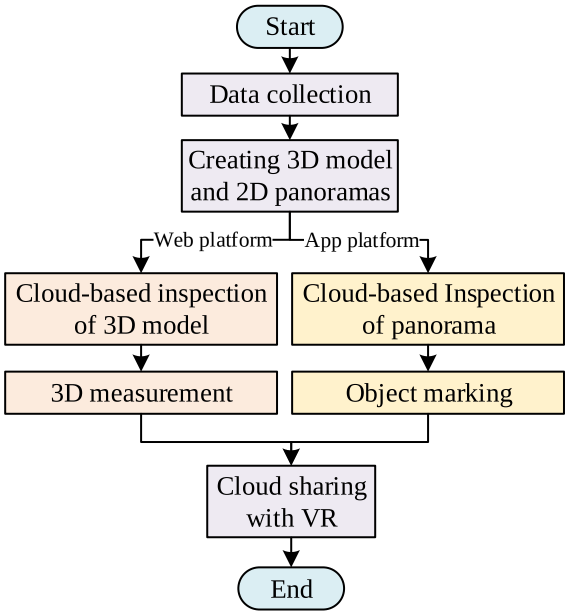


Figure 1. Developed workflow for the proposed experimentations.

2.1 Case Studies for Experimentation

The experimentation has been carried out in two places. The first place is Quadrangle Building construction site in the University of New South Wales (UNSW). Figure 2 (a) shows the plan view of the construction site from 3D model. The part in the red polygon is the construction site. Temporary objects in this scenario are mainly construction fences shown in Figure 2 (b).

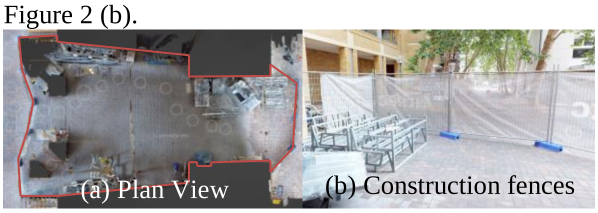


Figure 2. Quadrangle Building construction site.

The second place is a panel installation construction site with temporary objects such as unfinished panel installation shown in Figure 3 (b). The red rectangle in Figure 3 (a) is the location for data collection.

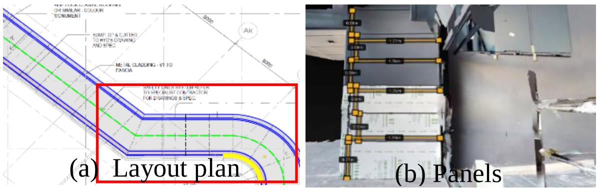


Figure 3. Panel construction site.

2.2 Data Acquisition Methods with Creating Models and Panorama

3D, 360 and GoPro cameras were used for image data collection. 2D camera is a traditional method for recording image data of temporary structures, which is considered as reference compared with other advanced cameras in this paper.

The first tool used for data collection is 3D camera. The structure light 3D camera in this paper can obtain panoramas with its self-contained App. It has an infrared light projector on the left side, an infrared light sensor on the right and an RGB camera in the middle. The projector and sensor create 3D models and the RGB camera creates the 2D panoramas. Thus, this paper uses it scan panoramas and collect 3D data of the site. A corresponding App of the camera is used for remote control. Data collection from 3D camera is shown in Figure 4.

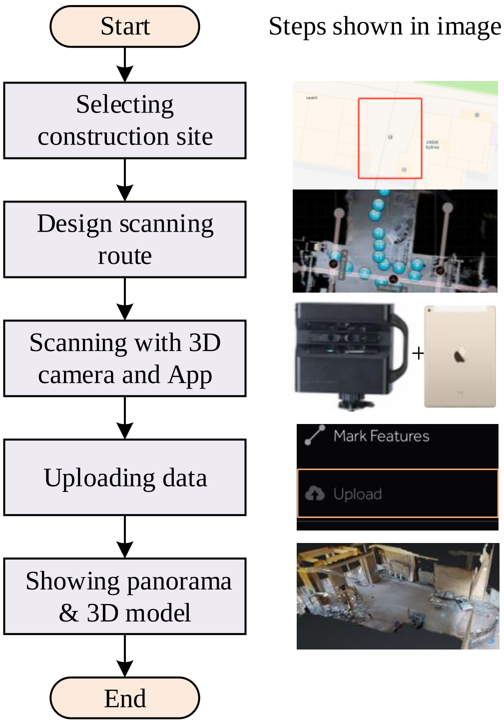


Figure 4. Steps of 3D camera data collection.

The second tool is a 360 camera shown in Figure 5. It is applied to record 2D panoramas of objects in construction site. It is small and portable with two fisheye lenses. The tripod under the lenses can help to fix the camera. Besides, a corresponding App in smart photo or tablet can aid to camera remote control. In order to compared with other cameras, the locations of 360 camera are the same as the locations of 3D camera. Thus, quality of pano images from 3D and 360 cameras can be compared, which helps site engineers to choose which device is more suitable for their construction projects. Data collection of 360 camera is quick and easy. Operators only need to tap the button for taking photos or recording videos on the device. If remote control is required, the corresponding App can be connected to the camera and operators can control the camera even a few meters away.

The third camera is a type of action camera, GoPro. GoPro has already been applied in civil engineering for displacement monitoring [11] and heritage reconstruction [12]. In this paper, GoPro is carried on with a headset by the authors to record the progress of the workflow from data collection to VR display. It is an advanced waterproof camera with wide angle lens shown in Figure 6. It is only around five hundred grams, so it is light enough to be carried on. Thus, it is widely used under the water, hiking and other sports. One of the most attractive functions is its anti-shake function, which is better than most traditional 2D cameras. This is the reason that this paper chooses GoPro to record videos other than ordinary 2D cameras.

Figure 5. 360 camera.

Figure 6. GoPro camera.

3D models will be created automatically by the 3D camera company after the collected data is uploaded by the operator. It could help to reduce modelling time. Besides, data of panoramas and 2D videos do not to be processed, so they can be shown directly in cloud-based platform. 3D models and panoramas can be seen in the website after automatically data process.

2.3 Inspection of structures

Two platforms for data from 3D and 360 cameras respectively are applied in this paper shown in Figure 1. One is an online website for inspection data from 3D camera. The other is an App for panoramas from 360 camera that can be used in tablet and smart phone. Section 2.3.1 introduces measurement based on 3D models operated on the website. Section 2.3.2 explains how to inspect panorama in this App.

2.3.1 3D Model Measurement

Dimension measurement in construction is usually by tape measure or laser scanning. Tape measurement is easy but has limitations. For example, it cannot be used for measuring height of scaffoldings in tall buildings and it takes long time to measure of objects [13]. Besides, although laser scanning spends less time and has higher accuracy, the device is expensive and requires high professional operation to process the scanned data. Laser rangefinder is easy to measure and cheaper than laser scanner, but it is arduous and can only be worked in situ. It is also necessary to calibrate the laser rangefinder regularly, which takes workers time. Thus, this paper attempts to apply offsite 3D model measurement in construction. After obtaining 3D models from section 2.2, operators need to log on the website of the 3D camera company. Then, they can measure the distance from 3D models directly.

The measurement is compared with tape measure which is reference. The accuracy of the method is calculated by Relative Error and Root mean square deviation (RMSE) [14]. The equations are:

$$\text{Relative Error} = \frac{s_1 - s_2}{s_2} \quad (1)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{t=1}^{T}(s_1 - s_2)^2}{T}} \quad (2)$$

T represents total times of measurement. s_1 means distance measured from 3D model. s_2 means distance from tape measurement. The results reflect the difference of measurement based on 3D model and tape. If the number is small, it means the difference is small. Thus, it could be judged that the method has a high accuracy.

2.3.2 Marking Objects

After taking photos by 360 camera, panoramas of temporary structures can be marked by every partner in the App. Thus, it is easy to communicate with each other using this App. Three main steps are included in adding markers. First, 360 photos should be imported into this App. Second, tapping the screen. The screen will show options including Talk+Draw, Markerup, Create Link, Comment and Insert Image. Users can choose what they need and even record their voice in this 360-view scene. After choosing an option, users can add their markers. Other users will see the changes and markers immediately if the data is revised by one user.

2.4 Panorama Shown in VR Headsets

The processed data from the two cloud-based platforms can both be shown in VR headset, which can provide visual experience to users. After logging in the platforms, the operator can choose certain accounts to access to data. Thus, engineers can share the space to multiple users and protect data that can only be seen by certain persons. It is convenient for site engineers recording temporary objects and checking construction conditions. It also provides an easy way for different offsite partners to realise and discuss danger and errors.

For the web platform for 3D camera data, VR experience can be achieved by clicking white circle button in the scene to move forward or backward. Users can see virtual scene as if they are in reality.

In order to show 3D spaces in VR headset, the user need to operate three steps after turning on the headset shown in Figure 7. The first step is logging in the website in VR headset. Next, selecting one of the scanned spaces and tapping VR button. Then, the left button in VR headset screen is the option that operators need to tap for this VR headset.

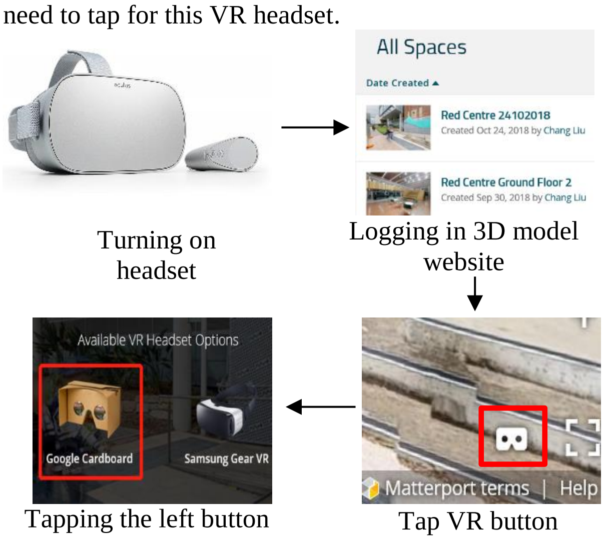


Figure 7. Showing 3D spaces with VR headset.

3 Results and Findings

3.1 Comparison of Results from Advanced Cameras and 2D Camera

The processed data results are listed in Table 1. 3D camera can create both 3D models, 2D images and 2D pano images. The quality of 2D images from 3D camera is the same as the quality of panoramas collected from 3D camera because the panoramas are merged from those 2D images. Besides, both 3D and 360 can create wider range 2D images than 2D camera. After comparing the data, the authors found that the quality of panoramas from 3D camera is the same as quality of images from 2D camera and is higher than panoramas from 360 camera, but data collection of 3D camera spent more time than 360 camera.

Table 1. Results from different devices.

Device	Processed data	Measurement available	Marking available
3D camera	3D models, 2D images and panoramas	Yes	Yes
360 camera	Panoramas and videos	No	Yes
2D camera	2D images	No	Yes

Moreover, process recording videos from GoPro have deformation at edges shown in Figure 8. The left walls in Figure 8 (b) is not a straight line, while Figure 8 (a) can show straight line taken by the 3D camera. Besides, the recording area of GoPro is larger than 2D camera but smaller than 360 camera because it only has one fisheye lens and cannot show panoramas.

Figure 8. Images from 3D camera and GoPro; (a) 3D camera; (b) GoPro.

Based on results, it can be concluded that the accuracy of 3D models from 3D camera is enough for ordinary inspection of temporary structures. However, due to environment and device limitation, thin objects are hard to be scanned by 3D camera. That may be reason of accuracy of the first place is lower than that of the second. 360 camera is more convenient and portable than 3D camera.

As for video recording, 360 cameras can record the changes in all directions, which has the largest recording area, but the pixel of image in videos is not as high as 2D camera. The chosen 3D camera in this paper cannot record videos.

The authors in this paper created twenty-two models. The average data processing time of the models is less than one day. The time mainly depends on the area of the scanned place. The larger area needs more time.

As introduced in 2.2, after creating 3D models and 2D pano images from captured data, results can be shared in cloud-based platforms. In order to inspect 3D models, partners in a certain construction project should log in a web page designed by the 3D camera company to see the models directly. Besides, measured distance based on 3D models and panoramas collected by 3D camera can also be inspected on the webpage which is introduced in section 2.3.1. Th authors found that the change of the view from 3D model to 2D pano image can be operated easily by clicking different buttons.

Although panoramas from 3D camera can be seen from the aforementioned webpage, panoramas from 360 camera needs another platform to be observed. The platform is an App which can be downloaded both in smart phone and tablet. The App can show 2D images and panoramas but not 3D models. Since the App can show all construction site views from different directions, it is easy to help offsite engineers to inspect construction site situation. The authors in this paper imported the data from 360 camera and conventional 2D camera to the App to create over twenty spaces. The data was collected every week and showed that the construction process can be shown directly by the image recording. Partners can add markers easily based on the attempt by the authors which is introduced in section 2.3.2.

3.2 Inspection of Structures from Results

3.2.1 Comparison of 3D Model Measure and Tape Measure

The authors measured length and height of the fences based on 3D models of the first construction site and results are listed in Table 2. Table 3 lists results from wall panel construction site. Figure 3 (b) shows the measurement of panels based on 3D models. All the results measured based on 3D models are compared with the referenced tape measure results. The relative error and RMSE for analysing error are also listed. It needs to mention that relative error results keep three decimal and RMSE results keep one decimal in Table 2 and 3.

Table 2. Results from Quadrangle Building.

Width (cm)	Tape (cm)	Relative error	RMSE (cm)	Length (cm)	Tape (cm)	Relative error	RMSE (cm)
238	233	0.021		178	177	0.006	
231	233	0.009		181	177	0.023	
226	233	0.030	4.0	187	177	0.056	9.5
233	233	0.000		195	177	0.102	
232	233	0.004		180	177	0.017	

RMSE of width and length of fences shown in Table 2 are 4cm and 9.45cm respectively. The results showed that the accuracy of measurement from 3D models are enough if the requirement of accuracy is not very high. Thus, it could help engineers to decrease measurement time for height of floors even buildings.

Table 3. Results from wall panels.

Object	Place	Dimension (cm)	Tape (cm)	Relative error	RMSE (cm)
Width of Wall panel 1	Left side	59.0	58.0	0.017	0.9
		57.0	58.0	0.017	
		57.0	58.0	0.017	
		58.0	58.0	0.000	
		58.0	58.0	0.000	
		58.0	58.0	0.000	
		58.0	58.0	0.000	
		56.0	58.0	0.034	
	Right side	58.0	58.0	0.000	
		58.0	58.0	0.000	
		58.0	58.0	0.000	
		57.0	58.0	0.017	
		58.0	58.0	0.000	
		58.0	58.0	0.000	
		58.0	58.0	0.000	
		60.0	58.0	0.034	
		57.0	58.0	0.017	
Length of Wall panel 1	Right side	177.0	177.0	0.000	1.6
		177.0	177.0	0.000	
		176.0	177.0	0.006	
		174.0	177.0	0.017	
Length of Wall panel 2	Left side	75.0	77.5	0.032	1.5
		76.0	77.5	0.019	
	Right side	77.0	77.5	0.006	
		77.0	77.5	0.006	

The results in Table 3 show that relative error is low for the second construction site, and RMSE is even no more than two centimetres. Thus, It could be stated that the accuracy of measurement results from the second place are better than those from the first place. This may due to the shape of measured objects. As aforementioned, the 3D camera in this paper is hard to collect data of thin objects. Steel tubes and iron wires on the measured fences in the first place may not be captured by this 3D camera, so the loss of thin object data may influence the accuracy of measurement. The detected objects in the second place are panels whose data are easier to be captured, so their collected data are more accurately than data from Quadrangle Building.

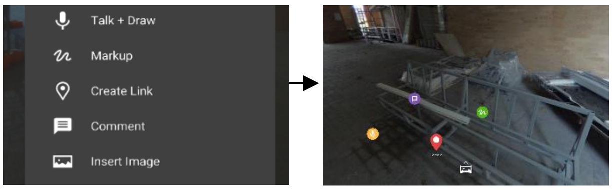
Although there are other methods for fast and accurate measurement of distance such as a laser rangefinder, these methods suffer from the following problems. First, lack of demonstration of real time data to other partners off site in a construction project is a main problem. Second, they will be time consuming and labour intensive if construction workers miss measurement of an area. Third, the difficulty of measurement between two points in case of existence of an obstacle cannot resolved now. Fourth, inability to store data results in the users have to record them manually. Visualising the measured distances by these methods in a digital environment is either impossible or inaccurate with time consuming operations.

Compared with the conventional measuring method, the major advantages of our proposed workflow are to overcome all these problems through automatically storing and sharing accurate 3D data in a cloud-based real time platform.

As for updating indoor 3D models specially for as-built BIM models, measuring floor height is time consuming and labour intensive. This becomes more difficult when the floor height is high such as the height of floors in shopping centres. Our method in automatic measurement of indoor buildings would be of high importance to deal with the problems of lacking time and budget for updating the as-built 3D models. It could also help to increase safety because construction workers do not need to stand in a high space to measurement dimension and height. The third benefit is that it can help to save labour because traditional methods may spend one hour while this method spends only ten minutes for data collection of the same place. However, the limitation is that the data obtained from 3D camera is hard to build 3D models of small or thin objects like thin tubes. The measurement of them cannot be operated.

3.2.2 Marking Objects from 360 Camera Data

Our method is easy to check the progress of construction. Engineers can see how much work has been done via cloud-based 360 views. In order to simulate communication of different partners in a construction project, several markers are added in the cloud-based App as shown in Figure 9. The markers will only show up when fingers tap them, so they do not block items in a construction site panorama. Based on the time of adding markers, the authors find that operating this function in the platform is quick and convenient. Voices, notes and markers can all be shown in one 360 view scene from different accounts that have access to the platform. Thus, different partners can share information quickly with others in this project. It can help to adjust the design during construction and warn dangerous area in time for optimizing construction management with providing effective communication for partners.



(a) Choosing one option (b) Adding markers

Figure 9. Markers in panorama.

3.3 Visualization

VR headset can access to data from both two cloud-based platforms, which helps to have a better understanding of construction environment. After processing all data, the authors invite testers to inspect VR scenes of the two places with VR headset. Based on the feedbacks from testers, VR scenes from both two places can help to understand information in construction site, which is better than 2D drawings. The quality of images in VR from both 3D and 360 cameras are high enough for inspection, while 3D camera images own higher pixels than 360 camera data. Engineers can inspect and discuss construction site situation in office shown in VR headset. Thus, they do not need to check the space in situ. What they need to do is only add markers, and then on-site construction workers can know the problems and dangers immediately shown in the cloud-based platform. One limitation is that some testers had headache or uncomfortableness of eyes if carrying on VR headset for a long time, so it is better to inspect not in a much long time.

Game engine is common for building 3D environment in VR. Operators can revise 3D models, add items and even add animation in game engine, which can provide a more vivid virtual environment than current cloud-based platform. This paper attempted to import 3D models into game engine to provide a virtual environment to multiple users in certain construction project. It can provide more options to revise models compared with cloud-based platforms, but it cannot share information in real time. In this paper, processed 3D models are imported in Blender, an open source game engine. Since the built 3D models can be downloaded in .obj format from cloud-based platform, Blender can read this format and show the models. However, after importing the data of the construction site, the model is shown without texture (see Figure 10 (a)). Figure 10 shows the comparison in different platforms. Based on it, it could be stated that 2D panorama has the highest pixel. Although Figure 10 (a) and (b) are from the same 3D model, Figure 10 (b) is clearer than Figure 10 (a). This may due to the .obj format has data loss besides texture loss.

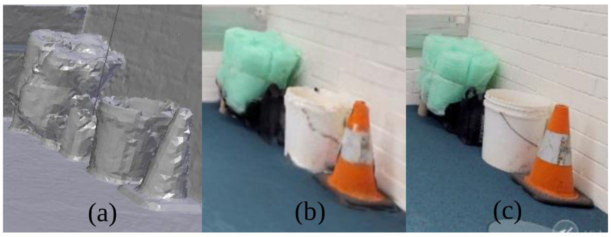


Figure 10. One scene in different platforms; (a) 3D model in Game engine; (b) the original 3D model in cloud-based platform; (c) Panorama.

4 Conclusion

This paper proposed a cloud-based recording and storing 3D data workflow of temporary structures for security purposes in construction. The novelty of the workflow is to provide a method of measuring and storing temporary structures data in a fast and safe way, because workers do not need to climb ladders or allocate a labour to observe and produce inspection reports in the construction site. The measurement results were evaluated based on computational error analysis methods relative error and RMSE. The results show that the accuracy of measurement is enough for inspection, so different partners can participate safety management off site in a cloud-based platform by inspecting information from construction site. Time latency would be eliminated, and efficiency of safety management can increase, because the time of transmitting data could decrease with the workflow.

Challenges and opportunities of temporary structure data sharing from advanced cameras for construction safety management have been identified with the several attempts in this paper. First, the cloud-based platforms in this paper can show 2D images, 2D pano images and 3D models. They provide more information than traditional safety management methods because traditional image methods only record ordinary 2D images. Based on the results of case studies, the accuracy of 3D model is enough for ordinary inspection. Thus, different partners can share information in real time. Second, in order to help engineers to measure dimensions off site, there is an attempt to inspect temporary structures based on 3D models and panoramas, which contains dimension measurement and marking addition. It needs to mention that the data that is hard to be obtained by tape measure such as height of a floor or the dimension of a wall can be measured in this workflow, so the workflow can save labour and time. Third, the workflow adds VR experience, which is few applied in safety management at the current stage. Based on the feedbacks from testers, VR can simulate the construction environment, so different partners can walk in VR environment by tapping the button to have a better standing of on-site situation and locations of construction objects in a construction project. It would be convenient to discuss and revise arrangement and method for construction. Although the workflow can realize cloud-based inspection without VR, the understanding would be as clear as the workflow with VR. Thus, VR is an important part in this workflow.

This study discussed significant potential benefits of the advanced cameras. However, the limitation of the study is that information of 3D models and panoramas are shared in two different cloud-based platforms. Besides, thin objects have not been shown in 3D models clearly because of the technological limitation of devices. Future work should consider how to integrate information from all resources to be shown in only one platform. Selecting a type of advanced camera for inspection of thin objects is suggested Besides, adding animation and items in game engine for cloud-based publication could be a direction for future work. Moreover, there is another direction is that integrating 3D modelling with BIM to add temporary objects in BIM. It can help to provide more building information.

References

[1] Australia SW. Number of Serious Claims by Industry 2000–01 to 2014–15. Online: https://www.safeworkaustralia.gov.au/statistics-and-research/statistics/disease-and-injuries/dis ease-and-injury-statistics-industry

[2] CIOB. Firm Fined after Scaffolding Collapses onto Primary School. *Construction Manager*,2019. Online: http://www.constructionmanagermagazine.com/news/firm-fined-after-scaffolding-collapses-primary-sch/

[3] Liu X., Song Y., Yi W., Wang X., and Zhu, J. Comparing the Random Forest with the Generalized Additive Model to Evaluate the Impacts of Outdoor Ambient Environmental Factors on Scaffolding Construction Productivity. *Journal of Construction Engineering and Management,* 144 (6): 04018037, 2018.

[4] Wong J., Wang X., Li H., and Chan G. A Review of Cloud-based BIM Technology in the Construction Sector. *Journal of Information Technology in Construction*, 19: 281-291, 2014.

[5] Matthews J., Love P.E., Heinemann S., Chandler R., Rumsey C., and Olatunj O. Real time Progress Management: Re-engineering Processes for Cloud-based BIM in Construction. *Automation in Construction,* 58: 38-47, 2015.

[6] Zou P.X., Lun P., Cipolla D., and Mohamed S. Cloud-based Safety Information and Communication System in Infrastructure Construction. *Safety Science*, 98: 50-69, 2017.

[7] Paes D., Arantes E., and Irizarry J. Immersive Environment for Improving the Understanding of Architectural 3D Models: Comparing User Spatial Perception between Immersive and Traditional Virtual Reality Systems. *Automation in Construction,* 84: 292-303, 2017.

[8] Du H., Henry P., Ren X., Cheng M., Goldman D.B., Seitz S.M. and Fox D. RGB-D Mapping: Using Depth Cameras for Dense 3D Modeling of Indoor Environments. In *Proceedings of the 13th international conference on Ubiquitous computing,* Beijing, China, 2011.

[9] Felli F., Liu C., Ullah F., and Sepasgozar, S. M. Implementation of 360 Videos and Mobile Laser Measurement Technologies for Immersive Visualisation of Real Estate & Properties. In *Proceedings of the 42nd AUBEA Conference 2018: Educating Building Professionals for the Future in the Globalised World*, pages 294-304, Singapore, 2018.

[10] Yang X., Li H., Huang T., Zhai X., Wang F., and Wang C. Computer‐Aided Optimization of Surveillance Cameras Placement on Construction Sites. *Computer‐Aided Civil and Infrastructure Engineering,* 33: 1110-1126, 2018.

[11] Lydon D., Lydon M., Taylor S., Del Rincon J. M., Hester D., and Brownjohn J. Development and Field Testing of a Vision-based Displacement System using a Low Cost Wireless Action Camera, *Mechanical Systems and Signal Processing,* 121: 343-358, 2019.

[12] Fiorillo F., Limongiello M., and Fernández-Palacios B.J. Testing GoPro for 3D Model Reconstruction in Narrow Spaces. *Acta Imeko,* 5: 64-70, 2016.

[13] Lyu H.M., Shen S.L., Zhou A., and Yang J. Perspectives for Flood Risk Assessment and Management for Mega-City Metro System. *Tunnelling and Underground Space Technology,* 84: 31-44, 2019.

[14] Sepasgozar S.M., Forsythe P., and Shirowzhan S. Evaluation of Terrestrial and Mobile Scanner Technologies for Part-Built Information Modeling. *Journal of Construction Engineering and Management,* 144(12): 04018110, 2018.