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EVALUATION OF WALL EVENNESS USING DEPTH SENSOR FOR BUILDING QUALITY ASSESSMENT

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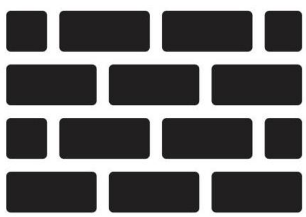
Graphical abstract



Abstract

The advancement of computing technology has spearheaded the change in the industry nowadays. Due to high speed processors which improves processes in industries, the construction industry has also adopted the Industry 4.0 via the Construction 4.0 Strategic Plan. Not only robots and its advanced technology impacted the assembly process in construction, it has also encouraged technologies to be applied in the quality assessment process, i.e. after a building has completed construction. The quality assessment robot is proposed in this paper, to address the wall evenness assessment as one of the criteria in the Internal Works from the Construction Industry Standards 7 (CIS7). It uses an Intel Realsense L515 LIDAR depth camera fitted onto a mobile robot, which houses a MiniPC, mobile robot controller and four 60mm mecanum wheels. The results of the assessment shows a promising 92.3% accuracy, which shows the viability of the proposed assessment method that could measure a 60cm x 50cm wall depth image from a 70cm center distance from the depth camera.

Keywords: Quality Assessment System, Building Construction Works, Internal works, depth camera, Mecanum wheels

Abstrak

Kemajuan teknologi pengkomputeran telah menerajui perubahan dalam industri pada masa kini. Disebabkan oleh pemproses berkelajuan tinggi yang menambah baik proses dalam industri, industri pembinaan juga telah menerima pakai Industri 4.0 melalui Pelan Strategik Pembinaan 4.0. Bukan sahaja robot dan teknologi canggihnya memberi kesan kepada proses pemasangan dalam pembinaan, ia juga telah menggalakkan teknologi untuk digunakan dalam proses penilaian kualiti, iaitu selepas bangunan selesai dibina. Robot penilaian kualiti dicadangkan dalam kertas ini, untuk menangani penilaian kesamaan dinding sebagai salah satu kriteria dalam Kerja Dalaman daripada Piawaian Industri Pembinaan 7 (CIS7). Ia menggunakan kamera kedalaman Intel Realsense L515 LIDAR yang dipasang pada robot mudah alih, yang menempatkan MiniPC, pengawal robot mudah alih dan empat roda mecanum 60mm. Keputusan penilaian menunjukkan ketepatan 92.3% yang menjanjikan, yang menunjukkan daya maju kaedah penilaian yang dicadangkan yang boleh mengukur imej kedalaman dinding 60cm x 50cm dari jarak tengah 70cm dari kamera kedalaman.

Kata kunci: Sistem Penilaian Kualiti, Kerja Pembinaan Bangunan, Kerja dalaman, kamera kedalaman, roda Mecanum

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1.0 INTRODUCTION

The advancement of technology nowadays which spawns the Industrial Revolution 4.0 enables several industries to elevate its processes and products. Some of the industries triggered are the manufacturing and the construction industry. In Malaysia, the Construction 4.0 Strategic Plan [1] outlined the four enablers which are people, integrated technologies, economy and governance. 12 main technologies that will change the future of the construction landscape are Building Information Modeling (BIM), pre-fabrication and modular construction, autonomous construction, augmented reality and virtualization, cloud and real-time collaboration, 3D Scanning and Photogrammetry, Big Data & Predictive Analysis, Internet of Things, 3D Printing and Additive Manufacturing, Advanced building materials, Blockchain and Artificial Intelligence. This strategic plan shows the interest of the government to start integrating technology with construction processes. Researchers in [2] highlighted the challenges of the implementation of construction robotics technologies in the construction industry, which includes cost, incompatibility of technologies, nature of construction industry, technological usability, technology adoption by workers, resources and retraining of workers. Of all the mentioned challenges, the research concluded that the cost to maintain the construction robot was the main challenge. Another research [3] used cross influence matrix multiplication method to analyze the barriers of application of construction robot, in which the factor 'lack of talent in the research field' was the highest driving force challenge.

In the construction industry, most of the application of the robots are in the assembly process, as well as deconstruction projects. Li Meng *et al.* [4] analyzes the characteristics and advantages of robot intelligence, autonomy and multi-function for assembly-type building construction robots. In the 1980s, Europe began developing robotic ground navigation system using Programmable Logic Controllers. Later in the 1990's, Asia started developing assembly-type construction robot technology by integrating sensors, machine vision for intelligent operation. In 1994, Pritschow *et al.* [5] proposed a brick-laying robot using a Swedish construction machine which was usually applied for removal of slag in industrial smelting furnaces and demolition works. The brick-laying robot was modified by fitting servo-valves and position and angle measuring systems as well as a robot wrist to increase its degree of freedom. Gambao *et al.* in 1997 [6], proposed a robot assembly system for construction using the Computer Integrated Construction (CIC) concept which attempts to integrate each phase of construction process through computers and communication technologies. The ROCCO robot's task was to assemble blocks in industrial buildings with a height of up to 8m. The robot could carry 500kg payload via its hydraulic actuators. The BROKK excavator robot was used in Lee H.J. *et al.* [7] proposal for semi-autonomous deconstruction, specifically for hammering. The commercially available machine was enhanced with visual sensors in which the human operator can remotely monitor the workspace. By using 3D software that can interactively place a simulated hammer, the human can determine the desired hammering point and trajectory. Before executed in the actual machine, the planned motion is visualized to the operator. This enhances the process safety and efficiency. The excavator robot was also studied by researchers in [8], this time for use in road construction, which could measure roughness of road surfaces and thickness of pavement layers, with the use of additional sensors such as Asphalt Concrete Density meter and MIT-SCAN-T2.

The mentioned research were single mobile robots with a robot arm manipulator that fulfils the purpose of a specific task. As sensors and communication technology advances, researchers integrated wearable sensors for human and robot collaboration work in construction [9]. This wearable sensor uses tap sensor on the fingers and convolutional neural network for hand gesture recognition. The high speed processing technology of computers nowadays enable simulation of multiple robots for efficient planning of construction work. For example, Hartmann *et al.* [10] proposed a multi-robot rearrangement planning for construction assembly. They combined optimization methods to solve manipulation constraints for the motion planning of the multiple robots used. Mattern *et al.* [11] simulated wire robots using a framework which involves process parameter optimization, discrete event simulation and continuous simulation. However, since the wire robot moves in its defined workspace, in actual implementation, no human is allowed inside the robot's workspace.

Some research of cooperative or multi-robots were also proposed in construction environment, such as [12] which proposes robots to perform work progress monitoring instead of human (project manager). Researchers proposed aerial monitoring via drone and ground monitoring via wheeled robots which navigates around flat area. Progress monitoring is proposed by comparing between design data (3D CAD) and collected data (video and point cloud) from the robot(s). Wallace *et al.* [13] investigated multimodal teleoperation of heterogeneous robots in a construction environment. The robots used were DRC Hubo humanoid robot and Spot from Boston Dynamics and integrated Virtual Reality as well as various sensors such as RGBD cameras. The robots successfully collaborated through synchronous and asynchronous mode.

The research mentioned previously were concentrated to construction process implementation using robots. After a construction work (i.e. buildings) finished, it is common to have quality assessment performed to ensure the finished work adhere to minimum standards. To date, only a few research have been focused on the quality assessment using robots for internal or external works of finished building or construction sites. Currently, the quality assessment is done by human inspection equipped with basic tools. If the construction site contains a large amount of houses or blocks, the assessment of the buildings would not finish in one day but require a few days. Due to this burden on the human assessors, some researchers proposed technologies to improve the assessment process.

A custom-built quality assessment robot carried out assessment of criteria of the structure quality. Maik Benndorf *et al.*, in [14] designed a bridge statics assessment robot for flood evacuation planning. The system utilizes vibration measurement sensors mounted on an Unmanned Ground Vehicle (UGV). The vehicle was also equipped with a robotic manipulator. In terms of quality assessment of internal works of a building, Rui-Jun Yan *et al.* [15] developed a custom-designed quality assessment robot. Several new technologies were integrated in the quality assessment robot, which was named as Quicabot. It includes thermal camera with a heater for hollowness assessment of the ground and walls, an RGB camera for crack detection, a laser scanner to evaluate the evenness of the ground and walls and alignment of two connected walls. It also uses an inclinometer to assess the ground inclination. Previously, we developed a Quality Assessment robot for the evaluation of wall evenness using laser levelers and image capture and processing using High Definition camera [16].

In this paper, we propose a method of assessment for the wall evenness criteria, by using a depth camera, Intel® RealSense™ LiDAR Camera L515 mounted on a mobile robot which follows the wall.

2.0 METHODOLOGY

This section explains the methodology to carry out the wall evenness assessment which includes the construction of the robot and its subcomponents and the method of wall evenness assessment.

2.1 The Quality Assessment Robot

A robot for the quality assessment of internal works, was designed, as shown in Figure 1. The earlier version of the robot was a multi-criteria assessing robot, but the one developed for this purpose is smaller in dimension and weight and solely for wall evenness criteria. Its specifications are shown in Table 1.

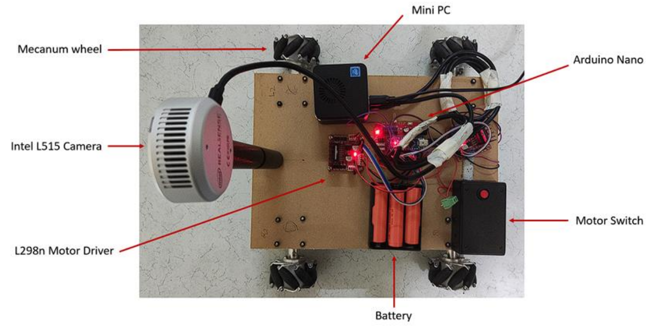

Figure 1 The wall evenness assessment robot

Table 1 Wall Evenness Assessment Robot Components

Main Part	Sub-component	Details
Robot base	Size	210mm x 297mm
	DC motors (4)	12V 150RPM 1.8kgfcm 36mm diameter
	Coupling (4)	6mm Key Hub for 60mm Mecanum Wheel
	Mecanum wheel (4)	60mm
	Motor Drivers (2)	2Amp 7V-30V DC Motor Driver (2 Channels)
Power supply	12 V DC Batteries	Rechargeable Lithium Ion 12V Batteries
Controller	Mobile Robot Controller	Arduino Nano
	Data acquisition and Processing	GMK M2T NUCBOX (Intel J4125)
	Display	13.3 inch Monitor
Sensors	Intel® RealSense™ LiDAR Camera L515	Depth Field of View: 70° × 55° (±3°) Depth output resolution: 1024 × 768 Depth frame rate: 30 fps

As seen in Table 1, several parts are needed for the robot to function. It includes the robot base, power supply, controllers and sensors. The robot structure is built from a 5mm acrylic plate which is 210 x 297 mm size.

The block diagram of the Wall Evenness Assessment Robot is shown in Figure 2. It consists of two main parts/controllers, which are the Main Processor and the Mobile Robot Controller. The main controller parts consists of the Central Processing Unit (CPU) and the Intel L515 Depth camera. The Mobile Robot Controller controls the four motors which are connected to the four Mecanum wheels.

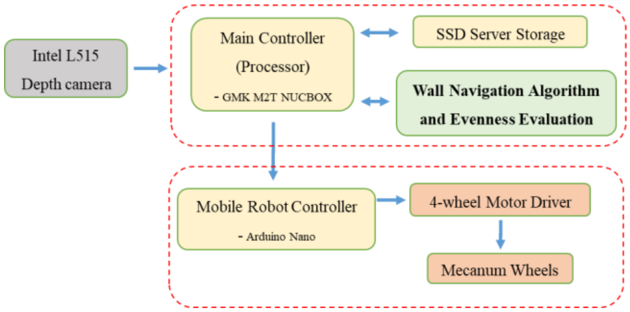

Figure 2 Block diagram of the Wall Evenness Assessment mobile robot

The Intel L515 Depth camera is used for two purposes; for wall navigation (moving along an assessed wall) and evenness evaluation. For wall navigation, it uses depth information on the far-left and far-right pixels to detect whether the camera is facing the wall (body of robot is perpendicular to the wall surface) at a desired distance, i.e. 700mm. If the robot is far from the wall, it will move and approach the wall. If it is within 600mm, the robot will stop its motion and second algorithm will commence. The second algorithm is the wall evenness evaluation, which will record a snapshot of the depth information saved to the SSD drive and also analyze it to determine the wall evenness based on a defined threshold variation.

Since the robot has a CPU connected to a display device, a Graphical User Interface (GUI) was developed for ease of operation of the robot, as shown in Figure 3.

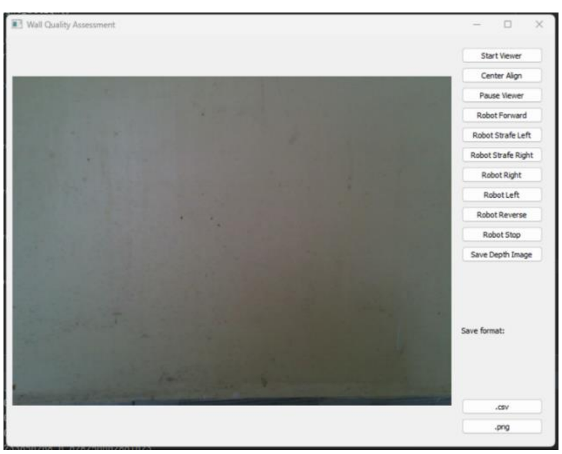

Figure 3 The wall-tapping mechanism and floor-tapping mechanism

The GUI has basic robot movement commands as well as visualization of the depth image. The basic commands are such as robot forward, robot reverse, robot strafe left and strafe right, robot right and robot left and robot stop. The strafe commands move the robot sideways, while keeping the wall in view of the depth camera as opposed to robot left and robot right commands which turns the robot's body to the left or to the right based on the center of the robot's body. The depth camera image can be viewed on the screen by clicking the 'Start Viewer' button, which will show a 640 x 480 resolution depth image. Other than viewing the image, the depth information can also be saved in Comma Separated Value (CSV) format which contains every pixel depth value in millimeters. The depth image can be saved in Portable Network Graphic (PNG) format. Both these formats will be saved in the SSD drive of the mini PC.

2.2 The Wall Evenness Assessment Approach

Before evaluating the wall evenness criteria, the robot needs to navigate from a start position more than 1m from the wall. This is to enable the robot to approach the wall and reach the desired distance of around 700mm from the center pixel of the depth sensor, as seen in Figure 4. At this position, the body of the robot should be aligned with the wall to enable the depth of the wall to be captured at parallel positioning from the robot.

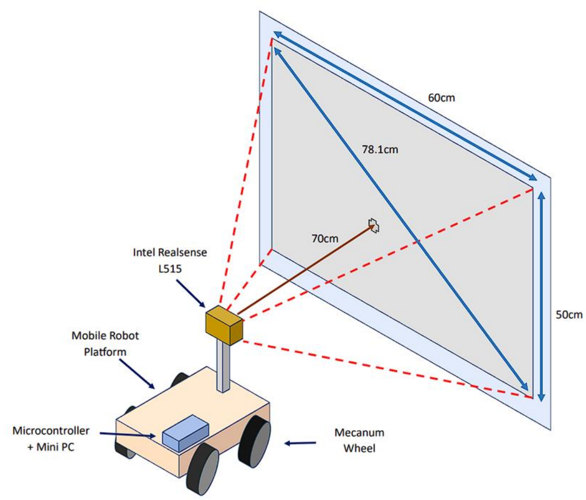

Figure 4 Illustration of the mobile robot capturing a depth image

The front view of the camera (depth image) can be illustrated as in Figure 5, where the resolution of the depth image is 640 x 480 pixels. Point A is marked on Figure 5 at the center of the image.

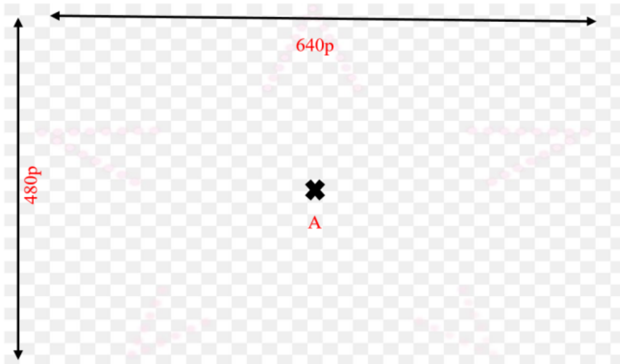

Figure 5 Illustration of the center position of the depth image

The wall navigation algorithm of the mobile robot is depicted in Figure 6. It uses the far-left and far-right pixel's depth value to determine whether the robot is aligned with the wall or not. Once the robot faces the wall, the robot is aligned to the wall surface by adjusting the left and right mecanum wheels to achieve similar left and right distances from the depth sensor reading (L metres). The wheels can rotate forward or backwards which will adjust the orientation of the robot, since the axis of rotation is at the center of the robot body. At these pixels, both values should be at the desired depth value that matches with the center pixel desired value. When it has reached this position, the complete depth image will be saved and analyzed

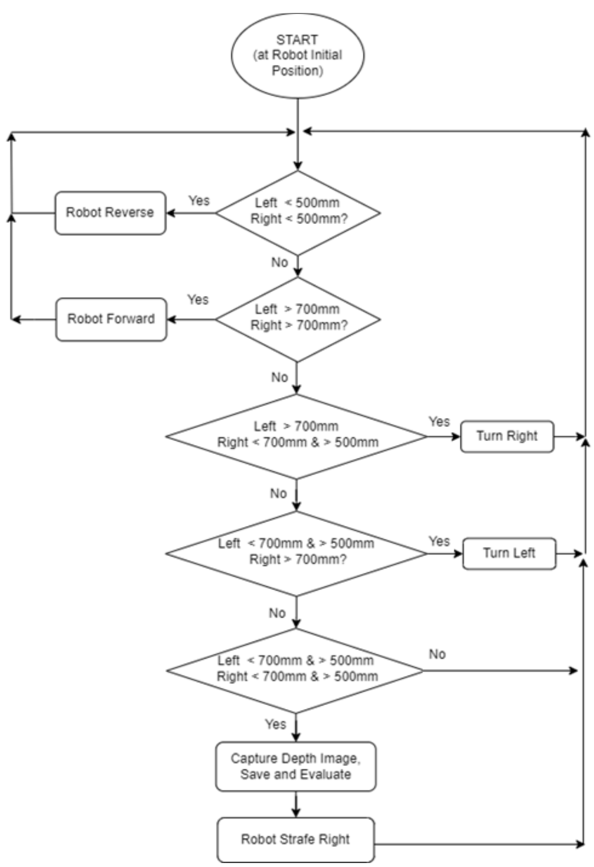

Figure 6 Wall Navigation Algorithm for the mobile robot

The horizontal and vertical image size of the depth image seen in Figure 4, can be determined via 2nd Principle Point Lens as in Figure 7 and 8 and equations (1) to (5). While the first principle states that a ray parallel to the principal axis refracts through the focal point, the second principle indicates that when light rays pass through the second focal point of a lens, the rays emerge parallel to the principal axis on the opposite side. When a light source or an object positioned such that one of the light rays passes through the second focal point of the lens, the ray bends upon refraction and exits the lens parallel to the principal optical axis. This forms a sharp image on the opposite side of the lens.

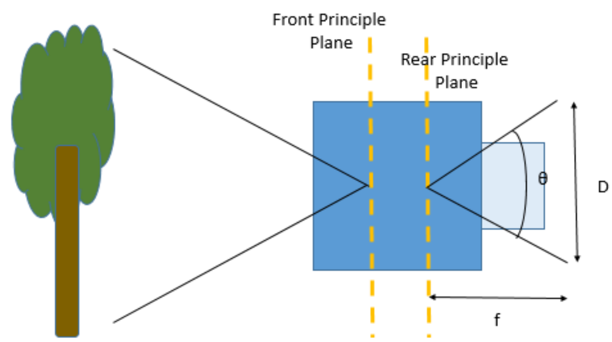

Figure 7 2nd Principle Point Lens illustration

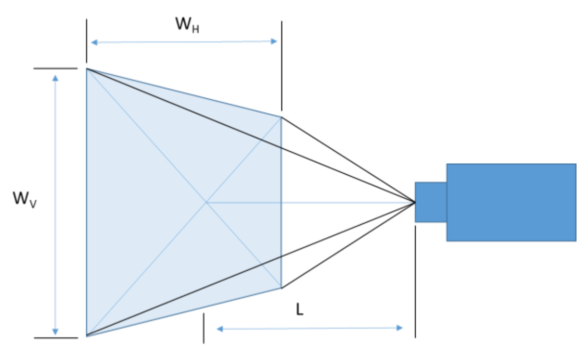

Figure 8 Subject Range Formula

$$\theta = 2\,tan^{-1}\frac{D}{2f} \tag{1}$$

$$\theta_H = 2 * tan^{-1}\frac{D_H}{2f} \tag{2}$$

$$\theta_V = 2 * tan^{-1}\frac{D_V}{2f} \tag{3}$$

$$w_H = 2L\,tan\left(\frac{\theta_H}{2}\right) \tag{4}$$

$$w_V = 2L\,tan\left(\frac{\theta_V}{2}\right) \tag{5}$$

Where Θ_H is the horizontal angle, Θ_V is the vertical angle, D is the image size, D_H is the horizontal image length, D_V is the vertical image length, f is the focal length, W_H is the horizontal length of the subject and W_V is the vertical length of the subject.

Both length and width of the wall can be determined using subject range formula using the official Intel Realsense L515 camera specification. According to the specification, L515 camera have Field of View (FOV) of 45° × 40° (±3°). Hence, the value of FOV and fixed distance of 0.7m, tested wall height and width can be easily be inserted to the subject range formula. This results in a horizontal length of 0.6m and vertical length of 0.5m.

In Figure 6, the robot approaches the wall to a desired distance and aligns itself with the wall (front facing position) by using the far-left and far-right depth values. If the robot moves too fast and is too close to the wall (i.e. less than 500mm), the robot reverses until it reaches the desired distance. Then, the depth information is captured, stored, and analyze to determine the wall evenness. After capturing depth information, the robot strafes to the right and repeats the wall alignment and depth information acquisition process until it reaches the end of the wall, as illustrated in Figure 9. The strafe motion is realized by using the Mecanum wheels attached to the motors.

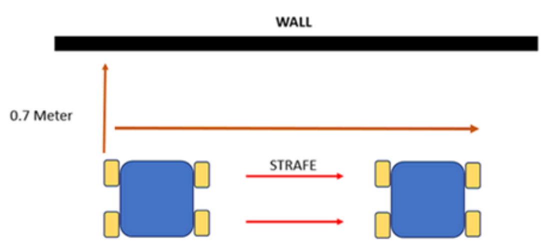

Figure 9 Illustration of the strafe motion

The conventional method of assessing the wall evenness is by using 1.2 m spirit level and steel wedge (taper gauge) held by a human assessor, as described in the Malaysian Construction Industry Standards (CIS 7), as seen in Figure 10.

Figure 10 Conventional method of assessing wall evenness

However this method requires contact with the wall and could be tiring if the amount of assessment is large (high number of samples of houses to be assessed). Some assessors might take large samples of the wall in a room, but others may only take samples of wall that he/she sees as a possible defect. This results in inconsistencies of the assessment evaluation.

In this research, we focus on the wall evenness assessment using non-contact based approach. To assist the assessment, the robot helps by acquiring depth images and processes the images to determine wall evenness. By using this method, depth information acquired will be at consistent distances. The picture of the robot performing evenness evaluation is seen in Figure 11.

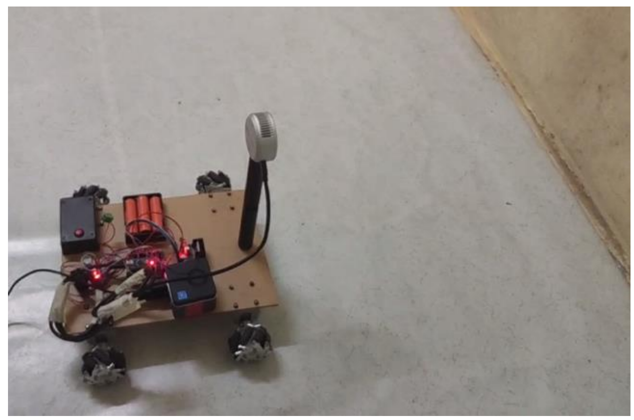

Figure 11 Mobile Robot performing Wall Evenness Assessment

3.0 RESULTS AND DISCUSSION

The depth image acquired and filtered is shown in Figure 12. It shows the varying depths at different positions (pixels) of the image. This image is a measurement of an even wall with the different shades represent the varying depths obtained from the sensor.

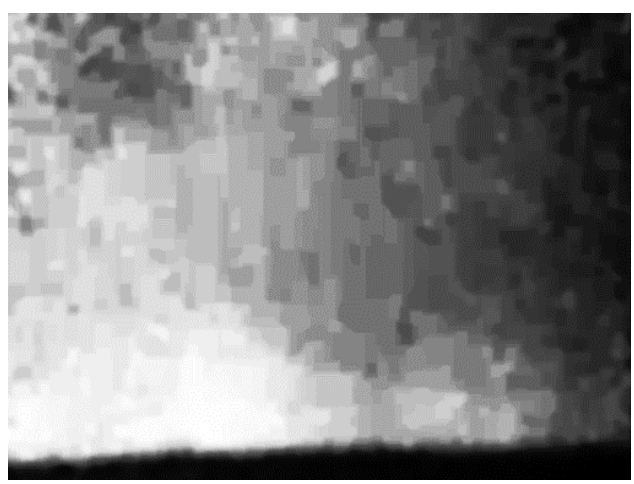

Figure 12 Depth image acquired by the sensor

To visualize the depth data, several samples are plotted. These plots are taken at certain vertical distance to show the varying depth information gathered, as shown in Figure 13. These are data from the same wall image, which is even. The collected data is also summarize in Figure 14.

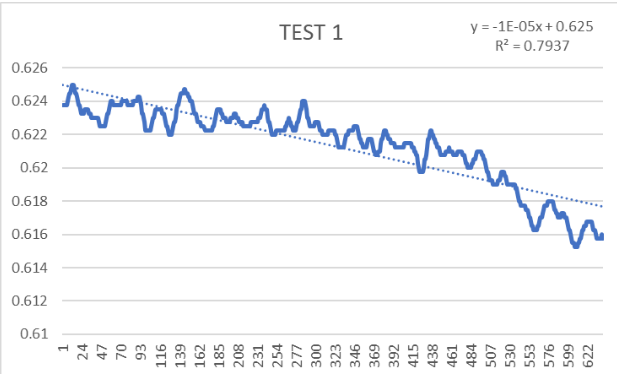

Figure 13 Depth data sample test

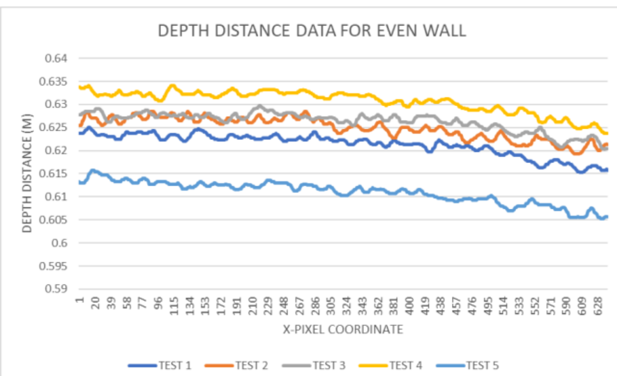

Figure 14 Depth data of the multiple readings from the depth image

The depth data shows that there is a slight decreasing value due to the left and right side of the robot which have a slight angle. This is because the reading is taken from the robot after the robot aligns itself to the wall by readjusting the four Mecanum wheels. Although, theoretically the sensor faces the wall in parallel axis, but due to motor braking and Mecanum wheels slip, the angle is slightly displaced.

3.1 Fixed Wall Depth Test

To test the ability of the sensor to measure the depth distance, we perform another test, this time to measure a wall depth value of 0.065 m, as shown in Figure 15.

Figure 15 Measurement of Fixed Wall Depth.

This depth wall test was conducted five times in fixed mobile robot position of 0.7m from the wall to control any unwanted misalignment present from mobile robot movement that may cause data variation. This test will help to determine the accuracy of depth distance collected from the quality assessment system compared to manual inspection. The results of this test are shown in Figure 16, measured at 1st pixel (minimum depth distance) and 305th pixel X-coordinate (maximum depth distance). The results are also shown in Table 2. Tests 1 until 5 was to confirm the consistencies of the minimum and maximum depth distance at five different readings at five different times in the day (8.00 am until 12am at hourly intervals). Results show that its consistency is acceptable, with an average distance of robot to wall at 7cm (0.7m minus the 0.63m reading) and maximum depth varies at a maximum of 1.5 mm range and the minimum depth varies at a maximum of 1mm.

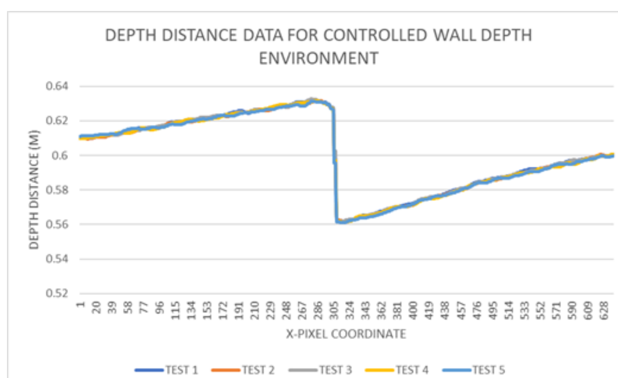

Figure 16 Depth Distance Data for Controlled Wall Depth Environment

Table 2 Fixed Depth Test Results

Test	Maximum Depth Distance (m)	Minimum Depth Distance (m)	Depth Difference (m)
1	0.631750047	0.562000036	0.069750011
2	0.631750047	0.562000036	0.069750011
3	0.632750034	0.561750054	0.07099998
4	0.631500006	0.561250031	0.070249975
5	0.631250024	0.561000049	0.070249975
		TOTAL AVERAGE	0.07019999

Based on the results, the average height difference between the lower wall part and the higher wall part is 0.07m which is much higher than manual inspection value of 0.065m. Therefore, it can be stated that the quality assessment system has +-0.05m in depth accuracy and percentage error of 7.69%.

3.2 Uneven Wall Assessment

For the uneven wall test, an image with wall deformities that show a hole in the wall is seen in Figure 17. The depth sensor will be tested on this uneven wall to assess its capability. The same procedure used previously to assess the even wall, will be used on the uneven wall. The uneven wall test was also conducted via manual inspection using spirit level and taper gauge before the quality assessment system is used to test the wall condition as shown in Figure 17. According to Construction Industry Standards 7 (CIS7) from CIDB, the wall is considered uneven when it exceeds 3mm. After manual inspection, the uneven wall contains deformities which is a hole with the depth of 0.0065m.

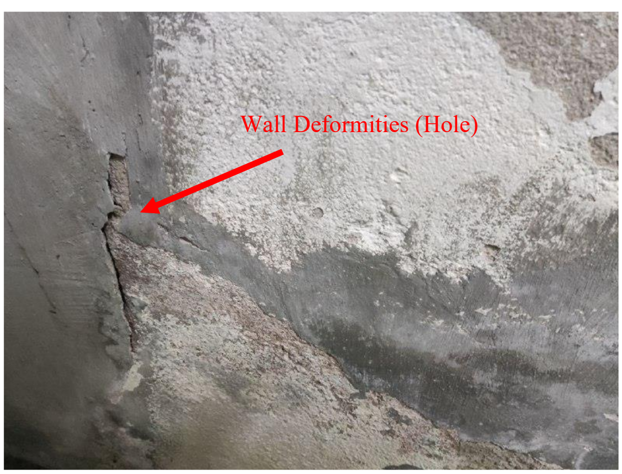

Figure 17 Uneven wall picture

The collected depth distance data for an uneven wall is shown in Figure 18. All five-test result shows the same graph pattern, the 1st X-pixel coordinate slightly decrease until reaching around 190th X pixel coordinate before sharp decrease in depth value until reaching 250th X pixel coordinate. Then, the graph will sharply increase in depth value until reaching 280th X pixel value and stablise until reaching around 510th X pixel coordinate. The fourth test has the highest depth data collected due to the mobile robot stops 2cm further from the wall. However the pattern of the depth is almost similar to the other tests.

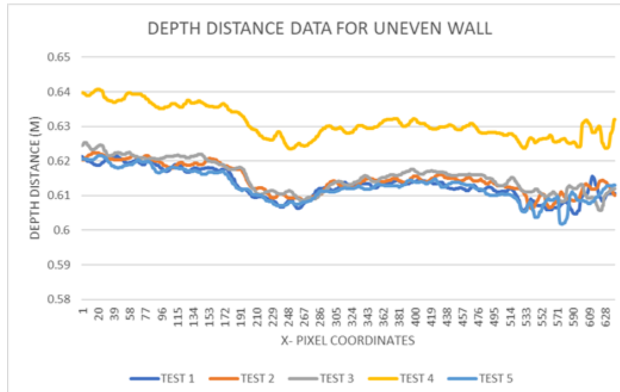

Figure 18 Uneven wall data

The results in Figure 18 is not on the same level, thus the detrend process was applied on the even and uneven wall data and its results are shown in Figures 19 and 20.

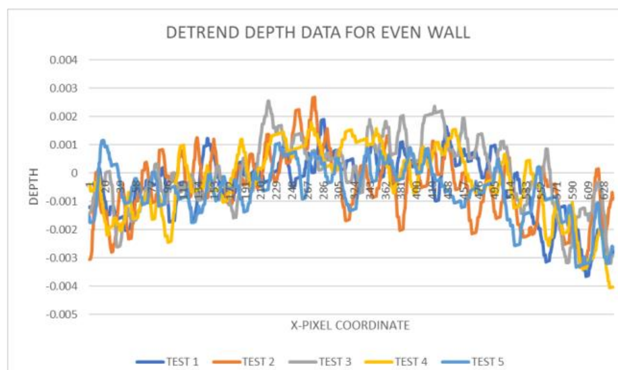

Figure 19 Detrend plot for the Even Wall

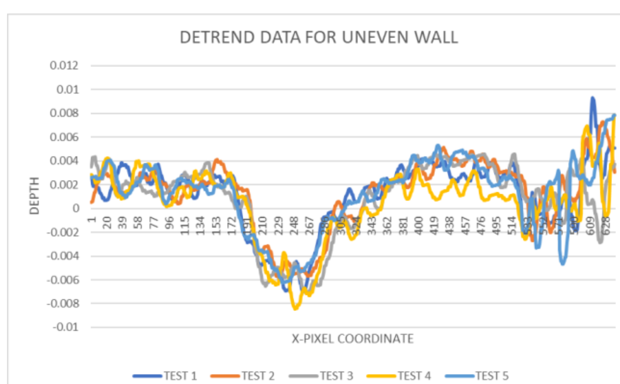

Figure 20 Detrend plot for the Uneven Wall

Detrend depth data for each test shows that depth value of each pixel varies from pixel to pixel. The highest detrend depth data value was 0.0027m in second test while the lowest depth data value was -0.004m in fourth test. Based on the graph, for an even wall the value of each pixel can varies in either +0.003m until -0.003m respectively. The highest depth value difference was measured during the second test with the value of depth is 0.0026m while the lowest depth value difference was measured at 0.004m. Therefore, when comparing even wall to the depth wall test results conducted, the overall quality assessment system has an approximate depth variance of 0.0014m.

Summary of uneven data plot can be observed as shown in Figure 20. The uneven wall detrend depth data has the same graph shape when compared to its initial uneven wall results which there were sharp decrease and sharp increase between some of the X pixel coordinates.

Based on the plotted detrend uneven wall, on all test results the graph stablise around 0.004m to 0.00m at 1st X pixel coordinate until 190th X pixel coordinate before sharp decrease around 250th X pixel coordinate around -0.008m depth. The graph was then increase sharply after the 250th X pixel coordinate until reaching 300th X pixel coordinate and then stablised again around 0.004m to 0.000m. After 500th X pixel coordinate until 640th X pixel coordinate, the depth value sharply increasing and decreasing within these pixels. The sharp increase and decrease of the depth value indicate there were deformities on the wall, i.e. unevenness. The variation of the deformities shows a reading of an average of 0.07m, which has a difference of 7.69% from the manual reading performed, or an accuracy of 92.3%.

4.0 CONCLUSION

This paper proposed a method of assessing wall evenness using a depth camera which is the Intel Realsense L515. The advantage of using this sensor is that it can accommodate two purposes of the assessment process; wall navigation and wall evenness assessment. This eliminates the need for other sensor for alignment to ensure that the body is front-facing the wall. This improvement enables the size of the robot to be small and operates on a 12V DC power supply, ensuring mobility during the assessment process. The evenness evaluation performed using the depth camera highlights the promising potential of this method for the use of wall evenness assessment, with a 92.3% accuracy compared to manual measurement.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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