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A Rover Team Based 3D Map Building Using Low Cost 2D Laser Scanners

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ABSTRACT This paper presents a solution to develop 3D map of indoor places using a team of rovers equipped with low cost 2D laser scanners. An orthogonal combination of two RPLidar 2D laser scanners has been used on every rover to build 3D point cloud map of the explored regions. Each rover of the team has been distantly placed inside the surveying environment in order to independently scan and built the unique 3D point cloud map of the region. The interfacing of scanners and the processing of simultaneous localization and mapping (SLAM) technique for each moving rover have been achieved using Robot Operating System (ROS). The individually build 3D maps have been merged in offline mode through sensor fusion application using Kalman Filter (KF) technique. Different indoor vicinities have been tested and complete 3D point cloud maps have been established which have been found accurate when compared to ground truths. The developed point cloud map has been further utilized to establish Building Information Model (BIM) and found valid for the surveyed region. In comparison to existing surveying and scanning solutions of the regional market, the presented method has been found precise, quick and convenient to provide structural details of surveyed entities at highly affordable rates.

INDEX TERMS 2D laser scanner, map merging, ROS, rover, SLAM.

I. INTRODUCTION

The role of mobile robotics has been increased with the advancement in the sensor technologies and the availability of low cost and effective rovers. The main reason that made mobile robotics as one of the most prominent field for domestic and industrial applications is its adoptability to various environments by utilizing heterogeneous sensors. The mobile robotics has become the essential part of many industrial operations including those which may consider hazardous for human workers and also need high accuracy and precision [1]. In domestic applications, the mobile robots are more popular in multiple tasks such as cleaning, educational and assistive applications [2].

The most challenging task for any mobile robot during performing assigned job is to localize itself in the region and to perceive the surrounding at the same time. Exploring unknown environment and to build its 3D representation is one of the most focused multi-disciplinary research field which has been evolved through the usage of Simultaneous Localization and Mapping (SLAM) technique [3]. Latest developments in sensor technologies have significantly resolved the localization problem along with the quality enhancement in modelling the environments. Visual sensors and laser scanners have considered as the most prominent devices for perception in a variety of robotic applications. Laser scanner has capability to produce accurate Cartesian scan points of surrounding in different lighting conditions whereas visual sensor delivers rich appearance information and often they employed together on mobile robotic units to build 2D/3D maps of the navigated region. This research work presents an innovative low cost solution to produce 3D map model of the explored region using a team of two rovers as shown in Fig. 1. The solution has been established to incorporate in surveying applications for indoor regions.

The deployment of these rovers can be possible in any structured indoor vicinities in order to perceive the unique building data for accurately modelling the surveyed region. Many research groups have used different kind of rovers equipped with a variety of laser scanners for developing the map model of the targeted region. The complexity arises when multiple rovers provide individual mapping results of the portions of the environment they explored and the final map of the environment needs to generate by knowing the

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(a) (b)

FIGURE 1. A team of two rovers surveying multiple indoor regions.

correct transformations of all individual maps [4]. The task of determining respective transformations of each rover has been addressed by different researchers through centralized or distributed computational algorithms. The transformation results have been generated either through planned meet up of rovers or by map merging techniques.

In continuance to these state of art contributions, this research work is presenting a unique solution of utilizing a team of two small and low cost rovers for surveying indoor regions and to produce Building Information Model (BIM) [5]. An innovative orthogonal integration of two low price RPLidar 2D laser scanners has been carried out on each rover along with required electronic and computational units in order to perform 3D scanning and mapping of the vicinity using Robot Operating System (ROS) [6]. The surveying job has been performed by placing each rover inside distinct remote places of the vicinity and operated them independently to scan respective regions and to record all sensorial data. At the end of surveying, a planned face to face meet up of both team members has been organized to build mutual transformation through sensor fusion using Kalman Filtering (KF) [7]. By incorporating sensorial data and transformations in offline mode, complete 3D point cloud map of the explored vicinity has been established and further processed to acquire BIM of the region. The novelty, efficacy and adoptability of indigenously proposed solution have been evaluated in multiple indoor regions and accurate results have been witnessed in short durations at highly affordable rates if compared to available solutions.

This paper has been arranged comprehensively in various sections. In Section II, a brief narration of related state of the art has presented. Section III provides details of mechanical design and instrumentation scheme of the rover system. Section IV elaborates information of single and multi-rover based point cloud generation and map merging procedures. While Section V demonstrates real test results of indoor vicinities and finally conclusion has presented.

II. RELATED WORK

The selection of appropriate laser scanner is considered as the fundamental step for indoor surveying applications and many research works have discussed characteristics of popular 2D laser scanners [8]. A comparative study of available 2D laser scanners has performed and summarized in Table 1. Indoor mapping task requires perception accuracy at higher scanning rates in order to efficiently model the surveyed environment using moving scanning platforms [9]. If moving platform has similar speed as of humans then all available scanners can perceive properly.

TABLE 1. A comparison of multiple 2D laser scanners.

Characteristics	Units	Hokuyo 30LX	Hokuyo 04LX	RPLidar A1
Maximum range	m	30	4.0	6
Standard deviation	mm	3	3	<5
Scan angle	Degree	270	240	360
Angular resolution	Degree	0.33	0.36	≤1
Scan rate	Scan/sec	40	10	5.5
Weight	kg	0.5	0.4	0.4
Power rating	w	4.2	4.0	5
Approximated cost	$	7000	2000	400

The Hokuyo scanners provide mostly better features however their costs are much higher that cannot justify for low cost scanning systems. Researchers have presented usage of low cost scanners such as RPLidar series for indoor mapping applications [10]. Based on satisfactory 2D mapping performance during movement, this research work has utilized an orthogonal combination of two RPLidar laser scanners for 3D scanning and mapping applications.

Researchers have integrated laser scanners along with other sensors on different kind of mobile robots or rovers. A research group has utilized Powerbot differential drive rover capable of carrying up to 100 Kg payload and equipped with efficient processing unit [11]. The research team mounted 2D SICK LMS 200 laser scanner with Bumblebee X3 stereo camera to generate 3D colored map of some indoor regions. Another research group has utilized popular Pioneer 3DX rover and has installed two 2D SICK laser scanners to acquire 3D scanning data of the region [12]. A 6 DOF SLAM technique using ICP based scan matching has been used to develop complete map of the indoor region. Same group has reported another mapping result using Husky rover equipped with 3D laser Z+F imager for building maps. Some researchers have utilized comparatively small rover unit for interfacing multiple horizontal and vertical 2D SICK laser scanners along with DSLR camera [13]. They have utilized 2D Hector SLAM algorithm to generate robotic poses during exploration of the region. Later using DH parametric values, vertical scans have been merged to generate complete 3D map of the vicinity. In addition DSLR images have been utilized for diffusing color information on developed maps. A summary of these mapping rovers has presented in Table 2.

There are various other innovative research works have reported in the scientific community in which majority solutions have emerged using combination of expensive rovers and scanners. Some researchers came up to produce mapping solutions using low price rovers equipped with 2D laser scanners by extracting line features of the region [14]. A GMapping SLAM based solution presented by researchers using low price RPLidar laser scanner equipped on turtlebot

TABLE 2. Comparison of experimental rovers.

Rover Name	Scanner Type	Camera	Other Sensors
PowerBot [11]	SICK LMS 200	Bumblebee XB3	Odometer
Pioneer 3DX [12]	SICK 2D	Nil	Odometer
Husky [12]	3D Z+F Imager	Nil	Odometer
4 wheel robotic platform [13]	Multiple SICK 2D	DSLR camera	Odometer and IMU

FIGURE 2. Rover unit used for scanning operation.

rover [15]. With the evolution of single rover SLAM, researchers started to present multi rover SLAM solutions from last two decades. An innovative multi robot centralized mapping procedure has presented by a robotics group that has incorporated KF based robot to robot mutual measurements along with duplicated land marks present in individual maps [16]. Some researchers proposed global map merging solution using probabilistic Gaussian process applied on the individual RBPF based feature maps [17]. A recent work on map merging solution has presented use of prominent features of vertical lines and right-angled points of suppositional box in a KF framework [18]. Multiple indoor mapping results have presented in the work. A comprehensive review has been published on multiple robot map merging procedures [19]. The authors presented state of the art research works by categorizing them as per type of maps generated and adoptability of the algorithm chosen for map merging. By observing the existing developments in this field, this research work is contributing to present an economical 3D map merging solution for surveying jobs that can produce BIM of the explored environments.

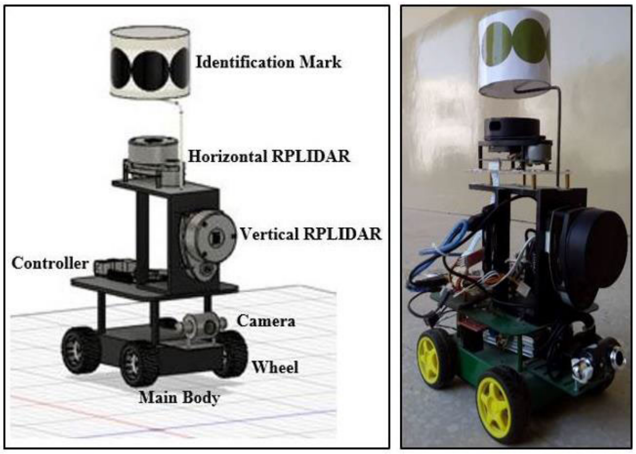
III. DESIGNING OF ROVER BASED SCANNING SYSTEM

Designing of mobile robotic scanning setup demands selection of appropriate rover platform, suitable placement of laser scanners along with the designing and development of mechanical and instrumentation units as presented in following sections.

A. MECHANICAL STEUP

The mechanical design starts from the selection of the rover platform for this research. The complete rover system has been fabricated into two sections. The lower section is a type of low cost close chamber rover unit that has been purchased from the market as shown in Fig. 2. The upper section has developed with a support of 5cm long brass spacers mounted on the rover unit as shown by its CAD model in Fig. 3 (a).

The rover unit has four driving motors which are placed in the closed chamber and each motor is connected to single wheel. The distance between left and right wheels is 14 cm and between front and back wheel is 13.5 cm. The diameter and width of the wheel is 6.25 cm and 2.5cm respectively. The wheels are fabricated with normal plastic and covered with rubber tires. The front wheels have interfaced with two encoders to get the rotational feedback from the wheels.



(a) (b)

FIGURE 3. Labeled CAD model and mechanical structure of rover based scanning system.

In base plate of the rover unit, two batteries are placed alongside the motors. First battery is assigned to deliver power to motors while the other one is used to power up the onboard controller, scanners and other accessories.

In order to integrate scanners and other relevant components, an orthogonal acrylic based platform has been developed and interfaced with the upper section support. The platform has a height 12.5 cm to hold two RPLidars in horizontal and vertical direction each. The space at the upper section has been occupied by the electronic boards. A cylinder of about 8.5 cm diameter and 7.5 cm height is placed at the top of rover by a thin rod. The rod is mounted at the top side of acrylic platform and the cylinder has been colored to tag each rover for visual inspection. The completely fabricated rover system is shown in Fig. 3 (b).

B. INSTRUMENTATION HARDWARE DESIGN

The instrumentation circuitry of the experimental rover setup comprises multiple scanners, sensors and electronic boards wirelessly interfaced with ROS running on the laptop. ROS has the ability to compile the data from the multiple sensors and to store them to process for offline work. The raspberry pi (model 3b) is the main controller that is directly used to interface with the webcam, two RPLidars A1 scanners and UWB DWM1000 senor as shown in Fig. 4. One scanner is mounted in horizontal direction and the other is mounted in vertical direction on acrylic platform. One arduino nano controller is used as slave controller to interface UWB sensor and to update the main rasp pi controller. The other one arduino UNO controller is used for driving the rover as per received command from the main controller. It controls the wheel through L298N, a dual H bridge driver unit. One more task for this ardunio UNO is to take wheels feedback using optical encoders integrated at front wheels. The interfacing scheme of main controller with slave controllers and other components mounted on the rover has been shown in the block diagram.

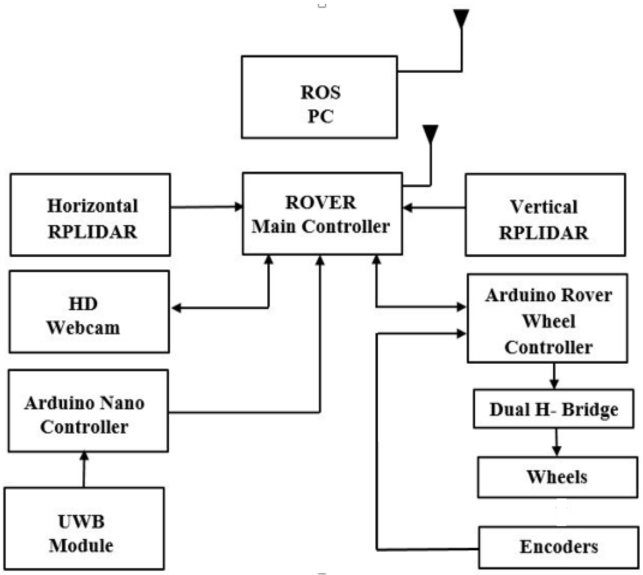


FIGURE 4. Block diagram of instrumentation system.

The complete information of on board sensors have been wirelessly recorded at the ROS PC (laptop) for offline processing of the data using Matlab coding to combine both horizontal and vertical scans, to perform segmentation of 3D point cloud data and to merge individual maps.

IV. DEVELOPMENT OF 3D MAP USING MULTI ROVER SYSTEM

This section explains the methodology to develop 3D map of the surveyed region using exploration of two rovers from distinct locations inside the vicinity.

A. SINGLE ROVER BASED 3D MAP DEVELOPMENT

The single rover exploration has been carried out in different indoor regions and 3D map has been developed using SLAM technique. The mechanism for establishing 3D map of the navigated region requires mainly a correct 2D pose estimation. The main concept of the SLAM is to estimate most probable pose x and map m by factorizing complete SLAM posterior $p(x_{1:t}, m_{1:q}|z_{1:t}, u_{0:t-1})$ into factored form as shown in (1) [20].

$$p\left(x_{1:t}, m_{1:q}|z_{1:t}, u_{0:t-1}\right) = p\left(x_{1:t}|z_{1:t}, u_{0:t-1}\right) . \prod_{j=1}^{q} p\left(m_j|x_{1:t}, z_{1:t}\right) \quad (1)$$

The posterior representation is showing 2D pose of the rover by x, the developed 2D environmental map by m, horizontal laser scan based observations by z and controls (odometric updates) by u. This research work has utilized the Hector SLAM ROS package which is a popular online implementation of SLAM estimations [21]. Hector SLAM does not require controls u by odometry rather perform scan matching to predict the covered motion. It generates occupancy grid map of the surveyed environment along with related 2D pose of the moving rover. In order to test the scanning result of the rover, an exploration inside a corridor has been performed which is having walls and pillars as shown in Fig. 5. The rover movement has been controlled manually by sending commands wirelessly. The live data of both scanners, camera and other sensors have been wirelessly transmitted by the rover to the ROS running laptop for SLAM processing and recording.

FIGURE 5. Multiple views of corridor vicinity.

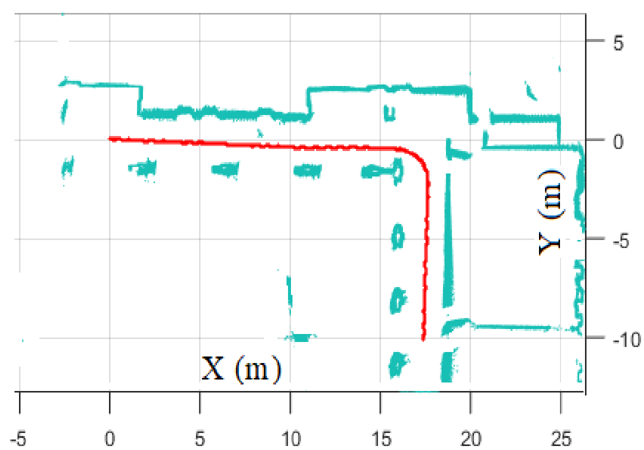


FIGURE 6. 2D pose and map generation.

The live scans of horizontal scanner is used to estimate 2D map and pose of the vicinity which have shown here by red and cyan colors respectively in Fig. 6. Later, vertical scanner data has been transformed into referenced frame of horizontal scanner in offline mode using MATLAB coding.

The translational (x_2, y_2, z_2) and rotational $(0, \theta_y, \theta_z)$ values of vertical scanner with respect to referenced scanner has been already assigned during fabrication of the right-angled support at which both scanners have been integrated in middle of respective plane. So, every single scan point P_2 of vertical scanner has been transformed using standard transformation procedure as shown by (2).

$$S_{2T} = Trans\,(x_2, y_2, z_2)\,Rot\,(z, \theta_z)\,Rot\,(y, \theta_y)\,P_2 \quad (2)$$

Here, S_{2T} is the transformed scan of vertical scanner into horizontal frame and has been combined with referenced scan S_1. Because each scanner has 360 scan points in a unit scan so total points in the accumulated scan S_C have been reached to 720 counts as shown in (3).

$$S_C = S_1 + S_{2T} \quad (3)$$

Now using the distinct recorded pose (x_n, y_n, θ_n) at respective time, the accumulated scan S_C can be transformed into the SLAM referenced system to gradually provide a reconcilable 3D point cloud map. The overall transformation of the scan S_C into these SLAM coordinated frame have shown in (4).

$$S_G = Trans\,(x_n, y_n, 0)\,Rot\,(z, \theta_n)\,S_C \quad (4)$$

By incorporating all recorded scans at unique time stamps along with respective pose values of the rover, the complete 3D point cloud map of the navigated vicinity has been produced in offline process as shown in Fig. 7.

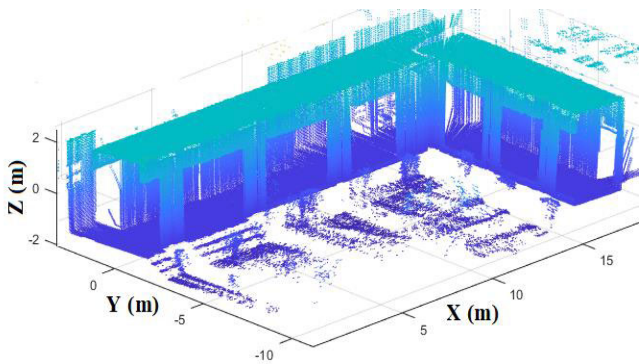


FIGURE 7. 3D point cloud of the corridor environment.

The established point cloud is representing the surveyed environment of 25×16 m^2 dimension and showing thorough information of open spaces, structures and vegetation. The time taken for moving the rover inside the vicinity was around five minutes and time elapsed for building the point cloud in offline mode was around fifteen minutes. In comparison to manual measurements, the low cost rover based scanning technology is reflecting the benefit of quickly building comprehensive knowledge with ease of operation. Furthermore, Random Sampling Consensus (RANSAC) based segmentation of the generated point cloud has been performed in Matlab [22]. This is the procedure to sort out scanned points affiliated to particular planes of the structure such as floor, ceiling and wall planes. In order to observe some inner structural planes, segmented ceiling plane has been pull out from the actual point cloud and remaining planes such as wall, windows and pillars have been shown in Fig. 8. Each scanned entity has been appeared similar to its actual shape.

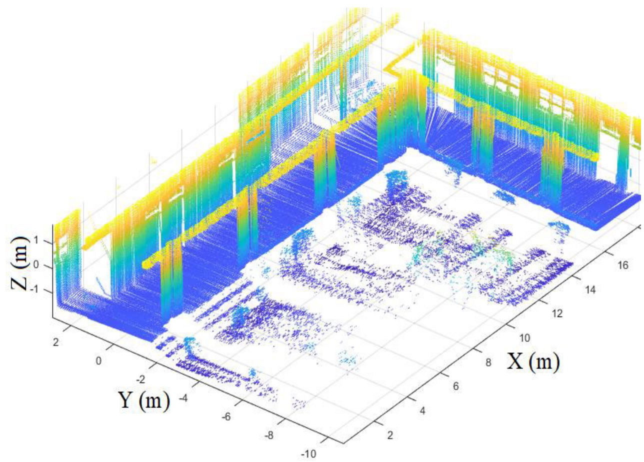


FIGURE 8. 3D point cloud representing multiple inner planes of corridor.

The measurements of the generated point cloud has been found accurate as compared to ground truth of the corridor where the rover has moved as shown in Table 3.

TABLE 3. Comparison of measured results.

Navigation unit	Rover 1		Rover 2	
	Actual	Measured	Actual	Measured
Length (m)	36.8	36.65	46	46.2
Width (m)	2.5	2.46	2.5	2.47

B. MULTI ROVER BASED 3D MAP MERGING

For surveying jobs of large buildings, a single rover exploration could be a time consuming operation to scan completely the surveyed vicinity. Therefore a team of rover can do the same job in more efficient manner. In order to perform a team based scanning operation, another rover exploration has been carried out in the same vicinity from other end using the same approach. The initial and final positions of both rovers in vicinity have shown in Fig. 9.

The developed 2D map and pose of the second rover has shown by cyan and red colors respectively in Fig. 10.

Later, in offline mode with the same procedure as discussed for first rover, the 3D map has established using recorded poses and scan values as shown in Fig. 11. The map is comprising of same structure of walls, pillars and open spaces. The total time consumed for exploration and 3D map development was around fifteen minutes.

The developed point cloud has segmented and visualized more clearly by removing ceiling plane as shown in Fig. 12. Other planes such as wall, windows and pillars can be seen easily and their dimensions have found nearly accurate as

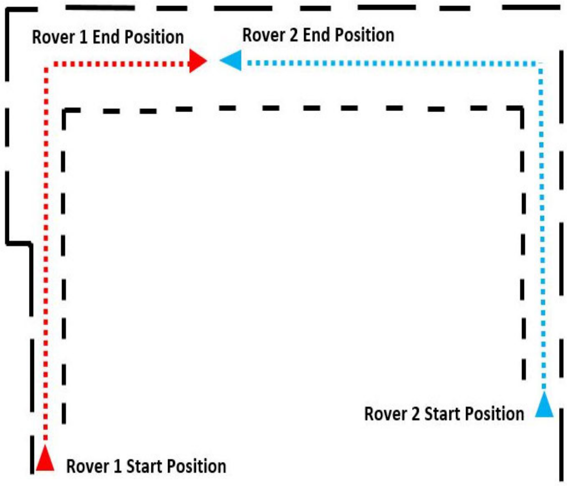


FIGURE 9. Placement of rovers inside corridor vicinity.

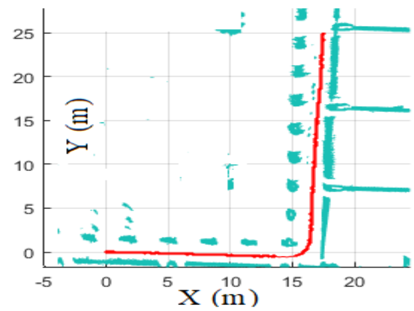


FIGURE 10. 2D pose and map generation from second rover.

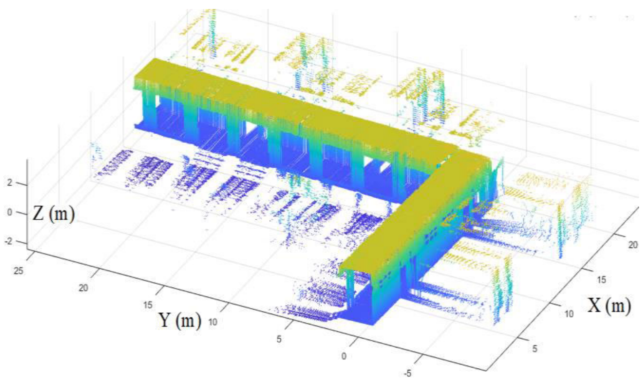


FIGURE 11. 3D point cloud of the corridor environment of second rover.

compare to actual dimensions as presented in Table 3. All scanned entities have observed similar to their actual shapes.

As both rovers have moved in the same corridor independently and have developed their individual 3D maps in context to their local frames. So a relationship is needed among their local frames to merge individual maps. For this purpose a controlled face to face meeting has established at the end of their explorations as pointed earlier in Fig. 9. This is very similar to the scenario that two workers have started their job from different ends in some vicinity and moving to

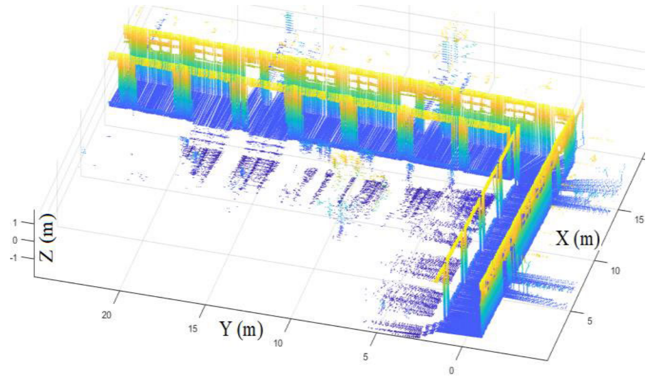


FIGURE 12. 3D point cloud representing multiple inner planes of corridor.

end individual tasks at a common meeting point. An offline framework has developed for identifying the translational and rotational values exists among the rovers using recorded online data of UWB sensor, camera and horizontal scanner during their respective explorations as shown in Fig. 13.

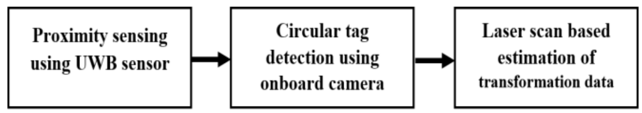


FIGURE 13. Framework of finding transformation parameters of rover.

At the first stage of the framework, the UWB sensor data is used to approximately localize the second rover which was approaching towards first one. In case of a team of more than two rovers, the unique data tags of UWB sensor can easily distinguish which two rovers are going to meet in the vicinity. Therefore the UWB sensor assures the identity with proximity of the incoming rover within the range of other team member. As the approaching distance among rovers gets smaller, the visual identification through on board camera images can be clearer by detecting the circular tags of the rover as shown in Fig. 14.

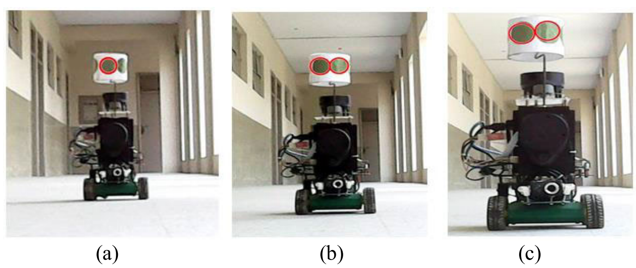


FIGURE 14. Visual identification of incoming rover.

At the last stage, horizontal scans of first rover have used to detect approaching rover as shown in Fig. 15 (a).

Red triangle is indicating first rover and small cyan circle pointed by black arrow is indicating second incoming rover. During the continuous approach of the second rover, the range in between both rovers got smaller as shown in Fig. 15 (b) and

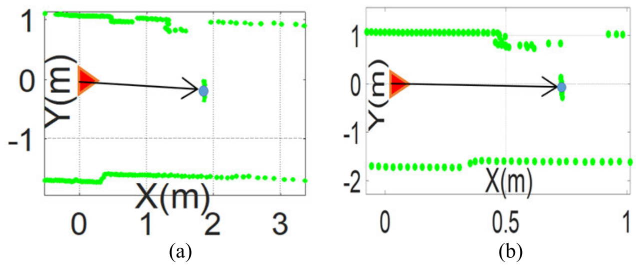


FIGURE 15. Scans based range measurements among rovers.

continued to decrease further. Since both rover explorations have been wirelessly controlled so an approximated face to face gathering of both rovers have performed at a minute distance among them. In order to calculate the translational t_h and rotational θ_h values of approaching rover, a Kalman Filter based estimation technique has been applied using sequential horizontal scans [23]. As the second rover approaches to first rover's vicinity as shown in Fig. 16, each horizontal scan detects presence of the incoming rover at a certain translational and rotational values. So a continuous set of transformation parameters have gathered and utilized in KF formulation.

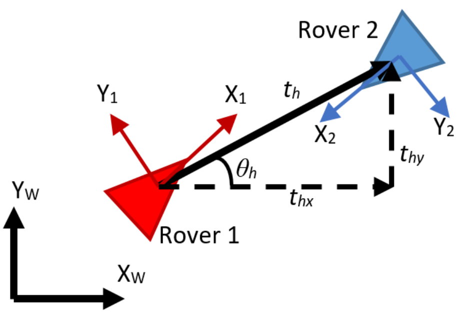


FIGURE 16. Representation of range-bearing parameters among rovers.

The prediction of state vector $X = [t_h; \theta_h]$ and covariance matrix P have carried out using the standard KF equations as shown by (5) and (6).

$$X_P = AX_{n-1} + BU_n \tag{5}$$

$$P_P = AP_{n-1}A^T + Q \tag{6}$$

Here X_P and P_P are new predicted values of state vector and covariance matrix. A is the unity state transition matrix, U_n is the control vector which is not used in this estimation and B is the control coefficient matrix with all zero valued elements for this application. By providing new measured values of transformation parameters of t_h and θ_h among rovers from the current scan, a set of corrective equations of KF has been applied in order to generate new estimate of X and P as shown in (7) and (8).

$$X_n = X_P + KY \tag{7}$$

$$P_n = (I - KH)\,P_P \tag{8}$$

Here X_n and P_n are new estimates, H is the measurement jacobean having unity elements while K and Y are the usual matrices evolved during KF processing. As the approaching rover has commanded to stop in the much closer proximity of few centimeters to the first rover, the iterative KF process has been stopped simultaneously and the final estimated values of t_h and θ_h have used to perform map merging. The translational t_h parameter has decomposed into its XY components as shown earlier in Fig. 16. The decomposed translational parameters along with rotational parameter has been finally utilized to transform each mapping point P_{G2} of the second rover into the coordinates system of first rover using (9).

$$S_{G2T} = Trans\left(t_{hx}, t_{hy}, 0\right) Rot\,(z, \theta_h)\, P_{G2} \tag{9}$$

The transformed map S_{G2T} is finally accumulated using (10) with the first rover's map S_{G1} to produce the complete map S_W of the navigated vicinity through both rovers.

$$S_W = S_{G1} + S_{G2T} \tag{10}$$

The completely merged 3D point cloud map has shown in Fig. 17. The overall size of the map has reached to $18 \times 38 \times 4$ cubic meter.

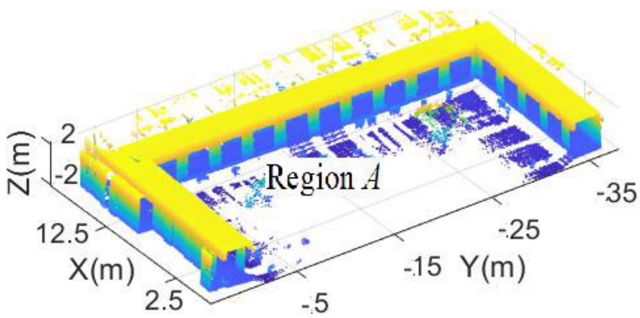


FIGURE 17. Complete 3D map of the corridor.

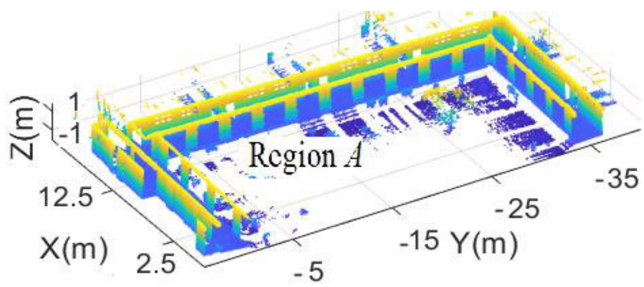
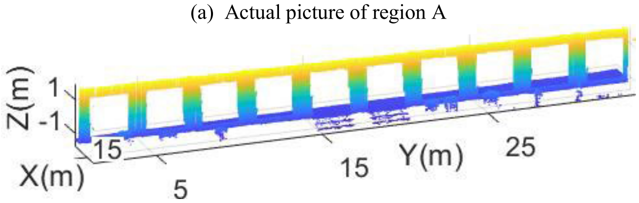


FIGURE 18. 3D point cloud map representing inner planes of corridor.

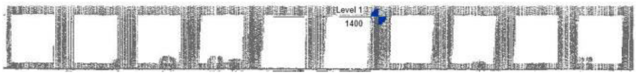
The complete point cloud map has segmented and later by removing ceiling plane of the map, a clearer view of interior of the map has shown in Fig. 18. Other planes such as wall, windows and pillars can be seen easily and their dimensions have found nearly accurate as compare to actual dimensions of the vicinity.

The developed map can be used for various applications specially for making BIM of the surveyed vicinity. In Fig. 17, a portion of the vicinity named as Region A has been shown which is selected to inspect the process of BIM development

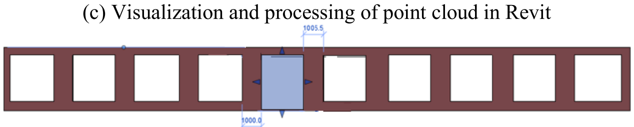
(a) Actual picture of region A



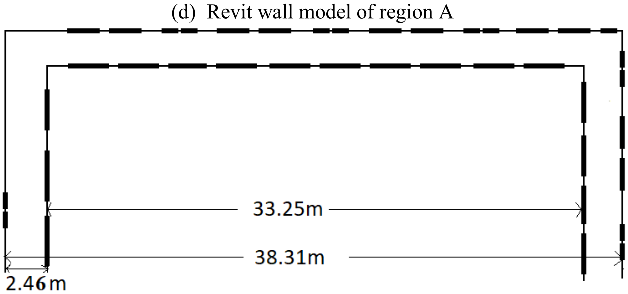
(b) Extracted point cloud of region A



(c) Visualization and processing of point cloud in Revit



(d) Revit wall model of region A



(e) Top view of complete Revit BIM

FIGURE 19. **3D point cloud processing for BIM development.**

of the region. Fig. 19(a) is showing the actual image of the region and Fig. 19(b) is presenting the extracted point cloud of the region. After performing some standard steps, the point cloud has been processed manually using popular Autodesk REVIT BIM software as shown in Fig. 19(c) [24]. The established BIM for the corresponding wall with open spaces has shown in Fig. 19(d). The BIM development has taken small time and additionally the result has been verified with ground truth of the region. Later the complete point cloud of the corridor has been processed in REVIT and the top view of the generated BIM has been shown in Fig. 19(e). The labeled dimensions have been verified through ground truths. Therefore rover based surveying, mapping and BIM development procedures have been successfully applied with minimal efforts in a short time. In comparison to reported 3D point cloud mapping solution using multiple expensive scanners installed on a rover [13], the developed results of the surveyed corridor are very promising and quite accurate, generated at affordable rates and found compatible to the requirements of surveyors, architects and relevant professionals.

V. RESULTS

In order to testify the rover based scanning procedure, some other places have been explored and surveyed using team of both rovers. An academic block has visited using both rovers

(a) (b)

FIGURE 20. **Surveying of an academic block using rovers.**

from different locations as shown in Fig. 20. First rover has placed at one end of the vicinity and wirelessly navigated in the area. Fig. 21 is showing 2D pose and map of the rover in red and cyan colors respectively.

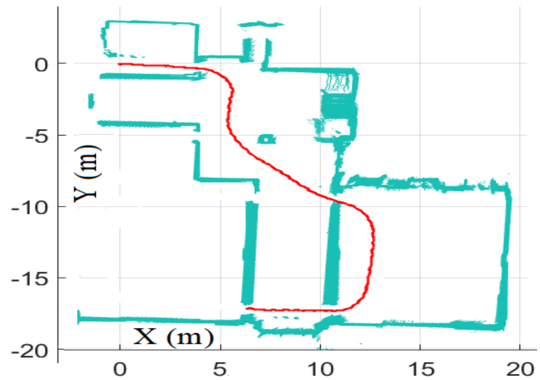


FIGURE 21. **2D map of the region developed by first rover.**

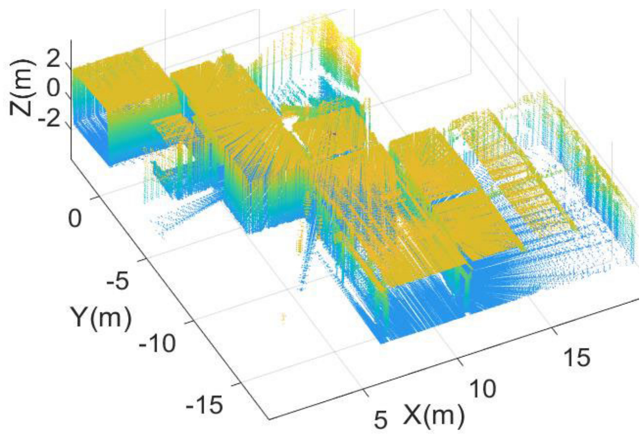


FIGURE 22. **3D map of the region developed by first rover.**

Using the defined procedure, the 3D map has developed as shown in Fig. 22. The rover has scanned approximately $20 \times 20 \times 4$ cubic meter space in the region in twelve minutes of operation. The map is indicating multiple rooms and open structure where the rover has moved. The second rover has placed at other end of the vicinity in a room and wirelessly navigated in the region. Fig. 23 is showing 2D pose and map of the rover in red and cyan colors respectively.

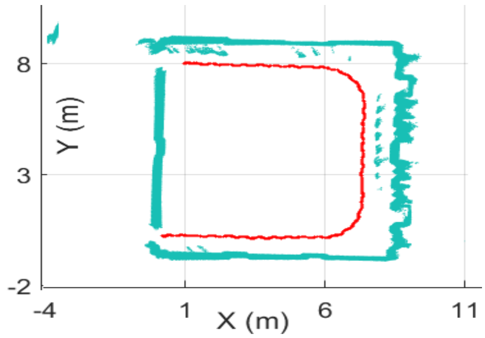


FIGURE 23. 2D map of the region developed by second rover.

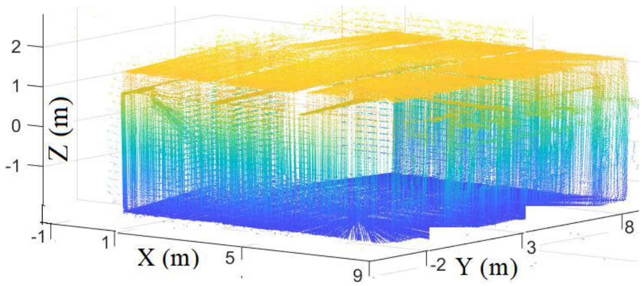


FIGURE 24. 3D map of the region developed by second rover.

The 3D map of the surveyed room has developed as shown in Fig. 24. The rover has quickly scanned the room in a few minutes and reaching to the location where first rover has ended its surveying.

As both rovers have ended their scanning operations and have met face to face as per defined procedure as shown in Fig. 25, the transformational parameters have computed and map merging has carried out.

(a) (b)

FIGURE 25. Face to face planned meeting of both rovers.

Fig. 26 is showing the complete 3D map of the region developed after individual maps merging. The complete region is having larger dimension however with the help of both rovers, the map has established more quickly in comparatively small amount of time. Later, the complete map has

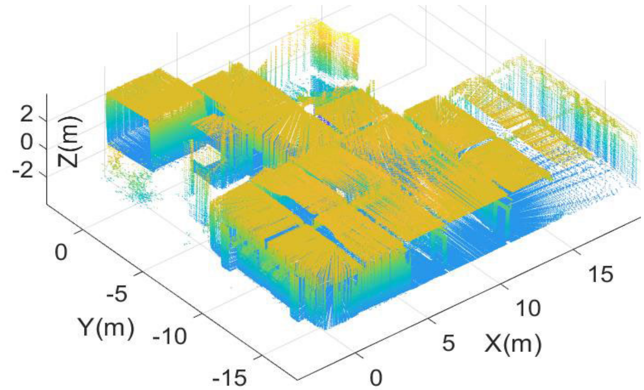


FIGURE 26. Complete 3D map of the region.

segmented in multiple planes and a ceiling less view of the region has shown in Fig. 27(a). Other planes such as floors, walls, beams, windows and stairs can be seen easily and their dimensions have found nearly accurate as compare to actual dimensions of the vicinity as presented in Table 4.

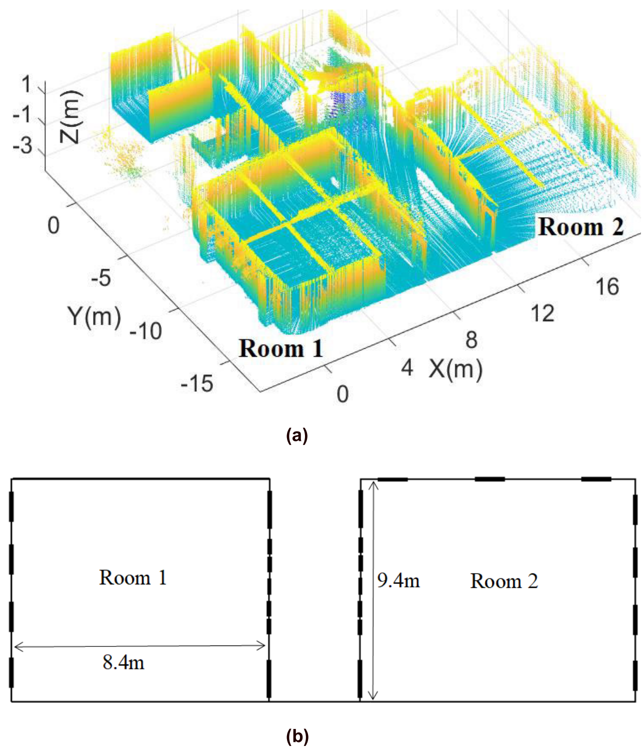
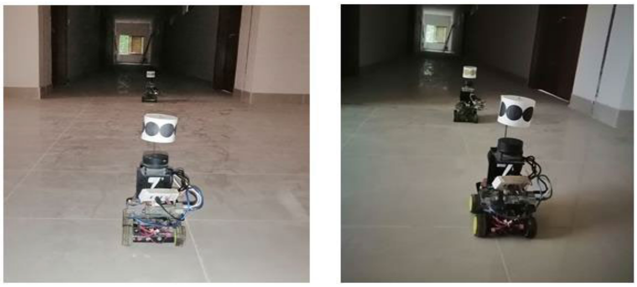


FIGURE 27. (a). Complete 3D map without ceiling plane. (b). Top view of Revit BIM.

The developed point cloud map has been further analyzed and processed for development of the BIM of two class rooms labeled as Room 1 and 2 in Fig. 27(a). The generated BIM has shown in Fig. 27(b). The labeled dimensions have been verified through ground truths.

Another newly constructed building's ground floor has surveyed using both rovers from different locations as shown in Fig. 28. The surveying has carried out in different light



(a) (b)

FIGURE 28. Surveying of newly constructed building.

conditions as compare to earlier surveying jobs and still scanning has successfully performed in the region. Both rovers have placed on different ends and navigated carefully due to presence of construction material on some locations. First rover has wirelessly navigated in the area and started to scan its surroundings. Fig. 29 is showing the developed 2D pose and map of the rover in red and cyan colors of the respective territory.

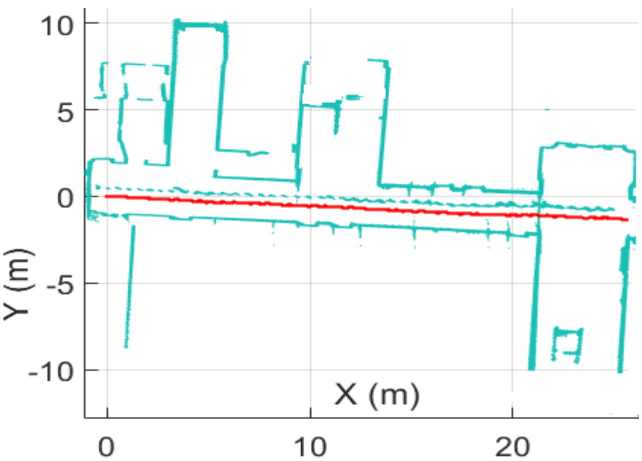


FIGURE 29. 2D map of the region developed by first rover.

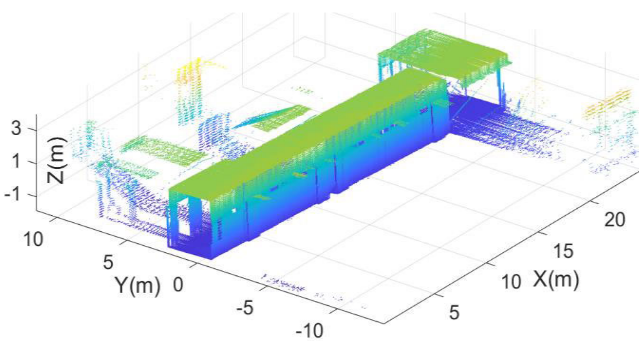


FIGURE 30. 3D map of the region developed by first rover.

Using the same procedure, the 3D map has developed as shown in Fig. 30. The rover has scanned approximately $30 \times 20 \times 4$ cubic meter space in the region in seventeen minutes of operation. The map is indicating a long corridor along with open spaces and other structures.

The second rover has placed at another end location of the floor and wirelessly navigated in the vicinity. The area has some navigational limitations in order to move freely inside the region but due to small size of the rover, the surveying job has been completed smoothly. The scanning of the region has performed as per planned actions. Fig. 31 is showing 2D pose and map of the rover of its assigned territory in red and cyan colors respectively.

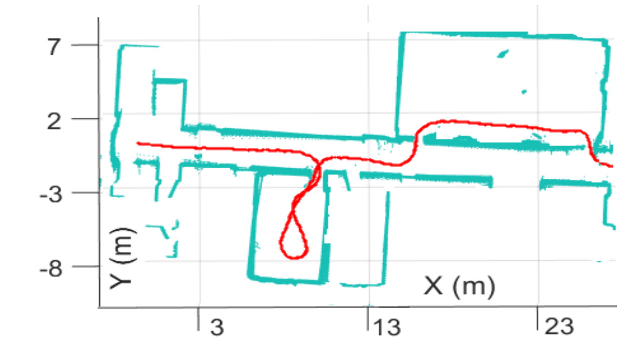


FIGURE 31. 2D map of the region developed by second rover.

The 3D map of the surveyed region has developed as shown in Fig. 32. The rover has taken fourteen minutes to scan the region and finally reaching to the location where first rover has ended its surveying.

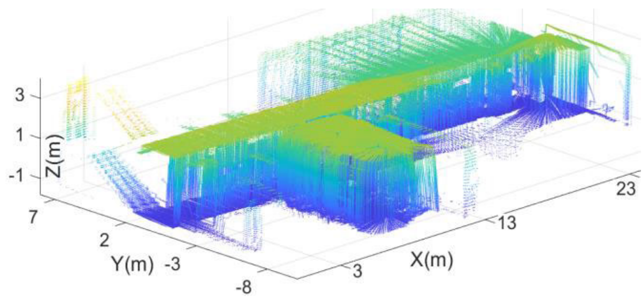


FIGURE 32. 3D map of the region developed by second rover.

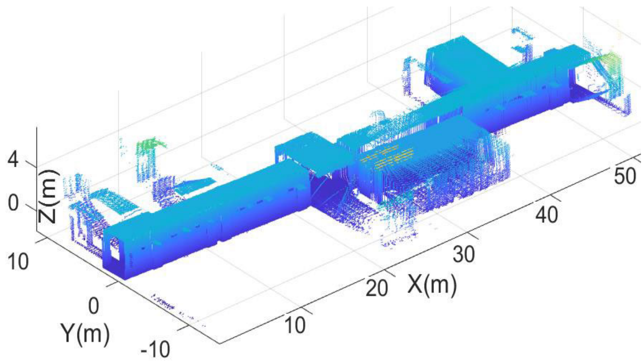


FIGURE 33. Complete 3D map of the region.

The transformational parameters have computed and map merging has carried out to make a global 3D map as shown in Fig. 33. The map is presenting the structural information of the long corridor and associated rooms where the survey has been conducted. The dimensions of the scanned map has been found nearly accurate as compare to ground truths of the building as presented in Table 4.

The developed map has further segmented into different planes and later by removing ceiling plane of the vicinity, a more visible view of the interior of the area has shown in Fig. 34(a). The map has been further processed to generate the BIM of the corridor as shown in Fig. 34(b).

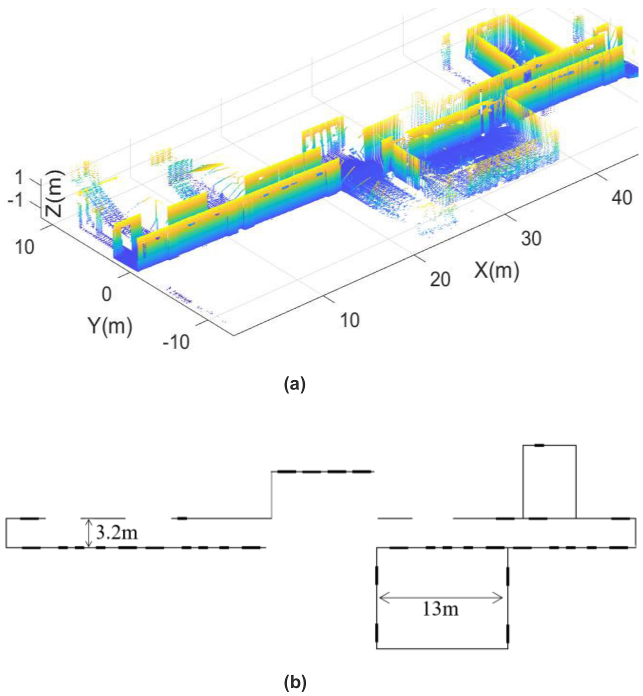


FIGURE 34. **(a). Complete 3D map without ceiling plane. (b). Top view of Revit BIM.**

The labeled dimensions of the developed BIM have been verified through ground truths. In comparison to reported 2D map merging solution [18], the developed BIM results of presented tests have been found quite satisfactory. The end user can view and compare the established 3D map along with BIM using standard softwares applicable for surveying applications. Therefore successful performance of the rover based surveying and scanning have been produced for multiple regions with varying characteristics. During these experiments, it has observed that the accurate 2D SLAM result can only achieve in those environments where significant structural changes are perceivable on both sides of the surrounding within scanning ranges of both scanners during movement of the rover. In those regions having parallel walls or having open spaces without any structures, the 2D SLAM result has found highly inaccurate and cannot use for establishing 3D map and related BIM. These shortcomings of the presented rover scanning system can be improved by introducing visual odometry along with inertial navigational solution and will consider in future enhancements of the setup.

TABLE 4. **Comparison of measured results.**

Surveying place	Academic block		New building	
	Actual	Measured	Actual	Measured
Length (m)	22.5	22.25	55	55.7
Width (m)	21.5	21.22	19.2	19.4

VI. CONCLUSION

This research work has presented the efficient working of a scanning and mapping system comprising of a team of low cost rovers. The established mapping results of the system have been found 98% accurate if compared with the physical dimensions of the explored regions. The total time consumed for building the surveying outcomes has been minimized to 85% or more when compared with the existing manual surveying techniques of regional market. The working of the system provides ease of operation at affordable rates. The successful map merging technique has been utilized to show the use of team of rovers for the surveying application of comparatively large vicinities. In addition, BIM development has been verified for multiple testing regions using the generated point cloud maps. It is indicating the vital achievement of the research work to help out quickly those who are related to the structural and architectural enterprises. Further future testing and analysis of the system requires usage of additional vision and inertial sensors in order to improve localization of the rover and visualization of the surveyed regions and will consider in the upcoming enhancements of the rover system.

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