INDOOR MOBILE MAPPING SYSTEMS AND (BIM) DIGITAL MODELS FOR CONSTRUCTION PROGRESS MONITORING

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ABSTRACT:

Technological developments of the last decades are making possible to speed up different processes involved in construction projects. It is noticeable what building information modeling (BIM) can offer during the entire lifecycle of a project by integrating graphical and non graphical data, in addition to this, mapping the site with a 3D laser scan has been proved to provide a feasible workflow to compare as built models with as designed BIM, in this way, an automatic construction progress monitoring can also be performed. Terrestrial laser scanners (TLS) are commonly used to map a construction site due the level of accuracy provided, but indoor mobile mapping systems (iMMS) could offer a more efficient approach by speeding up the acquisition time and capturing all the details of the site just by walking through it, provided that the point cloud is accurate enough for the purpose of interest. In this paper, an iMMS is used to track the progress of a construction site, the point clouds were uploaded onto a platform of autonomous construction progress monitoring to verify if the system can meet the requirements of available applications. The results showed that the iMMS used is capable to produce point clouds with a quality such that the construction progress monitoring can be performed.

1. INTRODUCTION

1.1 Background

During the last decades the construction industry has implemented different innovative solutions to increase the overall productivity along the life cycle of a project, from design tools like CAD and more recently BIM (Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2021) (Opitz et al., 2014) (Opitz, Windisch, & Scherer, 2014), to the implementation of planning, control and documenting tools that are notably valuable in the cases when the size of a project becomes challenging for these tasks. It has been demonstrated by El-Omari & Moselhi (2008) that 3D laser scanning and photogrammetric technologies can enhance the accuracy and acquisition time in construction sites for progress monitoring and control, both for structures and mechanical, electrical and plumbing engineering (Bosché et al., 2013). Drones and Unmanned Aerial Vehicles (UAVs), have been used for the task of construction progress monitoring by applying photogrammetric techniques in order to obtain a 3D representation of the construction site to subsequently run a comparison against the corresponding BIM model of the project (Kim et al., 2013), showing that an automated workflow can be implemented in order to increase the efficiency of traditional construction monitoring and reporting procedures (Anwar et al., 2018). Further analysis integrating BIM and point cloud based models can be done by assigning the elements of the BIM to its correspondant task of the construction schedule to identify the delayed works and obtain a grafic representation with the current status. However, drones and UAVs acquisitions have limitations in terms of surveying capacity, for instance, those instruments are not capable to capurte indoor information or

navigate through narrow places, but construction progress monitoring using remote sensing technologies also consider the implementation of laser scanners, RGB cameras and depth cameras (Rao et al., 2022), an integration of LiDAR and RGB camera is the common configuration of terrestrial laser scanners (TLS), known as a surveying tool capable to meet the industrial requirements (Fröhlich & Mettenleiter, 2004) and to obtain a precise representaion of buildings (Fryskowska & Stachelek, 2018). A drawback of TLS instruments is the time required to complete the acquisitions. Further developments with a LiDAR approach is its integration with an Inertial Measurement Unit (IMU) and RGB cameras to obtain accurate representations of different environments by means of simultaneous localization and mapping (SLAM) algorithms (Cantoni & Vassena, 2019) (Ceriani et al., 2015) (Zhang & Singh, 2015). This configuration of instruments is usually integrated in a backpack or harnessed type of wearable portable system, commonly known as indoor mobile mapping system (iMMS) (Lagüela et al., 2018) (Sanchez-Belenguer et al., 2018). To increase the range of acquisition of the system, the capture head of some systems is composed by two synchronized LiDAR sensors arranged in different orientation and connected to the IMU. Among the existing mobile mapping systems the ones that fits best for map an undergoing construction are those integrated in a backpack due the portability and flexibility offered at the site, in addition, the time required to complete the survey is the time employed by the operator to walk around the place. LiDAR mapping systems integrated with SLAM algorithms (LiDAR-SLAM) are less influence by the light and weather conditions, relying completely in the geometry obtained from the point cloud (Chang et al., 2020), however, the performance offered by iMMS's in terms of accuracy is yet

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lower than a TLS, given that the global accuracy depends on both, the accuracy of the LiDAR sensor and the performance of the SLAM algorithm, this last mentioned is highly influenced by the geometry of the object. Additionally, filtering processes are usually applied in order to reduce the noise of the sensors and obtain a more accurate geometrical representation. It is particularly important to highlight that for progress monitoring purposes, a less accurate point cloud model could be required, compared to the needs of a scan-to-BIM or an as-built vs as-designed analysis. Different platforms commercially available offer the possibility to automatically compare both representations, showing the portion that has been built by matching the points with BIM model elements.

1.2 Proposed workflow

Implementation of iMMS's can increase the efficiency of the surveying tasks by mapping the environment in a reduced amount of time, provided that the obtained point cloud meets the quality requirements, that is to say, density or amount of points per square meter and accuracy (Rebolj et al., 2017). iMMS's rely on LiDAR-SLAM to recreate the environment, nonetheless, results have shown to be less accurate with higher level of noise than static systems, this test is focus in the implementation of an iMMS and SLAM of recent development to verify if quality point clouds for construction progress monitoring can be obtained from this system. Randall (2011) defined an acquisition planning phase in which the intrument selection should take part, starting by identify the precision and accuracy required, in this case those requirements are defined by the analysis platform that was used and described in 3.2, in specific, it is necesary to fulfill the point cloud density that the system can obtain under the provided conditions. The characteristics of the instrument are detailed in 2.1.

To determine the feasibility of this workflow, a construction site was mapped at different times using a backpack portable iMMS, filtering processes were applied to identified the setup that fits best for this purpose and finally, the post processed data was compared with the BIM model of the project with 1) a point cloud processing software, 2) using a platform capable to perform the analysis autonomously.
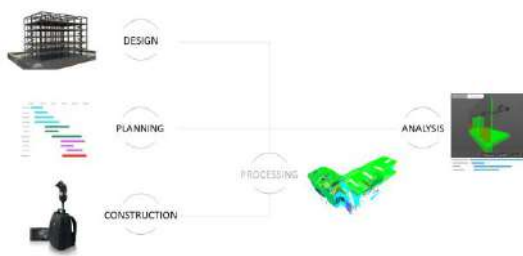

Figure 1. Proposed workflow.

Concerning the BIM model, structural and main architectural elements of the project were created using Autodesk Revit with a Level of Development (LOD) of 300 according to the LOD schema of the American Institute of Architects (AIA), in view of that, element's geometry is correctly described, its size, shape and location can be measured directly from the model (BIM Forum, 2021), in this way, an appropriate comparison between model and reality captured with the 3D laser scan can be performed. Elements with structural, insulation and finishing layers were modeled as a single parametric item. The interoperability between Autodesk Revit and the analysis platform is admitted by exporting the file with an Industry

Foundation Class (IFC) file, the preferred schema is the IFC2x3, since the interest of the exchange is to properly share geometrical information of the model.

1.3 Site description and data acquisitions

The system was tested under real conditions of construction progress monitoring by mapping a site located in the city of Como (Italy). The project consist in the construction of a single floor building intended for catering service, once finished it will be comprised of approximately 1,400 m^2. The scope of this test was the construction progress monitoring of the following reinforced concrete civil works: retaining walls, ground-bearing slab foundation, bearing walls, columns and top floor slab.

Figure 2. Construction site as of 19/10/2021.

The surveys were carried out on a monthly basis to capture the gradual progress of the construction, starting the 19th of October 2021 with the first acquisition and obtaining the last one on the 15th of March 2022 for a total of five different scans. No data was acquired during the month of February. The acquisition time for each survey ranged from 15 minutes at the beginning of the project were very few elements were already built, up to 30 minutes for the last acquisition. The iMMS system is capable to capture the details of the environment by walking through and following a simple path of acquisition, provided that the object of interest present a simple geometry such as walls and floors, smaller elements, in particular columns would require a more exhaustive trajectory definition in order to provide redundant measurements of all of the faces of the element during the post processing phase, this consideration was taken into account for the acquisition of March 15 (Figure 3), however, construction materials that were temporarily stored in the site made difficult to surveyed some areas.

As it occurs in nearly all ongoing construction projects, temporary structures such as formworks, props, scaffolds and construction materials were present most of the time, as highlighted by Rebolj et al. (2017), LiDAR instruments can face different difficulties when are used for surveying inside of congested places. The portability provided by the backpack iMMS allowed to follow the planned trajectory in almost all of the surveys, particular difficulty was faced when props of the top slab casting were present.

2. INDOOR MOBILE MAPPING SYSTEM

All the point clouds included in this test were obtained at the construction site (Figure 4) with a Heron MS Twin Color of the Italian company Gexcel, the instrument is a backpack type iMMS that incorporates SLAM technology (Gexcel, 2022a). The instrument's capture head is composed by two LiDAR
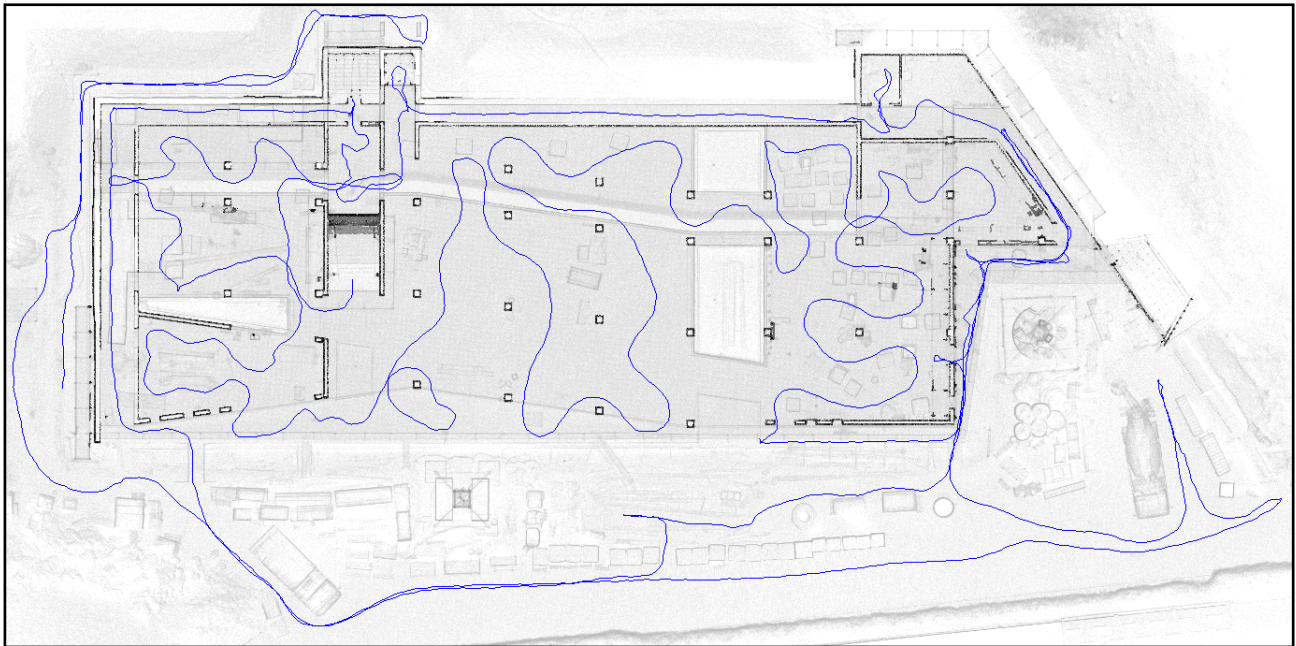
Figure 3. Plan view of the last acquisition showing the trajectory followed at the ground floor.

multibeam sensors, a panoramic camera and an IMU sensor. Each multibeam LiDAR sensor has 16 lines produced by Velodyne, one is positioned with internal rotation along the vertical axis and the other on a 45◦ tilted axis. Both LiDAR sensors have a 360◦ horizontal FOV (Field Of View) and 30◦ vertical FOV. The panoramic camera is installed and calibrated with the LiDAR sensors, capable to perform automatic acquisitions of spherical images (1920x 1080 pixel) at 15 Hz to colorize the point cloud, those images are stored with the raw data and can be retrieved at the post processing phase, additionally, 5k resolution RGB images can be taken on demand. The backpack is provided with a touch screen monitor of the rugged control unit that allows the user to check in real time a preview of the 3D point cloud model. The stated local accuracy of the Heron MS Twin Color is 2 cm, while the global point cloud model accuracy can vary according to the surveying object and data post processing.

Figure 4. Mapping the construction site with the iMMS.

3. THE TEST

3.1 Data processing

As mentioned in 2.1, Heron MS Twin Color collects in the field data from two surrounding LiDAR's synchronized with an IMU sensor and a panoramic camera. During the acquisition a geometrical SLAM process is applied in real time to the raw

data in order to create a preliminary trajectory of the iMMS system. During the mapping phase, the live trajectory and synchronized point clouds are displayed (as a preview 3D model) on the monitor of the control unit to support the operation, verifying the completeness of the survey.

The post processing starts processing the raw data with a desktop software where the SLAM algorithm runs. In this phase, the final and accurate trajectory is computed (control points or control scans can be applied as constrains if available) and the related colorized point cloud is obtained. This data processing is based on three main steps workflow having the goal to process the raw data so to obtain a point cloud model where all the possible geometrical drifts are minimized. The first step is based on the instrument's computated trajectory by means of an odometer module (Ceriani et al., 2015) that estimates the position of the two LiDARs sensors based on a sequential ICP registration process (Sanchez-Belenguer et al., 2019). These registrations are made with respect of the 3D point clouds accumulated along the trajectory and using the IMU raw data (speed and acceleration) to take the LiDAR sensors movements into consideration. The second elaboration step consists in the subdivision of all the trajectory in short chunks (named virtual local maps), along which the accumulated point clouds are not drifting and that can be virtually considered as a sequence of rigid static scans. The third steps requires to run a cloud to cloud registration and bundle adjustment between all the overlapping parts of the local maps, this last step guarantees a large number of loop closures along the operator trajectory.

Once the final trajectory is obtained, the final point cloud can be computed using the data acquired by one or both of the LiDAR sensor in order to reduce the noise. This test considered the implementation of a noise filter to evaluate its performance for the given conditions, this procedure was implemented using Reconstructor software (Gexcel, 2022b) that is fully integrated with the SLAM post processing software. In particular, three different point cloud models were computed by setting in Reconstructor the data import parameters. The aim of this analysis was to identify the best point cloud generation

workflow to make the progress monitoring process more efficient and more accurate. The first point cloud (PC1) was generated voxeling at 2 cm the LiDAR raw data acquired by both of the LiDAR sensors and using only the best points generated in the previously described odometer step, using a quality assessment filter. A second point cloud (PC2) was generated voxeling at 2 cm the LiDAR raw data but using only the information acquired by the iMMS oblique LiDAR sensor and selecting the points with the best registration values during the odometer step using a quality assessment process. A third point cloud (PC3) was generated voxeling at 1 cm, using only the iMMS oblique LiDAR sensor raw data and applying a noise filter to remove all the points that don't match the local geometrical behavior of the point cloud. The applied filter is based on an analysis of the points surrounding space, looking for planar and linear features at different scales. An example of how point clouds are visualized in Reconstructor is shown in Figure 5.
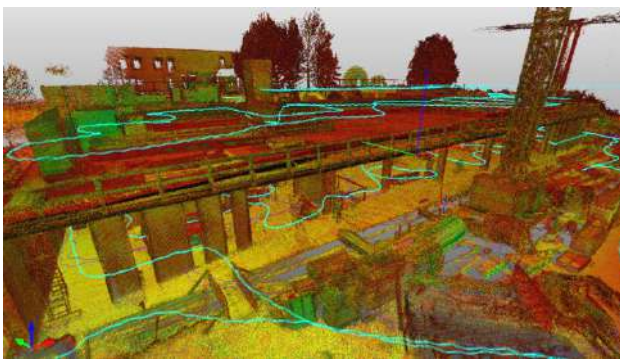

Figure 5. Point cloud with colorization based on reflectance. The trajectory is displayed in cyan.

During the acquisition phase, control points were not used and the relative orientation between the point clouds reference system and the BIM model one was initially unknown. The correct alignment was computed with Reconstructor following the subsequent steps: 1) The BIM model's IFC file was imported to Reconstructor, converted into a mesh model and sampled into a dense point cloud with a resolution of 1 cm, this point cloud was used as reference model to perform an automatic ICP (iterative closest point) registration with respect the surveyed and post processed point clouds (as built model). Finally, a mesh to cloud comparison process was performed to verify the quality of the alignment between models using the Inspection tool of Reconstructor software which algorithm is based on the measurement of the minimum distance between each point and the closest triangle mesh of the IFC model along the normal vector of the closer triangle.
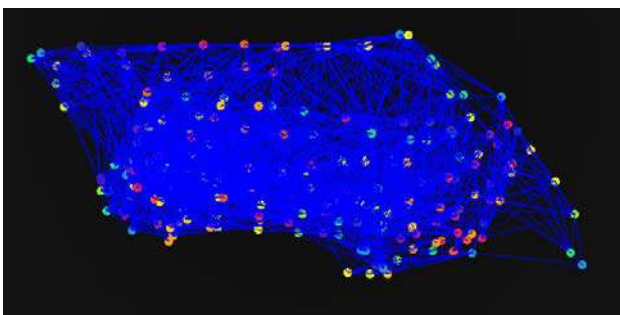

Figure 6. How the Global Optimization between local maps is shown in the post processing software.

3.2 Autonomous construction progress monitoring

Zhang, et al. (2009) examined the capabilities of new software's to provide a semi-automated workflow for progress measurement and other tasks related to project management by linking 3D representations and computer vision based recognition of the construction progress. As mentioned in 1.1, modern approaches of this method make use of LiDAR technologies to capture the reality, for this test, a web application called Sitemotion was used to integrate BIM models and laser scan. The platform provide a friendly interface capable to verify the construction progress, further, when adding the project's schedule and linking its tasks to the BIM, it is capable to show possible delays and schedule deviations.

The platform works by relating the surface of each BIM element with a neighboring set of points, once the algorithm finds a match of the geometry within a specified tolerance of 4 cm it will describe it as an executed work, thus, assigning a completion percentage. The requirements of the platform to perform the analysis are 1) BIM model has to be uploaded as an IFC file, IFC2x3 schema is preferred, 2) minimum point cloud density of 100 points per square meter, PTS and LAS files are admitted, the acquisition date must be included and once uploaded, the point cloud has to be associated to a model with which the comparison will be done, 3) common reference system between BIM models and point clouds. Once the files are processed, a graphical interface allows to create the construction schedule or to upload one in the format of xml or mpp files containing the schedule tasks with which the BIM model will be associated. Elements are presented with a color scheme to highlight the status of the object in case they are identified as on time or delayed accordingly.

4. RESULTS

Smaller or view occluded elements generally present less accurate representations, however, to verify if the global accuracy of the system could be improved, the last acquisition was performed following a more exhaustive trajectory around those elements, in particular, columns. This resulted to be true due to the higher amount of geometry captured by the LiDAR sensor, that intuitively results in denser point clouds, providing additional geometry during the odometry and bundle adjustment process that supports the algorithm in finding a better estimation of the LiDAR's position but also to obtain a more precise trajectory and point cloud, thus, higher global accuracy was obtained.

The amount of noise that the point cloud shows is that provided by both of the LiDAR sensors, additionally, the synchronization between them could not be perfect, thus, by removing the measurements of one of the sensors the resultant noise can also be diminished. It was tested the use of the oblique sensor only to voxelize the data, the result showed a more consistent geometrical representation of the elements. The resultant point cloud can be additionally improved applying a noise filter that removes the points that don't fulfill the geometrical characteristic of the point cloud (Figure 6). The Reconstructor's Inspection tool was used to verify the final accuracy obtained with respect to the mesh built from the BIM model, showing that using only the oblique LiDAR sensor and applying a voxelization of 2 cm, the majority of the points were located equal or closer than 5 cm in a perpendicular direction from the mesh surface with a mean value of 1.26 cm, while voxeling at 1 cm the mean value of this distance was 0.85 cm, thus, the global
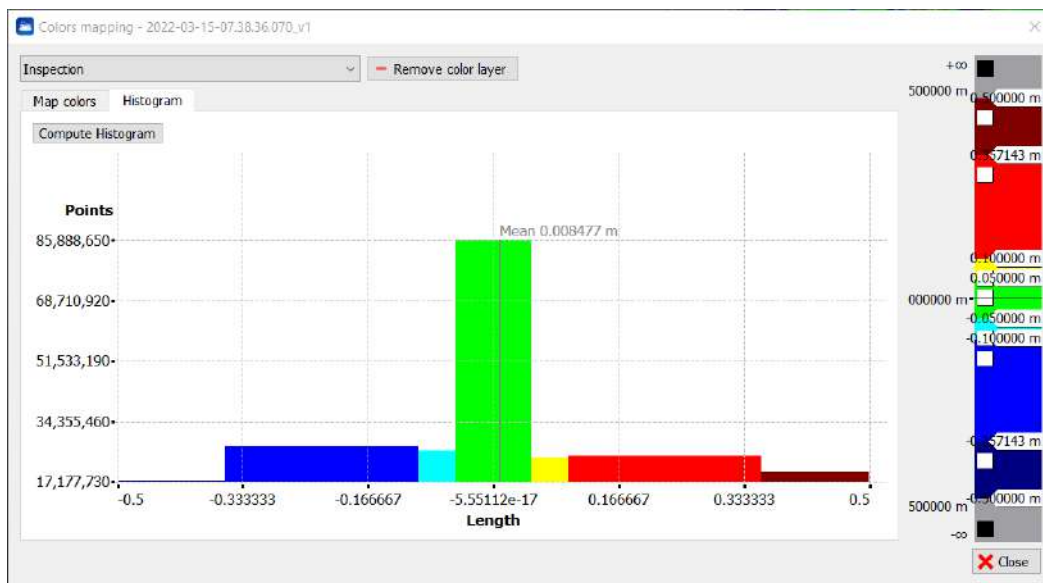
Figure 7. Inspection tool configured to compare BIM model based mesh and point cloud with voxelization of 1 cm.

accuracy is also improved with more meticulous voxeling parameters.

Cloud to cloud type of registration between surveyed point clouds and a BIM based synthetic point clouds showed to be an efficient workflow to provide referenced information in the autonomous construction progress monitoring platform without dealing with ground control points. Once the models were uploaded in the autonomous construction progress monitoring platform, this was capable to match the constructed elements that fulfilled the tolerance requirement.
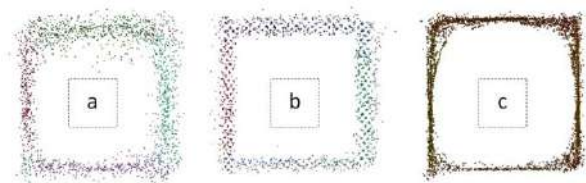

Figure 8. Horizontal section of one column surveyed and post processed with a) oblique and horizontal sensors, b) oblique sensor only, c) as previous plus noise filter application.

5. CONCLUSIONS

The iMMS used for mapping the environment of a construction site is capable to produce point clouds with quality parameters such that tasks of construction progress monitoring can be performed autonomously. Further, to obtain the required global accuracy required from platforms as the one implemented, the acquisition's trajectory has to be planned and executed in a more detailed manner when smaller constructive elements are present, in addition, is crucial to correctly set the voxelization parameters and the application of noise removing filters.

For those point clouds surveyed with less detailed trajectories, the construction progress monitoring platform was not capable to find a match for the columns given that the level of noise present was higher than the tolerance admitted by the platform of 4 cm, thus, to correctly integrate the monitoring platform

such that all the constructive elements under analysis are detected, adequate global accuracy of the iMMS is required.
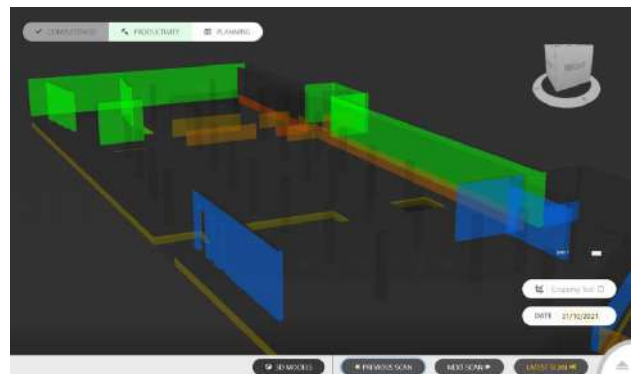

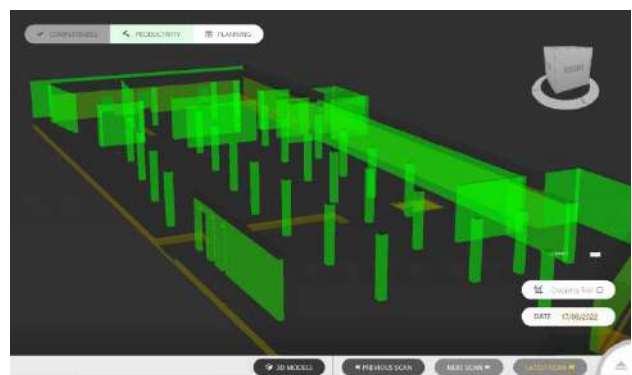**Figure 9.** Construction progress showed in Sitemotion as of 31/10/2021.

Figure 10. Construction progress showed in Sitemotion as of 15/03/2021.

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access to the construction site and providing technical information of the project.

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