Slam and Beacon Data for Automation of Indoor Construction Progress Tracking

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Abstract. Construction progress tracking and monitoring is a complex process that is crucial for the successful execution of projects and the delivery of a high-quality product to the client. However, these tasks remain mostly manual - time-consuming and error prone, which often leads to suboptimal quality, cost and schedule overruns. The present research proposes the use of an autonomous rover for the data collection from construction site. The objective is to create a hybrid data processing system using point clouds from the Simultaneous Localization and Mapping (SLAM) algorithm used for robot navigation, and beacons’ data integrated with BIM, to track construction progress and provide project managers with reliable information in quasi-real time. The paper is composed of four parts: first, a literature review of best practices regarding the technology used for progress tracking is performed. Second, we propose a framework for automated data collection and information processing for automated progress tracking and monitoring. Third, we present a real-world case study partially implementing the framework by using data acquired by an autonomous rover and BIM, and simulate a real-time reconstruction of the construction site status. Finally, the results are discussed, and future work is identified.

1. Introduction

Due to the nature of construction, with its uncontrollable environment, unique resources and fragmented operation, the construction industry suffers from low productivity, cost and schedule overruns, and recurring safety issues. Traditional methods of data acquisition and progress tracking remain manual, time-consuming and error prone. Yet these tasks account for a significant portion of construction workers’ time. This explains why work progress never meets early estimates, resulting in schedule and costs overruns and dissatisfied clients. The recent development of real-time data acquisition technology tools could address these issues and significantly improve industry productivity [15]. A lot of research is being developed to automate the progress monitoring management. This involves providing the right, accurate, and reliable information to the right person in the right place on time. Having a quasi-real-time information about the site works and their context would allow the construction manager to make right decisions and ensure that the project will be delivered within the defined parameters [10].

The study presented in this article is part of a larger research project on construction progress monitoring using autonomous rover and heterogenous data coming from mobile LiDARs and Beacons, all supported by BIM. The particular objective of this study is to develop an operational framework to recreate a model representing the as-built state of a construction site at the moment of the data collection by the rover, and compare it with the Dated 4D (D4D) model as planned. The paper is structured in four parts, namely: (1) literature review on new methods for progress tracking in construction (2) proposed
theoretical framework for automated monitoring of construction progress through technology association and data fusion; (3) description of a case study based on BIM, mobile LiDARs and Beacons technologies, for partial validation of the proposed framework; (4) discussion and future work.

2. Literature review

This literature review explores the process of automated progress tracking by examining data acquisition technologies, and methods for automating progress tracking tasks.

There are two types of imagery data collection technologies, structured data provided by Terrestrial Laser Scanning (TLS) and unstructured data from mobile LiDARs and photogrammetry, both of which provide point clouds. For information transfer technologies, the most commonly used ones are Radio Frequency ID (RFID), QR Codes, Bluetooth Low Energy (BLE) and Ultra-Wide Band (UWB). To automate data acquisition, these two types of technologies can be used with supporting equipment such as Unmanned Aerial Vehicle (UAV) or Unmanned Ground Vehicle (UGV).

Structured point clouds data can be transformed into a mesh model which can be automatically reconstructed (using specialized software) to generate an as-built 3D model. In the case of unstructured data, the raw point clouds acquired by the system must be preprocessed, first to reduce the noise and outliers, and then to align the different sets of point clouds to obtain the complete dataset. Object recognition can be developed by recognizing elements on point clouds by their geometry [2], texture [5], color [1], or position. The segmentation can first be planar to recognize vertical and horizontal elements, and then the points clouds can be segmented using Machine Learning and Computer Vision techniques to detect all types of features directly on the point clouds [2]. Following the recognition of the objects, and to obtain surfaces and then a 3D model, the objects are reconstructed by creating mesh models. This process can be automated by using advanced algorithms.

As far as the Beacon data is concerned, it can be connected to BIM using the ID feature and linking a database with the BIM model to retrieve the information [11].

Various techniques can be used to compare the as-built information provided by the scan with the as-planned provided by the 3D model. The comparison can be between the surfaces of two models [6], between two point clouds [4], or between a model and a point cloud [14]. Progress monitoring update is often referred to as an accomplishment of the research performed following object recognition and reconstruction. In the literature, three main techniques are used, firstly by calculating and comparing quantities, performing quantity extraction from both models [8][13]. Second, by recreating a schedule in relation to the detected object and comparing it with the original schedule [11]. Finally, the most widely used method is pattern labeling which provides an automatic visual comparison between as-built and as-planned surfaces [6].

Visualization of updated information between as-planned and as-built can be done by color-coded models [6], colored point clouds [3] to show the surfaces that do not correspond or with dashboards [13] to show a more detailed visualization using numerical information.

The diagram on Figure-2 provides a graphic summary of the literature and best practices review concerning the comparison and visualization methods for progress monitoring presented above.

![Figure 1. Associations of comparison and visualization methods for progress monitoring.](image-url)
3. Proposition of a framework

Based on the previous section and prior work of our team [7], a general framework of the research is presented in this section. The team has developed an autonomous rover that acquires data on construction site based on semantic information from the BIM model. The objective is to update the BIM information from the collected data. The point clouds are captured by a mobile LiDAR, which can generate a large unstructured point cloud of the building from the SLAM (Simultaneous Localization and Mapping) algorithm used for robot navigation. We are also able to generate an RGB-mapped point cloud using cameras installed on the rover. These point clouds will be used to detect building elements on site.

To identify some objects which cannot be ‘seen’ by LiDAR or cameras, a beacon-based system is developed and used for the detection of MEP equipment or secondary elements, the objective being to provide the maximum information to the BIM model, to determine the progress of the work on site.

In the following part, we present the whole framework (presented on Figure-2), from data acquisition to dashboards, in three major parts: the LiDAR-based system, the beacon-based system and the methods to update the Dated 4D model (D4D).

![Proposed framework diagram](image)

**Figure 2.** Proposed framework.

3.1. LiDAR based – process

From the on-site acquisition with the autonomous rover, two types of point clouds are collected, SLAM-mapped point clouds from LiDARs and RGB-mapped point clouds from RGB cameras.

These point clouds are less accurate and less dense than the typical point clouds used in construction from Terrestrial Laser Scanning or even from photogrammetry. To overcome this problem, the point clouds are pre-processed to improve their quality. The element detection system needs a certain quality to reconstruct the element to form an as-built model.

The point clouds need to be processed individually, creating a study area, a bounding box which can be a floor or more precisely a part of the building that needs to be explored. Noise reduction is applied with the (Statistical Outlier Removal) SOR Filter to remove points with outliers in each point cloud. Point clouds from different sources are aligned with the Iterative Closest Point (ICP) algorithm, which creates a single point cloud with all the information retrieved from the scans. The RANSAC algorithm is tested to segment the point cloud into different planes, which can help the element detection system, but the low density does not allow for proper detection of the planes and thus of the element. However, after processing the point clouds, it could be determined that with this type of point cloud, only structural elements can be detected.

To enable element detection, after pre-processing the point cloud from SLAM, a patching technique from the BIM model is used to enhance the point cloud without losing the scanning information. The structural elements are isolated on the Revit Model, and with a Dynamo script, we export the studied area into a mesh model and then into a dense point cloud, thus creating a point cloud of the ‘as planned’.
After aligning the as-planned and as-built point clouds with the ICP algorithm, these point clouds are compared using a cloud-to-cloud distance method. Then, with the scalar field corresponding to the distance between the two models, we can create an as-built point cloud with good density and better quality than the raw point cloud data.

By applying the RANSAC algorithm after this process, we can analyse the quality differences between the raw laser data and the data acquire with the proposed method for processing the point cloud.

3.2. Beacon-based process

This step of the system consists of assigning information to the physical resources, in order to detect the position of the elements that cannot be detected with the LiDAR-based process. This association is supported by attaching tags to the concerned items in order to provide a unique identification (ID) for each resource and to link the information to these IDs, and thus, to the resource. All kinds of information can also be added, such as product name, manufacturer, dimensions, installation instructions, delivery date, etc. The whole system works on the basis of the rewritable nature of the chosen technology. For the purposes of the project and the system, two technologies that can support this type of use are BLE tags and UWB tags, as they are both composed of rewritable tags and have readers with long enough range to remotely and wirelessly collect field data.

For the purposes of the data collection, a tag reader is placed on the autonomous rover to detect the position of elements. The coordinates (x,y,z), and their ID can be exported to a database, and compared to the same properties exported with a Dynamo script from the BIM model.

3.3. Updating the D4D model

The first step in updating the BIM information using the scans and the tags, is to create an as-built model. Once the point clouds are pre-processed and the tag locations are detected and stored, it is possible to update the BIM model with real-time information.

An as-built model can be created manually or automatically. Manual reconstruction consists of rebuilding a model from the geometric information of the point cloud aligned to the BIM model. For automatic reconstruction, machine learning or computer vision techniques for element recognition will have to be used and can be developed in future work. The structural information (walls, columns, ceilings, floors) is reconstructed from the information from the LiDAR-based process.

In parallel, the beacon-based process compares the position of the detected elements (x,y,z) with those of the BIM model, by exporting the coordinates of the BIM elements to a database and comparing them with those from the beacon system on the rover. This information will complement the as-built model and provide information about all element categories.

To compare with the as-built model, a D4D model is created. It is generated during the 4D simulation, on the day of the scan, to have “live” information during the construction. This D4D model is exported, and it is this one that is compared with the as-built model created from the rover-collected data. The 4D simulation is created with the Work Breakdown Structure (WBS) of the selected elements, the tasks of the planning are associated with the elements in the model.

For the visualization of the results, Autodesk Navisworks and BIM360 software can be used. With the “compare” tool, it is possible to have a colored visualization of the model to see which elements are well built or not. With this, it is possible to export a list with the name and the parameters. Different properties are used to compare the models: for structural columns - the height; for walls - the length; and for floors and ceilings - the area. The exported lists are then compared and thanks to the parameters, it is possible to calculate a percentage of progress at the chosen date and to see which elements are not as expected. Furthermore, with the WBS, it is possible to associate the elements that are not built as planned and to update the tasks as “done” or “not done”, to automatically update the status of the tasks on the progress schedule.

With all this information available after the comparison, dashboards are created to facilitate the understanding of the construction team. The objective is to have a dashboard with the percentage of progress, the tasks that are not well executed and the elements that need special attention.
4. Case study
A case study was developed for the partial validation of the proposed framework. Tests have been performed in a university building in Montreal. The data acquisition was supported by a Clearpath Jackal rover. The following equipment was mounted on it: two Ouster LiDARs (one to capture data around the rover, the other – above); one Velodyne LiDAR; and three Intel RealSense RGB cameras. This system allows the acquisition of different point clouds on site.

Difficulties arose with the RGB-mapped point cloud from the cameras as the acquired data had a lot of noise and the scan was not usable even with preprocessing. For this reason, the case study was conducted exclusively with the point cloud of the mobile LiDARs namely the Velodyne LiDAR and the Ouster. We carried out experiments to see what kind of elements can be detected with this type of point cloud. As explained in the previous section, the quality of the point cloud was improved by using the BIM model and comparing it with the scan.

With this system, we could more easily detect the elements and create an as-built BIM model. The structural elements were well detected, so we continued the experiment to the other structural parts of the building. An as-built 3D model was generated manually, from the pre-processed point cloud, with the structural elements that can be detected, namely: walls, ceilings, floors and structural columns.

Several tests were performed with BLE beacons (Confidex Viking model) to try the detection of the elements. The remote reader for the beacons was an Android smartphone equipped with a BLE scanner application. The beacons were placed on elements in the university and manually configured with their corresponding ID. The result of the beacons revealed a high percentage of errors between the position predicted by the Revit model and the position obtained by the scanner. The beacon information, such as the ID, was well detected but the distance was completely wrong, due to the presence of many metallic obstacles that interfered with the signal. In the next iteration of our system, a different and more advanced system with UWB beacons (Pozyx System) is developed to detect smaller equipment on the construction site.

The comparison system is currently used with the as-built model from the LiDAR-based process, while the information from the beacon-based system will be added in our future work.

The D4D model was generated with the schedule of the structural portion of the construction. After creating this model, the as-built model was imported, aligned and then compared with Autodesk Navisworks and BIM360 “Compare” tool. The results are very encouraging, the differences between the D4D model and the as-built model are well detected, and a list of “non-conforming” elements can be exported to create dashboards for the project manager.

![Figure 3. Results of the comparison, colored model and dashboards](image)

5. Discussion and future works
In this research, we explore the possibilities for developing an automatic reconstruction and progress tracking system based exclusively on unstructured data, without using Terrestrial Laser Scanning, or photogrammetry which are manual and time-consuming processes. The objective is to obtain enough information to reconstruct an as-built model and compare it with the as planned D4D model.

The main problems encountered are the insufficient quality of the data acquired on site and, for the LiDAR and Beacon data, a significant amount of pre-processing. However, this pre-processing allows the system to detect many categories of elements on construction site.
In our future research, we will focus on generating an RGB-mapped point cloud that can be used to complete the automatic reconstruction of the as-built model from the preprocessed point cloud. More investigation on planar and semantic segmentation, and more resources in terms of machine learning will help automate the process as much as possible. For mechanical equipment or secondary elements, we found that simple BLE detection with smartphone is not enough to detect the elements on the construction site, so a new UWB-based system under development will be integrated into the proposed framework.

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