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INITIATING DATA ACQUISITION FOR CONSTRUCTION PROGRESS CONTROL BASED ON LEAN PRINCIPLES USING 4D-BIM

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Abstract

Fast decision-making is crucial in the construction industry, particularly when responding to deviations during the building process. A building information model (BIM) may be used to facilitate decision-making as it should accurately reflect the construction site's current state. This paper outlines a data acquisition framework, based on lean principles for construction progress control. The BIM is abstracted to "critical surfaces" based on information on the schedule, which is then compared with the surface reconstructed from the acquired point cloud data using the RANSAC algorithm. Integrating the resulting data back into the BIM provides reliable construction site information.

Introduction

Motivation

During the construction phase, particularly in infrastructure projects, there are frequent decision-making instances since construction processes are intricate and diverse, primarily due to unique production requirements, such as in the construction of bridges. It is essential to continually enhance and update the BIM with the latest information on the site's condition during construction. However, the current process of manually planning and executing data acquisition lacks accuracy and adequate coverage (Zhang et al., 2016).

Using drones for data acquisition can be beneficial; however, the planning process for data acquisition has been time-consuming, prone to errors and ineffective thus far. Surveyors/pilots must manually extract information from 2D-drawings or poorly detailed geometric models, locate relevant components of the structure and create a plan for data acquisition. This leads to a decrease in cost-effectiveness, an inadequate or excessive amount of data, and a lack of efficiency (Biswas et al., 2015). Furthermore, the acquisition of construction-related data has been insufficiently handled until this point. As per a survey conducted among construction managers by Ailland (Ailland, 2013), only 23% of the respondents maintain daily construction diaries. Additionally, in 65% of the cases, it takes up to a week for manually collected construction-related data to process it. The prolonged duration in a construction project poses a significant challenge in obtaining a precise and up-to-date understanding of the ongoing construction activities. This situation becomes even more challenging as the construction progresses, with new layers of complexity and unforeseen events emerging at every stage. Therefore, it is imperative to adopt an approach that can provide accurate and real-time information about the project's progress to ensure efficient and effective project management.

However, the implementation of an optimization process called "*Planning For Scanning*" (P4S) for planning data acquisition can result in efficient data acquisition (Aryan et al., 2021). There has been limited research so far on how to automate data acquisition planning based on a BIM, especially using the schedule (4D-BIM), as stated by (Tschickardt et al., 2022). Automated data acquisition is critical to quickly obtain the necessary information to facilitate construction management decision-making. Automating construction progress control has been a topic of discussion for years. Current methods exist that enable model-based construction progress control using photogrammetry or LiDAR point clouds. Nevertheless, advanced hardware and complex algorithms are required to evaluate and process point clouds. Training algorithms to identify construction site components in point clouds is challenging due to the varying project types and component classes (Kaufmann et al., 2022). Existing methods acquire data for the entire site using various technologies, leading to an excess of data. It is impractical to train for all combinations, making lean construction progress control a more feasible approach.

Objectives

The framework proposed in this paper aims to initiate data acquisition in a construction project by utilizing a 4D-BIM and lean principles for progress control. The underlying assumption of this research is that the automation of data acquisition through event-driven, demand-oriented, and drone-assisted methods can significantly improve the efficiency of the construction site, specifically in terms of construction progress control.

The proposed framework consists of two main components:

(i) the development of an analytical model that defines tasks that can be acquired by drones by leveraging the semantics available in the 4D-BIM, and the subsequent initiation of drone-assisted data acquisition, and

(ii) the development of a lean implementation methodology for the efficient integration of the acquired data into construction progress control, with short feedback cycles.

The framework necessitates the following conditions:

- Regular updates of the 4D-BIM with current information on the construction site,
- Partially or fully automatic data acquisition utilizing drones with LiDAR or photogrammetry technology, and
- Uniform level of detail between the schedule and the BIM.

To ensure efficient implementation of the framework, it is necessary for the schedule to include a detailed representation of (half-)day tasks, with at least one task completed per week and a maximum task duration of one week. The BIM should be modeled with detailed scheduling and include ambient geometry such as cranes, etc.

Additionally, a weekly report will be prepared, providing a daily update on construction progress and comparing it with a tolerance threshold of one day (depending on the critical path). This allows for information on compliance with the schedule within a one-week period.

Currently, the framework is implemented for concrete works in infrastructure construction, particularly in bridge construction and is limited to planar surfaces and visible components.

Related Work

This chapter aims to provide a brief overview of the data acquisition planning, the fundamentals of lean construction and the current research status of model-based construction progress control.

Planning the data acquisition

The current manual data acquisition process is laborious, error-prone, and inefficient, necessitating the optimization of the process and the automatic generation of a flight plan for data acquisition that adheres to lean principles and achieves optimal coverage. This research aims to determine the points of interest (POI) for the drone mission based on a 4D-BIM, rather than focusing solely on an optimal flight path.

Automatically deriving POI from the 4D-BIM is a key aspect of this research and its successful implementation is critical. In previous work, (Biswas et al., 2015) and (Biswas, 2019), focused on identifying the surfaces of building components to plan POI for terrestrial laser scanners (TLS). (Aryan et al., 2021) reviewed several methods for automatic coverage planning using BIMs and found that only two, namely (Biswas, 2019) and (Heidari & Varshosaz, 2016) , proposed a P4S approach for surface coverage within a geometric model. Heidari & Varshosaz utilize point sets that are homogeneously distributed to abstract surfaces of components, simplifying the surface coverage problem to point coverage. Conversely, (Biswas, 2019) aims to determine the precise surface coverage of the components, offering the benefit of higher accuracy as point clouds can be matched with the surfaces of the BIM components. Alternative methods for determining POI are available in various literature. (Freimuth & König, 2015; Morgenthal et al., 2019) use a grid system with a predetermined distance to the entire structure, while (Freimuth & König, 2019) use a navigation volume with unoccupied voxels for flight path planning. (Hamledari et al., 2021) use either a single IFC file with schedule information or a 3D model, while (Ibrahim et al., 2019; Ibrahim & Golparvar-Fard, 2019) generate and use 2D site plans for planning. (Bolourian & Hammad, 2020) provide a review of previous P4S approaches involving drones.

Lean construction

The construction industry faces schedule and cost overruns, as well as construction defects that are difficult and expensive to rectify, due to the prevailing framework conditions and processes. The root cause of these issues lies in the conventional linear planning process, which involves a series of sequential actions (Spieth et al., 2016). The conventional approach's weaknesses can be addressed by using innovative methods like lean construction (Becker & Tschickardt, 2023). As per the "Pull principle" of lean construction, described by (Günther & Tempelmeier, 2009), production is driven by the customer's demand-oriented order, resulting in customer-oriented production. This approach involves structuring the production process based on the completion of each step, which then triggers production for the next corresponding step (demand-pull). In this manner, the order or demand for information is passed along from each production step antiparallel to the material flow, as depicted in Figure 1.

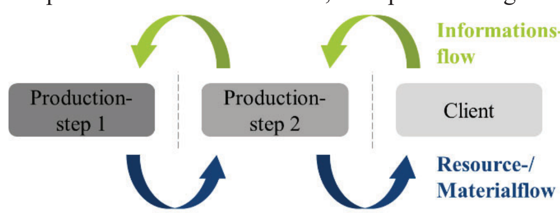

Figure 1: Pull principle (Günther & Tempelmeier, 2009)

Model-based construction progress control

During a construction project, unforeseeable factors like weather or delays in tasks may cause deviations from the pre-planned schedule. Construction progress control aims to detect such undesirable deviations and developments as early as possible, to take suitable measures in time. The topic of construction progress control has been extensively researched in automation for many years.

In addition to photogrammetric point clouds generated using machine learning methods in digital image processing (computer vision), LiDAR point clouds can also be utilized for model-based construction progress control. The authors of a study (Bosché et al., 2013) compare the geometric comparison between the as-built point cloud and the as-designed geometric model to "Scan-vs-BIM," similar to object recognition and reconstruction using point clouds (Scan-to-BIM). (Turkan et al., 2014) distinguish between "Scan-to-BIM" and "Scan-vs-BIM." While Scan-to-BIM approaches can recognize objects, they require additional information for unambiguous identification of objects with similar shapes, such as texture and material. In contrast, Scan-vs-BIM approaches allow direct identification of recognized objects because each object recognized in the point cloud refers to one or more uniquely placed objects in the BIM.

(Bosché & Haas, 2008) compared the acquired point cloud obtained through LiDAR with a synthetic point cloud generated from a geometric model converted to a triangulated mesh format. The detection of points in the acquired point cloud is based on a predefined threshold for the difference with the corresponding point in the synthetic point cloud.

Another approach by (Turkan et al., 2012) uses the fundamentals of object recognition and registration (Bosché, 2010), which is extended in (Bosché et al., 2013; Turkan et al., 2014). The authors detect temporary/secondary objects, such as reinforcement, formwork elements and formwork support, as well as structural components. Reinforcement and formwork components may be identified if they are inside, on, or below the component surface, while formwork props may be detected if the number of points within a designated area exceeds a certain threshold value. These approaches compare the acquired point cloud with points projected onto the surface of the as-designed BIM from the scanner's location.

(Hamledari et al., 2021) also employ computer vision methods and camera-equipped drones for construction progress control. Their approach utilizes an IFC file containing scheduling information such as *IfcTask* and *IfcScheduleTimeControl*. The IFC schema's standardized properties are modified and custom properties are added based on the construction progress for visualization. As soon as components are detected in the captured images, the construction site's progress is updated.

(Braun et al., 2021) propose a method that utilizes photogrammetric point clouds obtained from various sources such as drones, handheld cameras or crane-mounted cameras and computer vision algorithms. Their approach involves comparing the acquired point cloud data with the BIM and representing the associated construction processes using a graph-based approach. Deep learning techniques are employed by (Han et al., 2021) to detect construction images. In addition, (Golparvar-Fard et al., 2015) have also developed a method for monitoring construction progress using photogrammetric point clouds. The authors calculate the orientations of the images captured at the construction site using Structure from Motion (SfM) and generate a point cloud. They then segment the point cloud into voxels and mark each occupied voxel as progress for monitoring construction progress.

The approach by (Maalek et al., 2019) proposes using detected surfaces of components for construction progress control, with a comparison between the as-built and as-designed done similarly to previous authors (Bosché, 2010; Bosché et al., 2013; Bosché & Haas, 2008; Turkan et al., 2012), with a threshold to account for expected construction tolerances. However, in their experiments, only columns and floor slabs were investigated since the BIM did not include any reinforcement. In contrast, (Lee et al., 2019) uses a volume comparison method based solely on point clouds from different stages of construction, without the use of a BIM.

Research gap

Based on the comprehensive literature review of completed and ongoing research projects, it is evident that drone-assisted data acquisition is crucial for efficient construction progress control. To achieve this, flight plans and POIs must be determined based on a 4D-BIM to account for the current state of the construction site.

However, most of the reviewed methods for P4S rely on simplistic approaches that do not fully utilize the potential of a federated or aggregated 4D-BIM for accurate and efficient data acquisition. The research gap is the lack of existing studies utilizing a federated 4D-BIM for determining POIs, acquirable tasks and associated components. In contrast, the proposed approach in this paper includes also tasks related to demolition and removal, leading to a comprehensive management and control of day-to-day operations.

The literature review also indicates that data acquisition in construction progress control typically involves capturing the entire construction site using stationary or moving cameras or LiDAR. However, implementing a lean data acquisition process that focuses only on necessary data while minimizing disruptions to business operations has several benefits. The proposed approach eliminates the need for high-performance hardware and complex algorithms during subsequent analysis of the acquired as-built data.

Additionally, model-based approaches can only be used when the BIM accurately reflects the reality of the construction site. Nevertheless, there may be discrepancies that prevent components from being captured from certain POIs as expected. In such cases, a 4D-BIM that incorporates up-to-date information on the progress of construction and includes temporary construction equipment can be useful.

4D-BIM initiation and lean construction progress control framework

The initiation framework for 4D-BIM data acquisition and progress control involves two steps:

(i) task-based initiation of data acquisition and
(ii) surface-based progress control.

These steps are explained in detail in the following sections. The framework is being developed through a case study, which will be tested on a real project to demonstrate its feasibility.

The first case study focuses on the PPP A10/A24 availability model project (Tschickardt & Krause, 2019), in Berlin, Germany, where the BIM methodology was thoroughly implemented in an entire construction section, including two fuel and service stations and two engineering structures (bridge and noise barrier wall) with a total length of 5.5 km. The bridge structure and the task "*Construction of the foundation axis 10 (west), Pouring concrete*" are used for the framework.

The second case study is based on construction site in Bochum, Germany. The project involved the construction of a 2-span bridge. The abutments, pile caps, and foundation piles are planned to be constructed using reinforced concrete. The abutments are used for the framework.

Task-based initiation of data acquisition

A 4D-BIM comprises various domains that manage different types of information, which can be linked to one another. These domains consist of multiple elements and objects that are specific to each domain. For the geometric model, there may be partial models in various data formats (such as IFC) that provide information on dimensions and material properties. In the domain of activities, scheduling plays a crucial role in the approach described, and it is typically created using specialized tools like Microsoft Project, Asta Powerproject, or Primavera P6. As the schedule is being developed, it is automatically augmented with task-specific details, such as start and end dates or task duration, by the authoring tool.

The analytical model (see Figure 2) of the approach presented here outlines the tasks and related objects that can be acquired using drones on a construction site. This method is adaptable and not restricted to a particular type of project, as it can be scaled. The analytical model first examines whether a given task results in a geometric change in the 4D-BIM, then assesses whether the task can be simplified to a "critical surface," and finally determines whether there is enough navigable space available for the drone to operate.

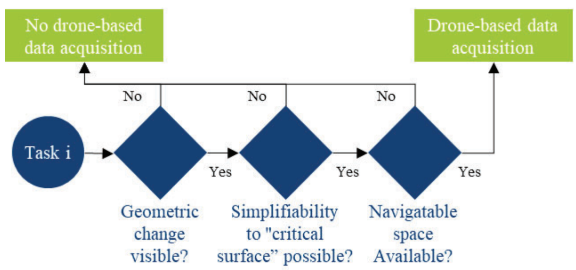

Figure 2: Decision diagram for the analytical model

To perform construction progress control, it is necessary to have a geometric change in the construction site. Simply linking a task with an object does not guarantee a geometric change. For example, the completion of concrete works may have a task associated with it, but it may not result in any geometric changes in the 4D-BIM or data acquisition. To address this issue, the implementation of drone-acquirable tasks and the identification of geometric changes are explained in the following section.

The presented algorithm operates on a schedule T within the 4D-BIM that comprises a set of tasks $\{T_i, \dots, T_n\}$ and visible elements at the start and end of each task, denoted by $T_{i,Start} = \{E_{i,S}, \dots, E_{n,S}\}$ and $T_{i,End} = \{E_{i,E}, \dots, E_{n,E}\}$. To determine whether a task causes a potential geometric change, the algorithm calculates the set difference between $T_{i,End}$ and $T_{i,Start}$, denoted by $T_{i,ES} = T_{i,Eend} \setminus T_{i,Sstart} = \{x | (x \in T_{i,End}) \wedge (x \notin T_{i,Start})\}$. If $T_{i,ES}$ is greater than zero, the task is assumed to cause a geometric change through production. If $T_{i,ES}$ is zero, the algorithm calculates the set difference $T_{i,SE} = T_{i,Start} \setminus T_{i,End} = \{x | (x \in T_{i,Start}) \wedge (x \notin T_{i,End})\}$ to check whether a potential geometric change occurs through demolition and removal. If $T_{i,SE}$ is greater than zero, the task is assumed to cause a geometric change through demolition and removal. If both $T_{i,ES}$ and $T_{i,SE}$ are zero, the task does not cause a geometric change. The algorithm then forms an intersection I_i over L_i and $T_{i,ES}$ or $T_{i,SE}$, where $L_i = \{E_{i,L}, \dots, E_{n,L}\}$ represents the linked elements with the task. If I_i equals zero, the task does not cause a geometric change. If I_i is greater than zero, the task is assumed to cause a geometric change. Thus, the algorithm determines whether the task causes a geometric change, and if so, whether it is a production of new construction or a demolition/removal process.

The case study provides an example using the task "Construction of the foundation axis 10 (west), pouring concrete". At the end of the task (14.07.2021 17:00), there are 2663 visible elements, while at the start of the task (14.07.2021 08:00), there are 2661 visible elements in the 4D-BIM. The two remaining elements are associated with the task of pouring concrete on each axis and are included in the intersection.

The following step involves determining whether the task can be simplified to a "critical surface". This step is essential since not all surfaces of the task's linked objects may be visible in the data acquisition (i.e., point cloud). Thus, it is necessary to determine a critical surface, which is guaranteed to be visible in the data acquisition, based on domain knowledge of the construction process. Unfortunately, this stage currently requires manual execution as automating it in an efficient and outcome-driven manner is not feasible. This is because the IFC structure or any lacks a provision to store information related to specific surfaces. For instance, a formwork element may comprise approximately 40 vertical surfaces, and querying only the orientation (vertical or horizontal) of the object based on the surface vertices' coordinates is insufficient for this use case. Consequently, it is not possible to determine whether the surface is inside/outside or front/back. Although the model author may excel in design and simulation and store information in the IFC, their knowledge about construction processes may not match that of the operational site team. Consequently, this gap in understanding can lead to inaccurate identification of critical surfaces, with flat areas being incorrectly designated as critical. Therefore, it is imperative that the work preparation department at the construction site uses their domain knowledge to identify the surfaces that need to be acquired for each task to avoid such errors.

Typically, planar surfaces are frequently produced on construction sites, allowing tasks to be abstracted to these surfaces. Therefore, the method of surface simplification presented in this study is highly valuable. By abstracting a task to a single surface of an object, only that surface needs to be reconstructed in the point cloud for surface-based progress tracking. Alternatively, an abstraction can be made to multiple surfaces of one object or one surface for multiple objects, requiring reconstruction of those surfaces in the point cloud. However, if a task is abstracted to several surfaces on multiple objects, then all surfaces of those objects must be reconstructed in the point cloud.

Geometrically generated surfaces are created for each task identified. These surfaces are included as an object in the

4D-BIM and are stored in a specific partial model “drone-acquirable object surfaces”, which may also used for documentation purposes. Each surface is tagged with metadata such as the date of acquisition, task ID, origin object ID, origin object code, consecutive numbering, minimum and maximum coordinates (x, y, z) and surface area. The data structure used for the drone-acquirable object surfaces is in the form of JavaScript Object Notation (JSON). The information obtained through drone-assisted data acquisition is utilized for subsequent evaluation processes, with a specific focus on construction progress control. JSON files' hierarchical structure enables the storage of interconnected data in a single document, resulting in a more efficient representation of complex relationships. This is essential in complex projects. The simplified task of "Construction of the foundation axis 10 (west), pouring concrete", which has only one surface, is highlighted in yellow in Figure 3.

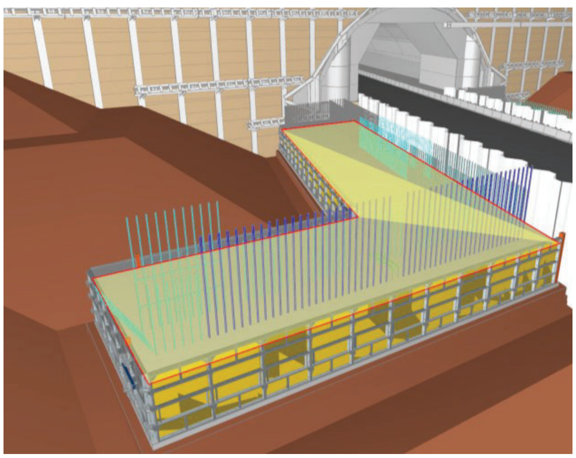

Figure 3: Simplification of the task “Construction of the foundation axis 10 (west), Pouring concrete”

This highlighted surface is then stored as an object in the 4D-BIM and in a JSON-File for further processing. For instance, information such as surface: 243m² (xs:double), OriginObjectID: (xs:string), linked task Id: (xs:string) and date of acquisition: 2021-07-14 (xs:date) are listed as examples. The determination of POIs is dependent on various factors, including the laser scanner's configuration, such as its vertical and horizontal field of view.

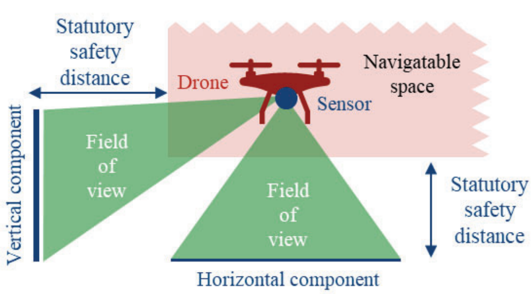

Figure 4: Navigatable space for drone-assisted data acquisition

Once the simplified surfaces' coordinates are provided, POIs can be calculated to ensure that the scanner's configuration and statutory safety distance are adhered to (see Figure 4). Other technologies, such as cameras, can also be employed to implement the methodology.
For instance, if the longitudinal shoring of a road bridge is to be acquired, the legal safety distance must be maintained, considering the ongoing traffic as "uninvolved persons" under the European Commission's implementing regulation (EU) 2019/947. This regulation mandates a safety distance, which may be reduced to five meters in slow flight mode (three meters per second). To define the POI of the surfaces to be acquired, a parameter study was carried out using Blender and BlAInder software to generate synthetic point clouds. The study involved varying the distance to the component (5 to 70 meters), drone speed (0.5 m/s to 5 m/s), sensor type (Velodyne Puck, camera of DJI Mini 3 Pro), and rotation rate (5Hz, 10 Hz, 15Hz and 20Hz) in case of LiDAR. CloudCompare software was then used to analyze the point clouds, with the "number of neighbors" geometrical feature examined at radii between 0.1m and 1m. The results of the study indicate that even low-cost sensors like Velodyne Puck or camera of DJI Mini 3 Pro, along with higher velocities or greater distances, can produce enough points for construction progress control. Detailed results will be published separately by the authors.
By considering the statutory safety distance and scanner configuration, the proposed method ensures optimal LiDAR coverage and quality during drone flight for data acquisition. A search algorithm is used to compute the flight plan, which is not the focus of this study. The data acquisition time is determined by introducing a "search time," starting from the task's end date minus a predefined tolerance. The acquisition process takes place within this interval until the critical surface in the point cloud is reconstructed. A one-day tolerance threshold is chosen to enable continuous monitoring of schedule compliance.

Surface-based construction progress control

Enabling surface-based construction progress control requires the drone to autonomously survey the construction site using a predetermined set of POIs and flight paths for identifying and acquiring critical component surfaces. The outcome of this aerial survey are georeferenced, component-specific point clouds. Georeferencing can be achieved using various methods such as control points and is a mandatory requirement. Without accurate georeferencing, alignment and comparison with the 4D-BIM cannot be performed. The proposed surface-based progress control, also referred to as lean progress control, depends on up-to-date information (as shown in Figure 5) and follows the pull principle of the lean methodology. This means that data acquisition is initiated only for construction progress control purposes.

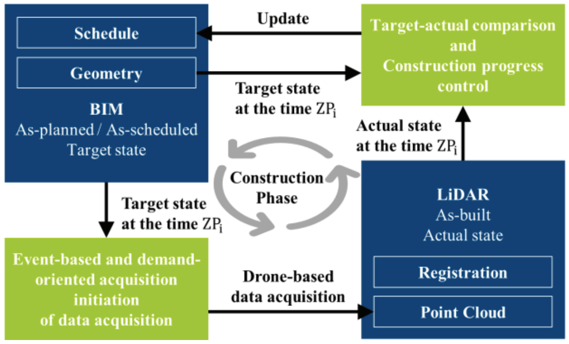

Figure 5: Construction progress control in project execution

The successful implementation of the method relies on its holistic and consistent use throughout the construction phase. As previously discussed, data acquisition based on the BIM's as-planned or scheduled target state is triggered only when necessary. Point clouds are used to represent the as-built state of the construction site, and the target-actual comparison process provides information on the current status of the site, which is then used to update the BIM.

In Figure 7, the process of surface-based progress control is illustrated. It involves three main steps: (I) using the coordinates of the simplified critical surfaces from the task-based initiation in a JSON file to create a two-dimensional surface, which is then (II) extruded into a volume of interest (VOI) based on the normal vector direction and construction tolerances allowed by the acquisition technology. The VOI is then utilized to isolate the area where the object's surface is expected from the point cloud acquired during the autonomous aerial survey. The subsequent step involves further filtering of all points within the VOI, based on the correspondence between the normal vector of the points and the target surface. The accuracy of points decreases significantly beyond a 70° angle of incidence, according to (Soudarissanane et al., 2009). For complex shapes, typically found on infrastructure construction sites, it is advantageous to use the tessellation of the triangles forming the surface rather than the stretched and simplified surface for extruding the VOI. This method breaks down the complex surface into the simple geometry of triangles, which can be extruded based on their normal vector, resulting in the correct VOI. This approach eliminates the need for sophisticated algorithms to reconstruct the polygonal boundary of complex surfaces.

The next step (III) involves using the RANSAC algorithm (Schnabel et al., 2007) to reconstruct a surface from the filtered points, as shown in Figure 6 for the example of the "Construction of the foundation axis 10 (west), Pouring concrete" task. Ideally, the reconstructed surface should correspond to the simplified nominal surface. If no surface can be reconstructed, the task cannot be reported as finished. The minimum number of support points per primitive form is set to 90% of the points of the VOI to eliminate orthogonal surfaces in the boundary area. The maximum distance to the primitive form is already given by the VOI, and the sample resolution of the filtered points is set to 0.1 meter. The RANSAC algorithm has proven to be an effective tool for surface reconstruction with these parameters and the filtered point cloud. The output is a CSV file containing information on the linked task ID and date of acquisition.

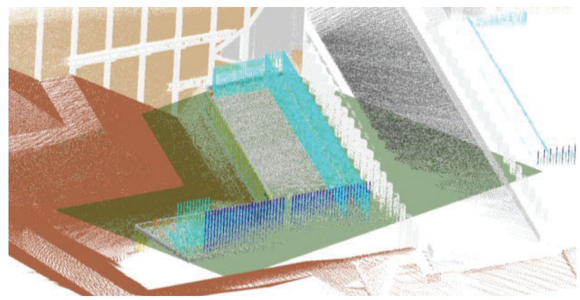

Figure 6: The identified surface of top edge concrete by RANSAC for the task "Construction of the foundation axis 10 (west), Pouring concrete"

On-Site showcase

The construction site in Bochum, Germany was utilized as second case study for the proposed method. The project involved the construction of a 2-span bridge, designed as a steel composite structure with a concrete deck above, intended to replace the existing bridge structure. To improve aesthetics and reduce span width, steel V-shaped columns will be used as intermediate supports, which will be connected integrally to the superstructure, resulting in spans of 41.0 - 20.0 - 41.0 meters. The abutments, pile caps, and foundation piles are planned to be constructed using reinforced concrete.

Figure 8 displays the 4D-BIM of the bridge construction site, specifically highlighting the construction task "Production of the abutment axis 30" and "Formwork stripping of the abutment wall and wing walls".

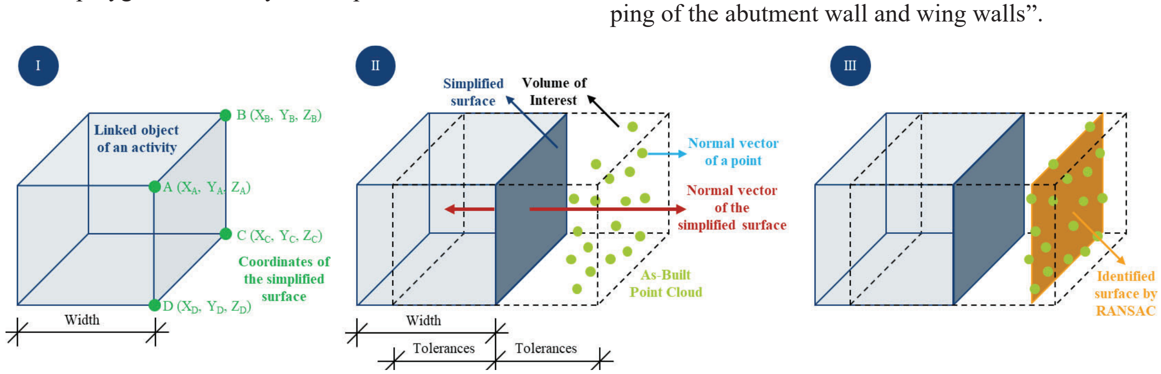

Figure 7: Surface-based progress track procedure

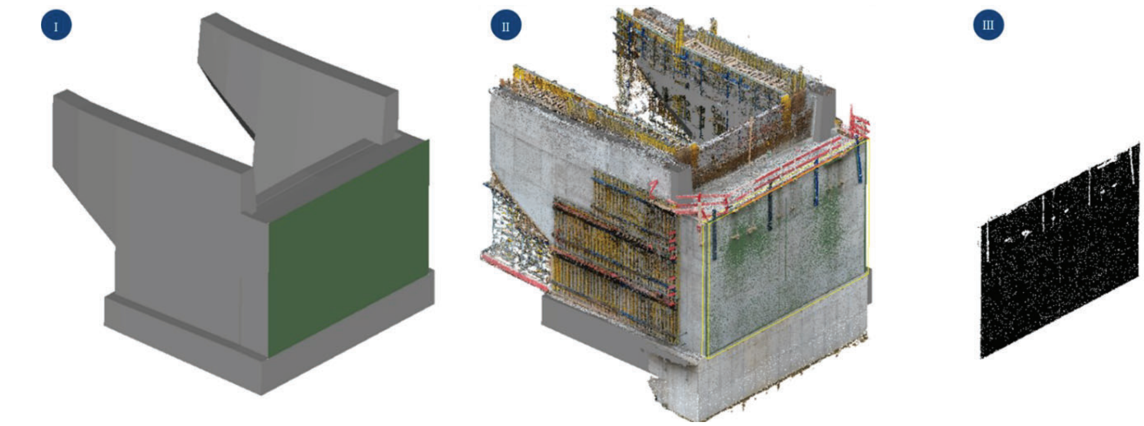

Figure 8: Task-based acquired point cloud and reconstructed surface based on RANSAC for lean progress control

The critical area, which needs to be examined in the acquired point cloud, is displayed in green. The design has not been modeled in detail, including formwork or reinforcement. The point cloud, acquired using a DJI Mini Pro 3 drone with georeferenced control points, is shown in (II), with the VOI for the critical area highlighted in yellow. The filtered points for the critical surface, to which the RANSAC algorithm is applied, are shown in (III). After comparing the reconstructed surface with the critical surface in terms of position accuracy and dimensions, the actual data is reported back to the 4D-BIM to provide a basis for the next data acquisition.

Conclusions and Outlook

The framework introduced in this research makes a significant contribution to the area of model-based construction progress control. Specifically, the framework offers an analytical model for defining drone acquirable tasks using the available information in the 4D-BIM, including geometric and schedule information. Additionally, the framework offers an event-based and demand-oriented data acquisition process that follows the pull principle, streamlines the analysis process through surface simplification, and eliminates the need for complex algorithms and high-performance hardware. Lastly, the framework contributes to automated and lean construction progress control by enabling short-cycle information supply for new construction or demolition/removal tasks.

The presented framework was tested on both synthetic and real showcase data. By identifying compatible tasks for drones at the outset of the framework, tasks are simplified into “critical surfaces”, which serve as a crucial component for flight planning. The drone can acquire the critical surfaces with sufficient navigable space, and lean construction progress control is enabled using the RANSAC algorithm. This algorithm evaluates only component-related point clouds to update the construction schedule and the 4D-BIM. The minimum number of support points per primitive form is set at 90% of the points of the VOI. The RANSAC identifies critical surfaces within the VOI and reports the actual data back to the 4D-BIM, providing the basis for the next data acquisition.

This approach offers several advantages, including the acquisition of data and information necessary for efficient construction progress control, as well as the elimination of the need for complex algorithms and high-performance hardware. Moreover, the framework can be implemented with other acquisition technologies, such as photogrammetry or mobile mapping systems, if a georeferenced point cloud is provided as the result of data acquisition. The methodology does not require further development, as data acquisition and subsequent analysis can be considered independent steps.

This approach is particularly suitable for infrastructure projects, such as bridge and road construction in open spaces. It is also feasible for structures like football stadiums, large factory halls, offshore wind farms/production platforms, and major concrete constructions for buildings, to a certain degree. However, interior construction and confined spaces are not implementable due to the UAV's geometrical dimension and the need for a reception signal. Moving forward, 4D-BIM is expected to provide temporary construction status, facilitating comprehensive model-based project management and precise schedule control of contractor's construction sites. It is also anticipated to become a contractual obligation for clients to ensure effective management of large-scale projects. Technological advancements, such as parameterized modeling, cloud-based data storage, and the use of an information structure according to ISO 19650, have made high modeling costs and complicated model handling obsolete, enabling efficient work.

This new approach is currently being implemented successively and will be tested on more projects to ensure its effectiveness and potential for broader use.

Acknowledgment

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