Automated progress monitoring based on photogrammetric point clouds and precedence relationship graphs

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ABSTRACT

Construction progress monitoring is an essential but time-consuming work on all construction sites. This research introduces a method to facilitate the as-planned versus as-built comparison through image based monitoring. A dense point cloud is reconstructed from the images that is compared to an existing 4D building information model (BIM). However, due to the numerous obstructions found on a construction site, only a minority of building elements can be detected directly. In this paper, we discuss how the detection results are significantly refined and enriched by using additional spatial and temporal information gained from the 4D BIM. In this regard, a precedence relationship graph is derived which helps to identify occluded elements and enhance the detection algorithm.

Keywords -
Progress monitoring, as-planned as-built comparison, point clouds

1 Introduction

In the construction phase of a building, it is important to know the current progress and to detect derivations from the schedule as early as possible. Today, theses scheduling derivations have to be detected in a manual process that is laborious and error-prone, in particular in the case of very large and complex construction projects. To improve the accuracy and reduce the manual effort required, the automation of construction progress monitoring is desirable.

A building information model (BIM) can help to automate this process. This digital model contains all relevant information of a building. Next to 3D geometry, also semantic descriptions like the used material and, important for this particular case, also temporal information and durations of all construction tasks are represented [1]. The additional information in 4D models supports the monitoring and optimization of construction processes as the comparison of the planned with the actual stage of construction can be realized.

In order to automate the monitoring of construction processes, monitoring techniques like laser scanners or photogrammetric images can be used. Both methods result in a point cloud that holds the current status of the construction site (as-built). This can be compared to the as-planned status from the building information model.

As described in several researches ([2], [3]), occlusions and limited acquisition points on site can disturb the resulting point clouds and therefore the overall accuracy of the as-planned vs. as-built comparison.

To address this issue, additional knowledge embedded in the BIM can help to improve the matching process. Process information like the planned start and finish dates for each building element help to predict in which timeframe an element should be visible in the as-built point cloud.

The proposed approach uses this information to retrieve a set of existing building elements at a certain time step *t*. Due to the mentioned shortcomings regarding occlusions, not all existing elements will be detected. Thus, a precedence relationship graph is introduced that holds information on dependencies between all elements of the building.

This paper gives an overview of the current state-of-the-art in section 2 and discusses the limitations of the approaches introduced so far. Subsequently, the proposed methods are described in section 3. Section 4 illustrates the potential of the developed methods by means of a case study - a construction site of a multi-story building.

2 Related Work

Construction progress monitoring has been investigated in several studies recently. This summary focusses on studies which address monitoring and image acquisition as well as additional process information provided by the building information model.

2.1 Monitoring

The matching of the as-planned model and the as-built point cloud can be realized in different ways. On the one hand, there is the possibility to transform the existing Building Information Model into a point cloud and to compare it with a generated as-built point cloud [2]. Another option is the transfer of the as-built point clouds into surfaces and perform a surface matching [3].

As-built point clouds can be acquired by laser scanning or image-based/photogrammetric methods. In [4] and [5] a system for as-built as-planned comparison based on laser scanning data is presented. The generated point clouds are co-registered with the model by applying an adapted Iterative-Closest–Point-Algorithm (ICP). In the presented approach, the as-planned model is converted to a point cloud by creating the virtual points using the known positions of the laser scanner. For verification, the authors use the percentage of simulated points that can be verified by the real laser scan. In [6], [7], [8] this system is extended for progress tracking using schedule information, for estimating the progress in terms of earned value and for detecting secondary objects. In [9] specific component types are detected using a supervised classification method based on Lalonde features derived from the as-built point cloud. An object is regarded as detected if the type fits to the type in the model. As above, the model also has to be sampled into a point representation here. In [10] a measure is introduced for distinguishing four cases (object not in place, point cloud represents a full object or a partially completed object or a different object) based on the relationship of points within the boundaries of the object and the boundaries of shrunk object. The authors test their approach in a very simplified test environment, which does not include any problems, which occur on data acquired on a real construction site.

The usage of cameras as acquisition device comes with the disadvantage of a lower geometric accuracy compared to the laser scanning point clouds. However, cameras have the advantage that they can be used more flexible and their costs are much lower. This leads to the need for other processing strategies if image data is used. Rankohi & Waugh (2014) give an overview and comparison of image-based approaches for the monitoring of construction progress. In [11] a single camera approach is used and images taken are compared over a certain period and rasterized. The change between two timeframes is detected through a spatial-temporal derivative filter. This approach is not directly bound to the geometry of a BIM and therefore cannot identify additional construction elements on site. In [12] a fixed camera and image processing techniques are used for the detection of new construction elements and the update of the construction schedule. Since many fixed cameras would be necessary to cover a whole construction site, more approaches rely on images from hand-held cameras covering the whole construction site as in our and the approaches mentioned in the following.

For correct scaling of the point cloud, stereo-camera systems can be used, as done in [13], [14] and [15]. [16] proposes to use a colored cube with known size as target, which can be automatically measured to determine the scale. In [17] image-based approaches are compared with laser-scanning results. The artificial test data is strongly simplified and the real data experiments are limited to a very small part of a construction site. Only relative accuracy measures are given since no scale was introduced to the photogrammetry measurements. [17] and [18] use unstructured images of a construction site to create a point cloud. The orientation of the images is performed using a Structure-from-Motion process (SFM). Subsequently, dense point clouds are calculated. For the comparison of as-planned and as-built model, the scene is discretized using a voxel grid. The construction progress is determined in a probabilistic approach, in which the threshold parameters for detection are determined by supervised learning. In this framework, occlusions are taken into account. This approach relies on the discretization of the space by the voxel grid, having a size of a few centimeters.

In the approach presented in this paper we calculate the deviation of point cloud and building model directly and introduce a scoring function for the verification process. In contrast to most of the discussed publications, we present a test site that presents extra challenges for progress monitoring due to the existence of a large number of disturbing objects, such as scaffoldings.

2.2 Process and dependency information

Process planning is often executed independently from conceptual and structural design phases. Current research follows the concept of automation in the area of construction scheduling. Binding process information and the underlying building information model provides additional information that can be used in the context of progress monitoring.

Tauscher describes a method that allows automating the generation of the scheduling process at least partly [19]. He chooses an object-oriented approach to categorize each component according to its properties. Accordingly, each component is assigned to a process. Subsequently, important properties of components are compared with a process database to group them accordingly and assign the corresponding tasks to each object. Suitable properties for the detection of similarities are for example the element thickness or the construction material. With this method, a "semi - intelligent" support for process planning is implemented.

In [20] a mathematical formalism is introduced that is based on the quantity theory for the determination of technological dependencies as a basis for automated construction progress scheduling. In [21] a branch-and-bound algorithm is introduced to determine optimal decompositions of planning and construction processes into design information and process information.

Another important aspect for the as-planned vs. as-built comparison are dependencies. Technological dependencies show, which element is depending on another element, meaning, that it cannot be built after the first element is finished. These dependencies can be stored in so called precedence relationships [22]. A solution to store these dependencies in graphs is shown in [23].

These innovative approaches to process modelling form a very good basis for automated construction monitoring, but have so far not been applied in this context.

3 Concept

This research focusses on enhancing the progress monitoring on construction sites by photogrammetric means. Photogrammetric methods are a convenient solution since – once calibrated – a commercially available camera can be used. The proposed concept focusses on incorporating additional information into the detection process. Detailed information on the generation and handling of point clouds is provided in [24–26].

3.1 Monitoring methods

All vision-based methods for monitoring have the problem that they can only monitor objects that are in direct sight. Objects that are occluded cannot be detected. However, particularly on construction sites, many occlusions occur. Scaffoldings, formworks and other building materials block the view on the surfaces of the building elements. Additionally, elements that are out of range of the monitoring system cannot be tracked. A monitoring system that only focusses on gathering data from the outside of a building can obviously not detect any elements inside of it.

To cope with those challenges, different methods for image capturing were compared.

3.1.1 Manual image acquisition

A still very labor-intensive manual approach is to take pictures with hand-held cameras while walking around the construction site. The advantage is that occlusions caused by large machines can be avoided since the process is not fully automated and the timing for the pictures can be chosen manually. Additionally, more camera positions help to generate a denser point cloud.

3.1.2 Image acquisition using fixed cameras

In order to automate the image acquisition, fixed cameras are a very desirable solution. To generate a point cloud for a large building and to cover all sides of it, a very large amount of positions would be needed since each visible point needs to be covered by at least two cameras (for stereo matching).

In a current case study, two cameras are fixed on the boom of a crane and take pictures in a certain time interval during the movement of the boom. Figure 1 shows the view from one of the cameras that shows the construction work on reinforcing mats for a slab. During the working day, the crane covers the complete construction site and thus a point cloud covering the complete building can be generated. The cable from the crane that can be seen in the top of the picture can be removed in the resulting point clouds.

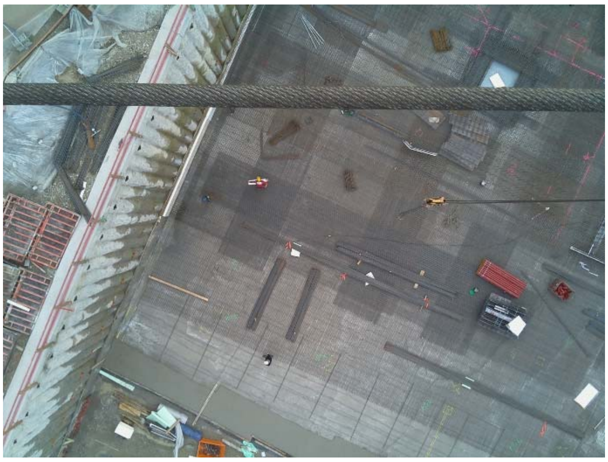

Figure 1: top view on a construction site from a fixed camera on a crane

3.1.3 Image acquisition using UAVs

Another promising approach is the use of unmanned aerial vehicles (UAV). By defining several positions over a construction site, an octocopter can fly to these positions at each monitoring time step and take pictures from nearly the same position every time (see Figure 2). This monitoring method can be executed after end of work to have the lowest amount of occluding objects on site. Since modern UAVs use GPS-based orientation, they can fly on their own to the predefined positions to automate this process. On the downside, especially in inner-city areas, many restrictions regarding UAVs are prohibiting their use.

Figure 2: Aerial view of a construction site from an UAV

In conclusion, there are several very promising methods for as-built monitoring. The best solutions for monitoring are always depending on the exact location and the surroundings of each construction site.

3.2 Point clouds

As described in [24], the generation of the point cloud consists of four steps: Data acquisition, orientation of the images, image matching and co-registration. The orientation is performed by using the structure from motion system VisualSfM [27]. For a better as-planned as-built comparison, the as-planned model is placed at the exact survey coordinates.

Due to occlusions and limited acquisition positions, rarely complete coverage of the construction site area can be reached. In order to capture the construction process, these point clouds are captured at certain time steps corresponding to the process schedule.

To ensure that the point clouds of all time steps are in one consistent coordinate system, control points are used which are stable and visible during the whole construction process. For each point in time, a „Dense Matching"-algorithm creates point clouds. The control points' position is known and therefore the point cloud is placed at the exact survey coordinates.

3.3 As-built as-planned comparison

For the as-built vs. as-planned comparison we realize a two-step approach. In a first step, only geometric information is used to match point cloud and model. To this end, the model is represented as a triangle mesh. A coverage rate is computed for each individual triangle: The distance between the points and the respective surface can be computed using barycentric coordinates [28]. Afterwards, all points that have a lower distance than a predefined threshold are considered as a match for the corresponding triangle. Finally, the coverage rate is computed as points per area. Detailed information about the thresholds is given in the case study.

This process is done for the complete building and not only for the as-planned status for the actual time step t in order to cover the case of an early schedule. In any other case, there might be detected points with no underlying surface to detect. This approach needs an always up to date as-planned building model that is updated with all geometric changes. Spatial deviations cannot be detected since only the planned geometry is used for matching.

3.4 Technological dependencies

As introduced in [20], technological dependencies can support the automated process generation. In construction planning, these dependencies stand for a forced sequence in the process. This means that a building element that has a technological dependency on another element cannot be built before it. This holds especially for e.g. columns built on a slab beneath it.

Technological dependencies can be represented using graphs [21]. The resulting graph is a so-called precedence relationship graph where each node represents a building element. The directed edges define the dependencies. The advantage of this type of representation is that it can be easily examined and all depending objects can be identified with one query.

The graph can be automatically created using a query language for building information models as described in [29]. In a first instance, all structural components are ordered in their vertical arrangement. This order produces a first graph. Next, all other elements are attached to their bounding structural components.

Important building elements like slabs play a crucial role in dependency graphs. No elements on top of them can be built, before the slab is completed. In the dependency graph, these elements are represented by so-called articulation points [30]. Removing an articulation point would result in disconnecting the graph.

Due to the high amount of occlusions on construction sites, the generated point cloud and hence the results from the as-built vs. as-planned comparison do not represent the correct actual stage on site in most cases. A purely geometry-based approach would thus fail to correctly detect the construction progress. The introduced precedence relationship graph holds additional information that adds a knowledge part to the detection process. With its help, a building element that is detected based on the present point cloud implies that all elements that are predecessors in the graph for this particular element have to be built, too.

3.5 Temporal information

The dependency graph introduced in section 3.4 adds a lot of information into the detection process and helps to make statements about building elements that were not visible during the monitoring process.

However, this improvement adds an uncertainty to the method: a falsely detected element could have a huge impact on all predecessors in the graph and make the complete result useless. Therefore, an element with many not yet identified, preceding objects needs additional attention before marking all elements as “built”.

Process information is used to make a statement about the correctness of the identified element. The construction time of the element is compared with the current progress time. If the detected element is assigned to a process that does not match the current process schedule, the detection status of said element will be discarded.

4 Case Study

The proposed methods were tested on several construction sites. In this example, a six story, inner-city building was monitored during construction with hand-held cameras from street view and the crane. Additionally, pictures from neighboring buildings were used to get a top view of the building.

A snippet of the generated point cloud is depicted in Figure 4. These points were matched against the triangulated geometry retrieved from the as-planned model as can be seen in Figure 5.

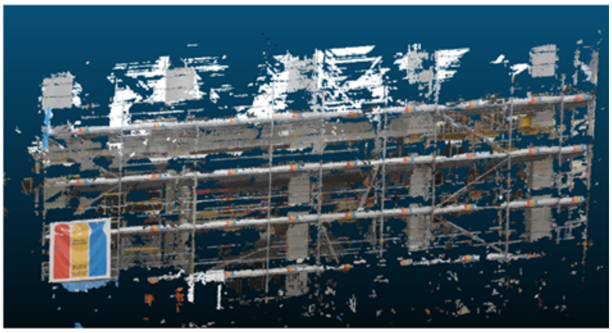

Figure 4: Generated point cloud from the construction site

The colors in Figure 5 represent the coverage rate in points per area, calculated for every triangle. Points were considered only when the distance between point and triangle is lower than 10 cm. Yellow has been assigned to triangles that matched between 10 and 500 *points per square meter*. Green is assigned for all triangles with a coverage rate higher than 500 *points per square meter*. A threshold is defined and only surfaces are considered that are matched by at least 10 points. The boundaries and thresholds were assigned based on experiments and comparison with the exact as-built data and were proven to give the most exact results for the given data.

The results show a good detection rate for the right part of the building. However, the left part shows insufficient detection of triangles. This is due to the scaffolding as seen in Figure 4 that leads to holes in the point cloud since the building parts cannot be seen from the point of observation.

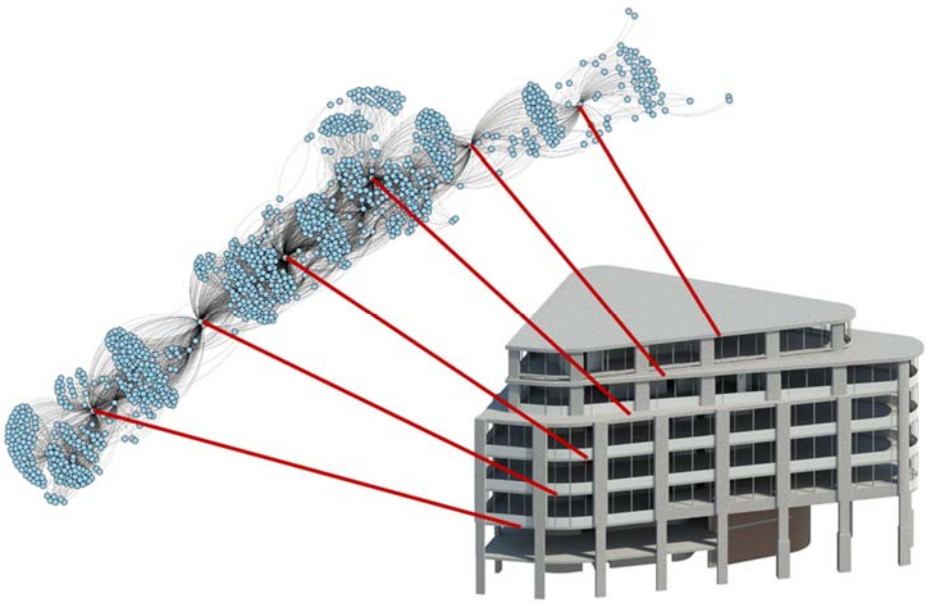

Figure 3: Precedence relationship graph with the corresponding model

The proposed concept now introduces the additional information from the building information model. Figure 3 shows the mentioned precedence relationship graph with the corresponding as-planned model. The graph is generated by a query language [29], [31]. The articulation points, marked by the lines in the figure, in the graph can be identified clearly and provide exact information about the technological dependencies.

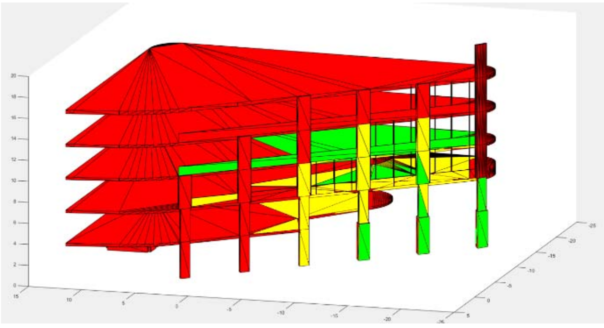

Figure 5: Triangles identified as "detected" by matching them against the point cloud

This information is now used to check for building elements that precede detected elements but are not detected themselves. The graph is examined and all predecessors of detected elements are taken into account. An additional plausibility check with the process schedule supports the hypothesis that especially the columns on the left side need to be built and therefore present in the current building state despite that they are not proven by the point cloud.

The final result of the detection process is depicted in Figure 6. The elements verified by the point cloud are marked in green, whereas the concluded elements are marked in yellow.

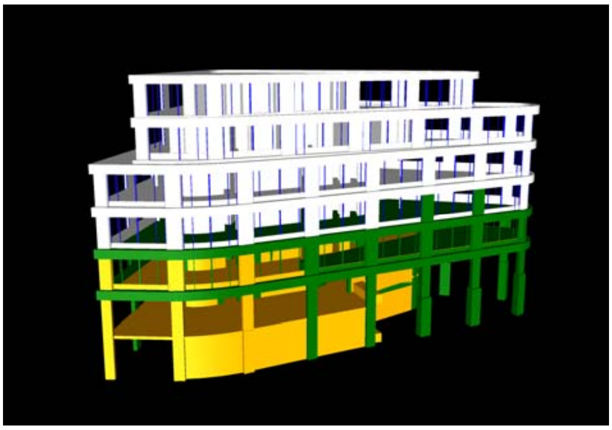

Figure 6: detected and occluded, but concluded building elements

5 Conclusion and Future work

This paper introduces methods to include knowledge from a building information model into automated progress monitoring. Since visual monitoring often lacks completeness, this additional knowledge provides useful support for the as-built vs as-planned comparison.

However, the used thresholds are currently fitted for the given case study and need to be proven against different cases to gain a more reliable level.

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