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Chapter 30

BIM-based progress monitoring

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Abstract On-site progress monitoring is essential for keeping track of the ongoing work on construction sites. Currently, this task is a manual, time-consuming activity. BIM-based progress monitoring facilitates the automated comparison of the actual state of construction with the planned state for the early detection of deviations in the construction process. In this chapter, we discuss an approach where the actual state of the construction site is captured using photogrammetric surveys. From these recordings, dense point clouds are generated by the fusion of disparity maps created with semi-global-matching (SGM). These are matched against the target state provided by a 4D Building Information Model. For matching the point cloud and the model, the distances between individual points of the cloud and a component's surface are aggregated using a regular cell grid. For each cell, the degree of coverage is determined. Based on this, a confidence value is computed which serves as a basis for detecting the existence of a respective component. Additionally, process- and dependency-relations provided by the BIM model are taken into account to further enhance the detection process.

30.1 Introduction

Large construction projects require a variety of manufacturing companies from different trades on site (e.g. masonry, concrete and metal work, HVAC). An important

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goal for the main contractor is to keep track of accomplished tasks by subcontractors, and the general time schedule. In construction, process supervision and monitoring is still a mostly analog and manual task. To prove that all work has been rendered as defined per contract, all performed tasks have to be monitored and documented. The demand for comprehensive and detailed monitoring techniques rises for large construction sites where the entire construction area becomes too large to monitor by hand and the number of subcontractors rises. Main contractors that control their subcontractors' work need to maintain an overview of the current construction state. Regulatory issues add to the requirement to keep track of the current status on site.

The ongoing digitization and the establishment of Building Information Modeling (BIM) technologies in the planning of construction projects can facilitate the use of digital methods in the built environment. In an ideal implementation of the BIM concept, all semantic data on materials, construction methods, and even the process schedule are connected, making it is possible to make statements about the cost and estimated project finalization. Possible deviations from the schedule can be detected and the following tasks rearranged accordingly.

A Building Information Model is a rich source of information for performing automated progress monitoring. It describes the as-planned building shape in terms of 3D geometry and combines it with the as-planned construction schedule. The resulting 4D model contains all relevant information for the complete construction process. Accordingly, the planned state at any given point in time can be derived and compared with the actual construction state. Any process deviation can be detected by identifying missing or additional building components.

For capturing the actual state of the construction project in an automated manner, different methods can be applied, among them laser scanning and photogrammetric methods. Both methods generate point clouds that hold the coordinates of points on the surface of the building elements but also of all objects occluding the building. A sample of a point cloud, generated in one of the case studies rendered during the duration of this research can be seen in Fig. 30.1.

The main steps of the proposed monitoring approach are depicted in Fig. 30.2. The minimum information that a BIM needs to provide is the 3D geometry and the process information (construction start and end date) for all building elements. From this, the target state at a certain time step *t* is extracted. Subsequently, the target state is compared to the actual state, which in the approach presented here is captured using photogrammetric techniques. Finally, any recognized deviations are used to update the schedule of the remaining construction process.

30.2 State of the art

Several methods for BIM-based progress monitoring have been developed in recent years (Omar and Nehdi, 2016). Basic methods start by including technical advancements like email and tablet computers into the monitoring process. These meth-

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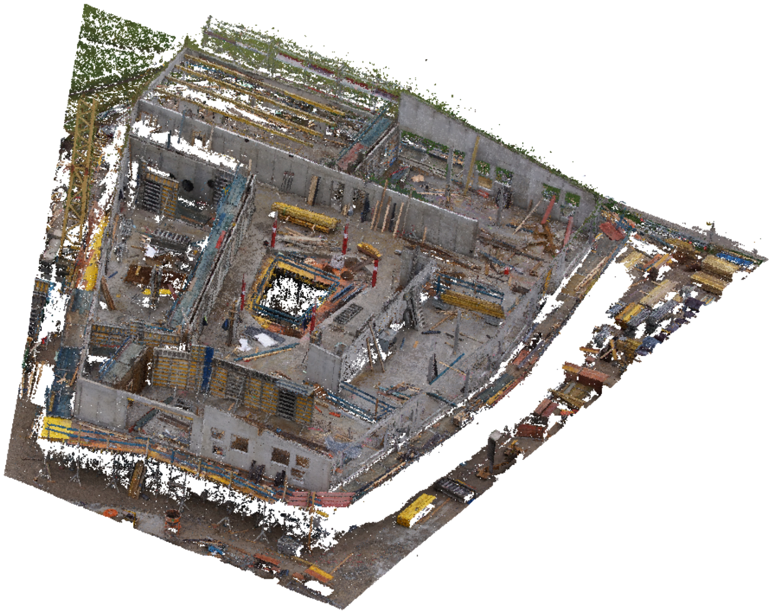

Fig. 30.1 Point cloud generated during the observation of the construction progress of a sample construction site

ods still require manual work, but already contribute to the shift towards a digital process. More advanced methods try to track individual building components with radio-frequency identification (RFID) tags or similar methods (e.g. QR codes).

Current state of the art methods propose using vision-based methods for more reliable element identification. These methods either make direct use of photographs or videos taken on site as input for image recognition techniques, or apply laser scanners or photogrammetric methods to create point clouds that hold point-based 3D information and additionally color information.

In Bosché and Haas (2008) and Bosché (2012), a system for as-built as-planned comparisons based on laser scanning data is presented. The generated point clouds are co-registered with the model using an adapted Iterative-ClosestPoint-Algorithm (ICP). Within this system, the as-planned model is converted to a point cloud by simulating the points using the known positions of the laser scanner. For verification, they use the percentage of simulated points, which can be verified by the real laser scan. Turkan (2012) and Turkan et al. (2011) use and extend this system for progress tracking using schedule information, for estimating the progress in terms of earned value and for detecting secondary objects. Kim et al. (2013b) detect specific component types using a supervised classification based on Lalonde features derived from the as-built point cloud. An object is regarded as detected if the type matches the type in the model. As above, this method requires that the model is sampled into a point representation. Zhang and Arditi (2013) introduce a measure

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for deciding 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 the shrunk object. The authors test their approach in a very simplified artificial environment, which is significantly less challenging than the processing of data acquired on real construction sites.

In comparison with laser scanning, the use of photo or video cameras as acquisition devices has the disadvantage that geometric accuracy is not as good. However, cameras have the advantage that they can be used in a more flexible manner and their costs are much lower. This leads to the need for other processing strategies when image data is used. Rankohi and Waugh (2014) give an overview and comparison of image-based approaches for monitoring construction progress. Ibrahim et al. (2009) use a single camera approach and compare images taken over a certain period and rasterize them. The change between two time-frames is detected using 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. Kim et al. (2013a) use a fixed camera and image processing techniques 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 (Kropp et al., 2018).

For finding the correct scale of the point cloud, stereo-camera systems can be used, as done in Son and Kim (2010); Brilakis et al. (2011a,b). Rashidi et al. (2014) propose using a coloured cube of known size as a target, which can be automatically measured to determine the scale. In Golparvar-Fard et al. (2011a) 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. Golparvar-Fard et al. (2011b) and Golparvar-fard et al. (2012) use unstructured images of a construction site to create a point cloud. The orientation of the images is computed using a Structure-from-Motion process (SFM). Subsequently, dense point clouds are calculated. For the comparison of as-planned and as-built, the scene is discretized into a voxel grid. The construction progress is determined in a probabilistic approach, in which the parameters for threshold for detection are determined by supervised learning. This framework makes it possible to take occlusions into account. This approach relies on the discretization of space as a voxel grid to the size of a few centimeters. In contrast, the approach presented in this chapter is based on calculating the deviation between a point cloud and the building model directly and introduces a scoring function for the verification process.

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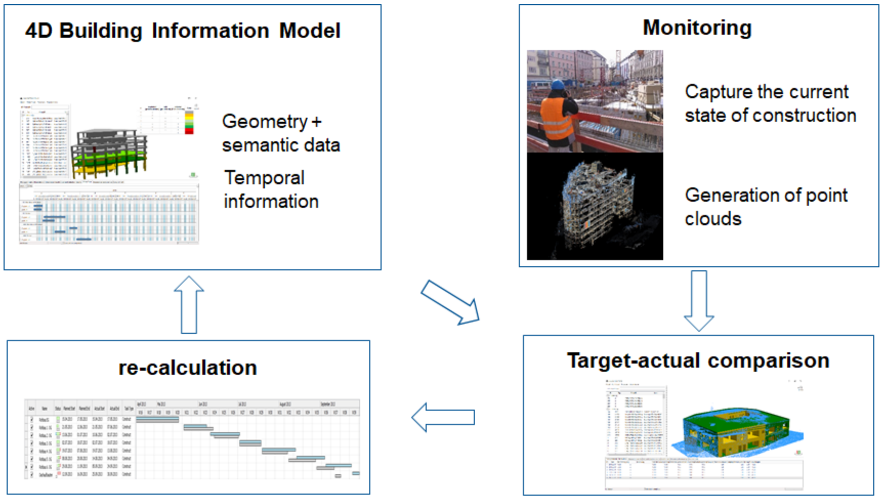

Fig. 30.2 Concept for automated progress monitoring

30.3 Concept

The presented approach for BIM-based progress monitoring is depicted in Fig. 30.1. On the one hand, a building information model is needed that not only holds geometric and semantic information, but also temporal data (process schedules). This BIM represents the as-planned state of the construction site. On the other hand, monitoring using UAVs or similar camera-based systems is required for the generation of as-built point clouds by photogrammetric means for the representation of the as-built status.

During the design and planning phase, the building model and the process schedule is modelled and combined in a 4D model. During construction, the site is continuously monitored by capturing images of the as-built state. These are processed to create point clouds, which are compared to the as-planned building model (as-builtas-planned comparison).

30.4 Data acquisition and point cloud generation

The generation of the point cloud consists of four steps: data acquisition, orientation of the images, image matching and co-registration.

In the following, different strategies for image acquisition on construction sites are introduced.

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30.4.1 Handheld camera

A circuit of the construction site with a camera acquires sufficient images to map the building: For the creation of the dense point cloud, images are taken in an approximated stereo geometry, and there should be enough overlap to ensure every object point is visible in at least three images. Additionally, images have to be acquired looking forward and backward to support the image orientation process, e.g. Structure-from-Motion (SfM). Additional images may be required to support the co-registration process, either for the co-registration of point clouds from subsequent acquisition data or of the model and point cloud. Images acquired for documentation by other project members can also be used for the reconstruction process.

Golparvar-Fard et al. (2011b) state that images acquired for documentation tasks are sufficient for an as-built reconstruction. In turn, images made for the purpose of reconstruction may be sufficient for documentation tasks. Only a single camera is necessary for acquisition, and no further equipment is required, making this acquisition method very affordable.

The acquisition geometry has to be adopted to the current state of construction. During the construction of basement elements, images have to be taken around the excavation looking downward. As the building construction increases in height the images are acquired from an appropriate distance to the building's façade. When a certain height is reached the use of upright format images (with decreased baseline) or the acquisition of a second row of images might be necessary. The stronger the camera is inclined upwards, the worse the conditions for rectification and stereo-matching. If the façade is not completely flat, but has, for example, protruding elements, the occlusions due to lower building parts will increase. Additionally, temporary objects, like scaffolding, can increase occlusions. In such cases, the problem gets worse for upward looking views.

Another source of occlusion, which is mainly relevant for the ground floor, is building site facilities (e.g., construction trailer, site fence), stored material (e.g., prefabricated construction products) or vehicles for delivery purposes (e.g., transit truck mixer). Depending on the surrounding of the construction site it may be possible to acquire images from elevated positions, e.g., from adjacent buildings, to reduce the amount of unseen surfaces. Additionally, platforms in the mast of the crane can be used as acquisition position. In this case, the baseline for stereo images is limited to the width of the mast (typically 1 m) or the distance between two platforms (typical values are 2.5 m, 5 m or 10 m, depending on the combination of tower sections) at different heights.

In the worst case, where a construction site is completely occluded, this acquisition technique cannot be used.

30.4.2 UAV

In the context of this chapter, UAV acquisition refers to the acquisition using a UAV system with a total weight of less than 5 kg that also adheres to the regulations for UAV flights in many countries, which are among others:

- maximum flight height of 100 m
- Free line of sight to the UAV in all cases
- No flights over streets
- No flights over crowds

The construction is acquired in nadir view at two different flight heights, which have to be adopted to the current construction state (typically the height of the building). The upper flight (e.g., above the cranes) is mainly intended for stabilizing the orientation process. Additionally, oblique view images are acquired during a flight around the construction site.

For UAV acquisition, the aircraft itself, a camera, and a remote control as well as a trained pilot are all necessary. The costs for a professional UAV including appropriate configuration can be in the range of several €1000. Additionally, there may be costs for software for flight planning.

Generally, all areas, which are not inside the building, are visible for the UAV. But there are also restrictions. A certain safety distance has to be kept to the building itself, nearby buildings, and the cranes. Inner city construction sites are often surrounded by busy roads, which limits the usage of an UAV or even makes it impossible.

30.4.3 Crane camera

Acquisition of construction site images using crane-mounted cameras is based on the fact that cranes can usually reach all areas of a construction site, i.e., the footprint of the booms cover the whole area. Images of the whole construction site can be acquired this way. Areas where no construction activity takes place are also covered, e.g., areas used for unloading construction material. These areas can be use to mount control points. To ensure complete coverage and sufficient image overlap for 3D reconstruction, several cameras have to be mounted on the boom. Cameras mounted on the boom are always located in the same plane. Because of this, cameras should be calibrated before they are mounted on the crane, since the structure on the ground may also be, at least approximately, a flat plane.

The required components for crane cameras are described based on the cameras used in the experiments in this chapter. A camera is composed of a watertight box which contains a single board computer for the control of the camera and intermediate storage of the images, the camera itself, and a mobile communication unit for data transfer. The acquired images are saved on internal storage and subsequently

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transferred to a server via a mobile internet connection. For the power supply, a cable is run up the center of the crane. Additionally a network cable is required for data transfer and camera control. For top slewing cranes (with crane cabs) there is power supply at the top of the crane, i.e., there is also a power supply available for the cameras. For (small) bottom slewing cranes it may be necessary to provide a power supply for the cameras from the bottom.

As stated, the crane usually reaches the complete active area. To receive images of the whole construction site the crane has to make a full circle, stopping at set angle increment to make the acquisition. This requires that the steering of the crane and the camera control is synchronized. Another acquisition procedure (which is used in the experiments here) makes the camera expose at a certain frequency (e.g., 20 seconds) within a certain time (e.g., 2 hours) and the movements resulting from construction activity is used to provide sufficient coverage. In this case, complete coverage cannot be ensured, but at least it is very likely to cover the entire active area. In this case, an overhead of acquired images may result that needs to be discarded to avoid unnecessary processing time.

With both procedures, it can transpire that the hook trolley obstructs the camera's view and therefore occludes the scene.

30.4.4 Conclusion

By way of conclusion, all methods have valid fields of application. However, UAVs tend to be the most productive way to perform an overall acquisition of a complex construction site with various levels and grades of complexity with regard to its geometry.

30.5 As-planned vs. as-built comparison

The as-planned vs. as-built comparison can be divided into several stages. This includes the direct verification of building components based on the point cloud, and the indirect inference of the existence of components by analyzing the model and the precedence relationships to make statements about occluded objects.

For the verification process, which in the first step is based only on geometric conditions, a triangle mesh representation of the model is used. Every triangle is treated individually. It is split into two-dimensional raster cells of size x_r as shown in Fig. 30.3. For each raster cell, an independent decision is made to determine whether the as-built points confirm the existence of this part of the triangle surface using the measure M. For the calculation of this measure, the points within a distance δd before and behind the surface are extracted from the as-built point cloud. The measure M is based on the orthogonal distance d from a point to the surface of the

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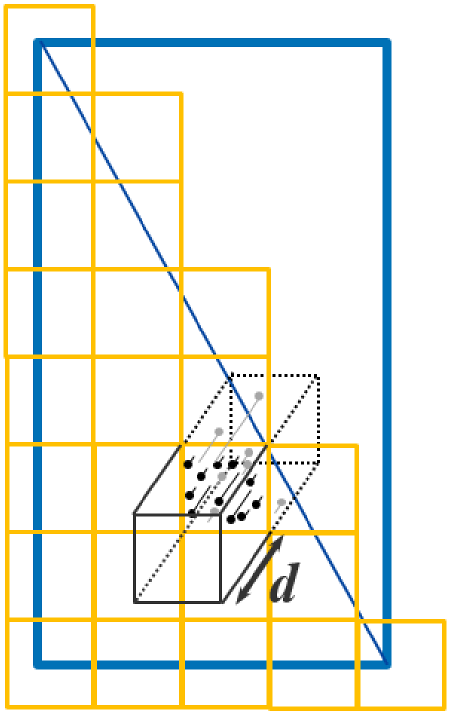

Fig. 30.3 Rasterization of a triangulated geometry for verification of relevant points

building part, taking into account the number of points extracted for each raster cell and the accuracy of the points σ_d and is calculated as follows:

$$M = \frac{1}{\sigma_d} * \sum_i \frac{1}{d_i * \sigma_{d_i}} \tag{30.1}$$

In order to visualize the results from the as-planned vs. as-built comparison, a 4D BIM viewer has been developed that incorporates all data from different observations and can also display point cloud data and corresponding images (see Fig. 30.4).

30.5.1 Enhancing detection rates

One of the main reasons for failed detections are occlusions. During construction, large amounts of temporary structures, such as scaffolding, construction tools, and construction machinery obstruct the view on the element surfaces. Limited acquisition positions further reduce the visibility of surfaces and impact on the overall quality of the generated point clouds. As introduced in Huhnt (2005), technological dependencies can help formalize the schedule sequence. A precedence relationship

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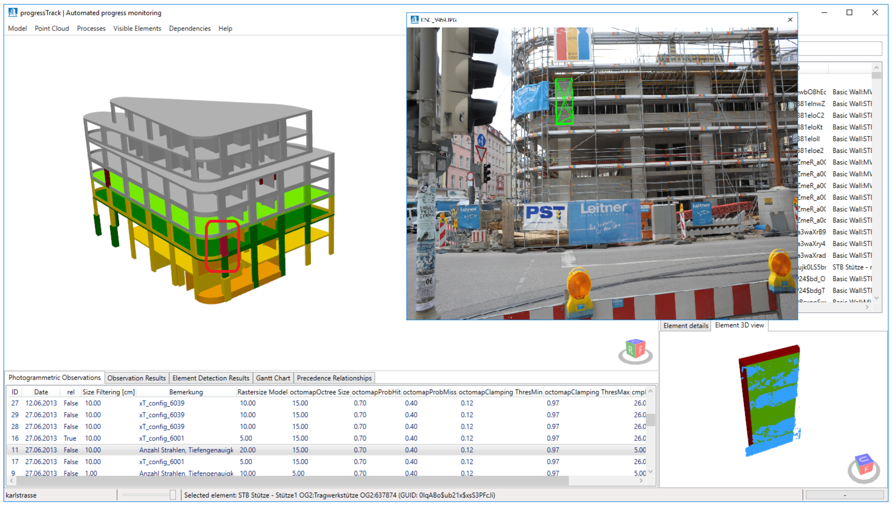

ID	Date	rel	Size Filtering [cm]	Bemerkung	Rastersize Model	octomapOctree Size	octomapProbHit	octomapProbMiss	octomapClamping ThresMin	octomapClamping ThresMax	cmpl
27	12.06.2013	False	10.00	xT_config_6039	10.00	15.00	0.70	0.40	0.12	0.97	26.0
29	27.06.2013	False	10.00	xT_config_6039	10.00	15.00	0.70	0.40	0.12	0.97	26.0
28	27.06.2013	False	10.00	xT_config_6039	10.00	15.00	0.70	0.40	0.12	0.97	26.0
16	27.06.2013	True	10.00	xT_config_6001	5.00	15.00	0.70	0.40	0.12	0.97	26.0
11	27.06.2013	False	10.00	Anzahl Strahlen, Tiefengenauigk	20.00	15.00	0.70	0.40	0.12	0.97	5.00
17	27.06.2013	False	10.00	xT_config_6001	5.00	15.00	0.70	0.40	0.12	0.97	26.0
9	27.06.2013	False	1.00	Anzahl Strahlen, Tiefengenauigk	10.00	5.00	0.70	0.40	0.12	0.97	5.00

karlstrasse

Selected element: STB Stütze - Stütze1 OG2:Tragwerkstütze OG2:637874 (GUID: 0lqABo$ub21x$xsS3PFcJi)

Fig. 30.4 As-planned vs. as-built comparison visualized using a corresponding point cloud (bottom right) and source image with re-projected geometry (top right)

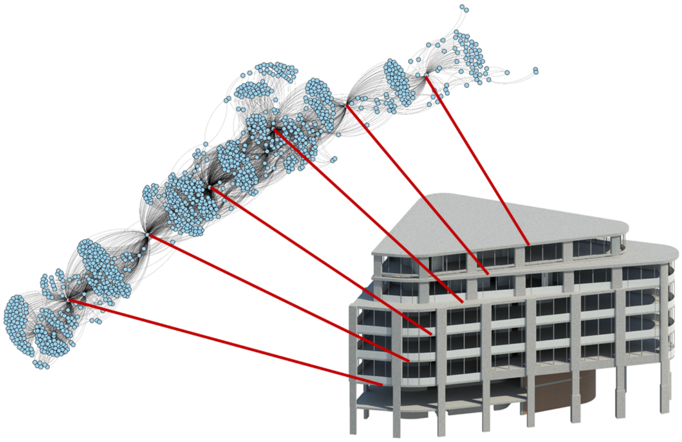

Fig. 30.5 Precedence Relationship Graph (PRG) that holds all technological dependencies for a specific construction site

graph (PRG) can hold this information and help to identify the described occluded elements (Braun et al., 2015a). The graph (see Fig. 30.5) visualizes the dependencies and shows that all following walls depend on the slab beneath them. These objects can be denoted as checkpoint components. They play a crucial role for helping to identify objects from the point clouds that cannot be confirmed sufficiently accurately using the as-built point cloud.

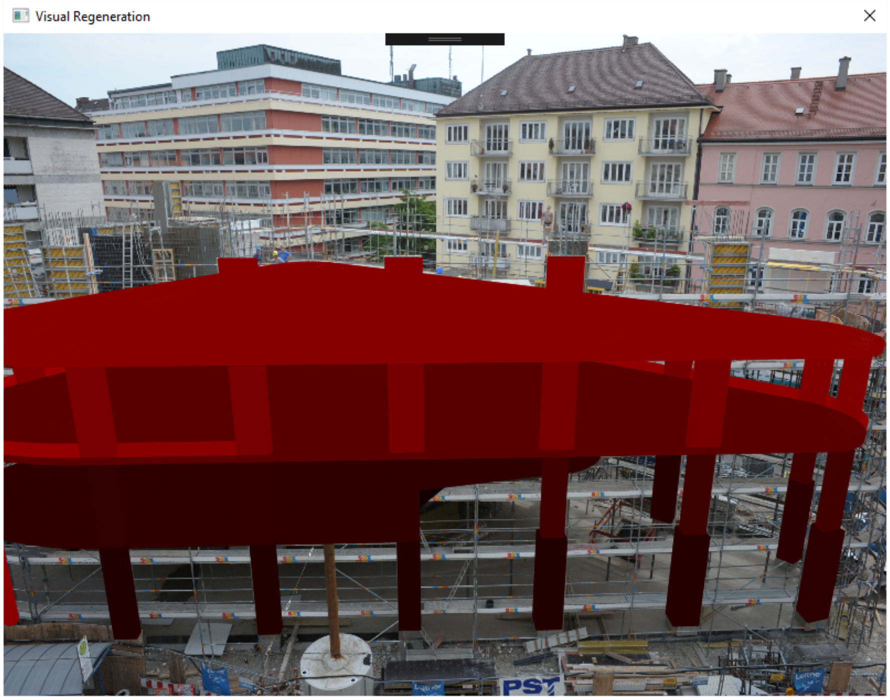

Fig. 30.6 Reconstructed 4D geometry based on estimated camera positions for the detection of visible elements

Another reason for weak detection rates lies in the difficulty of identifying building elements currently under construction. As such elements count towards the overall progress of construction, they cannot be ignored and play a crucial role in defining the exact state of the current process. The most challenging situations are construction methods or elements in which the temporary geometry differs greatly from the final element geometry. This applies, for example, to reinforcement bars or formwork. On the one hand, formwork may obstruct the view of the element, making it impossible to detect. On the other, the plane surface of formwork for a slab may be detected as the surface of the slab itself and thus lead to false positives. Due to these challenges, further enhancements to the comparison and detection algorithms are needed.

As depicted in Fig. 30.6, vision-based algorithms can help to identify elements that are visible from certain points of view. In order to enhance detection rates, visual renderings based on all camera positions were generated. Based on this additional information, the detection rates can be verified and final conclusions regarding the detection rates are more precise.

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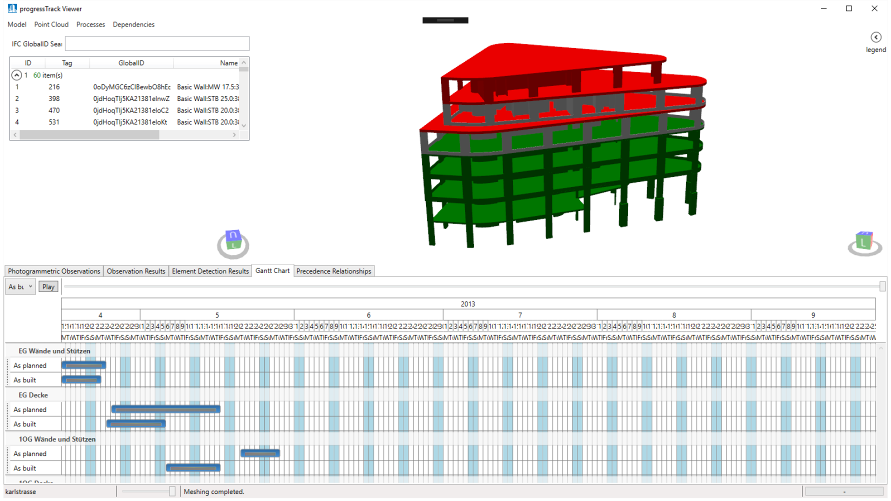

ID	Tag	GlobalID	Name
1 60 item(s)			
1	216	0oDyMGC6zClBewbO8hEc	Basic Wall:MW 17.5:3
2	398	0jdHoqTlj5KA21381elnwZ	Basic Wall:STB 25.0:3
3	470	0jdHoqTlj5KA21381eloC2	Basic Wall:STB 20.0:3
4	531	0jdHoqTlj5KA21381eloKt	Basic Wall:STB 20.0:3

Meshing completed.

Fig. 30.7 Results from the as-planned vs. as-built comparison of an observation incorporated with the corresponding process data. Green elements were built ahead of schedule, red elements behind schedule.

30.5.2 *Process comparison*

After successfully detecting built and not-built elements for each individual observation time, the gathered results can be combined with the corresponding process schedule of the construction site (4D BIM). The detected elements (as-built) of an observation are compared against the expected elements (as-planned) at the same timestamp t. Based on the schedule, predictions can be made on whether the construction progress is ahead or behind schedule (see Fig. 30.7). This information can then be used by schedule planners to adjust the schedule accordingly.

30.6 Case Studies

A set of comprehensive cases studies of real construction sites document in detail the detection rates achieved (Braun et al., 2014; Tuttas et al., 2016, 2014; Braun et al., 2015b). These were performed on five construction sites, in which the complete construction progress was monitored. The figures used in this chapter are drawn from these case studies.

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30.7 Summary

This chapter discusses general approaches to BIM-based progress monitoring. It presents a detailed overview of a concept for the photogrammetric creation of point clouds for construction progress monitoring, and for the procedure for as-planned vs. as-built comparison based on the 3D geometry. In addition, potential ways of improving these results by augmenting them with additional information from the BIM and accompanying process data have been discussed.

To determine the actual state, a dense point cloud is calculated using images from a calibrated camera. To determine the scale, control points are used, which requires manual intervention during orientation. The evaluation measure introduced for component verification detects built elements correctly but misses a larger number of them due to occlusion, noisy points or insufficient input data. There is, therefore, a need to extend this geometrical analysis with additional information and visibility constraints.

BIM-based progress monitoring is currently the subject of considerable research and development. Recent advancements show that progress monitoring based on UAVs and point clouds is becoming more reliable and demand for such methods is increasing in the construction industry. Automated progress monitoring facilitates the need to keep track of construction progress. However, not all elements can be detected with current methods. The concepts presented here assist in enhancing detection rates and support greater automation in the scope of BIM-based progress monitoring.

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