Incorporating knowledge on construction methods into automated progress monitoring techniques

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Abstract. The research conducted in this publication focuses on automated progress monitoring. The recording of the as-built state of a construction site is achieved by photogrammetric methods (e.g. UAVs) and compared to an as-planned (4D) BIM model. Comparison results of those two parts show that especially parts which were "under construction" are difficult to detect. The authors provide a method that uses the additional information on the construction methods provided by the respective construction elements including e.g. formwork or material colors. In conclusion, the overall detection rate of built elements and those that are currently under construction can be improved and therefore optimize the whole monitoring process.

1. Introduction

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 a complete and detailed monitoring technique rises for large construction sites where the complete construction area becomes too large to monitor by hand and the number of subcontractors rises. Main contractors that control their subcontractors' work, need to keep an overview of the current construction state. Regulatory issues add up on the requirement to keep track of the current status on the site.

The ongoing digitalization 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. On this basis, it is possible to make statements about costs and the estimated project finalization. Possible deviations from the schedule can be detected and following tasks are easy to identify.

This technological advancement allows new methods in construction monitoring. As described in (Braun et al. 2015a) the authors propose a system for automated progress monitoring using photogrammetric point clouds. The main idea is to use common camera equipment on construction sites to capture the current construction state ("as-built") by taking pictures of the building from a number of different perspectives. When enough images from different points of view are available, a 3D point cloud can be produced with the help of photogrammetric methods. This point cloud represents one particular timestamp of the construction progress and is then compared to the geometry of the BIM ("as-planned"). Details on the comparison algorithms can be found in (Tuttas et al. 2014; Tuttas et al. 2015).

In order to visualize the comparison results and the detected elements, and to verify the used algorithms, all gathered data is stored in a database that is accessible to the *progressTrack Viewer*. This tool displays all building element information as well as process data. The detected elements are highlighted for an easy identification. Figure 1 shows one of the construction sites

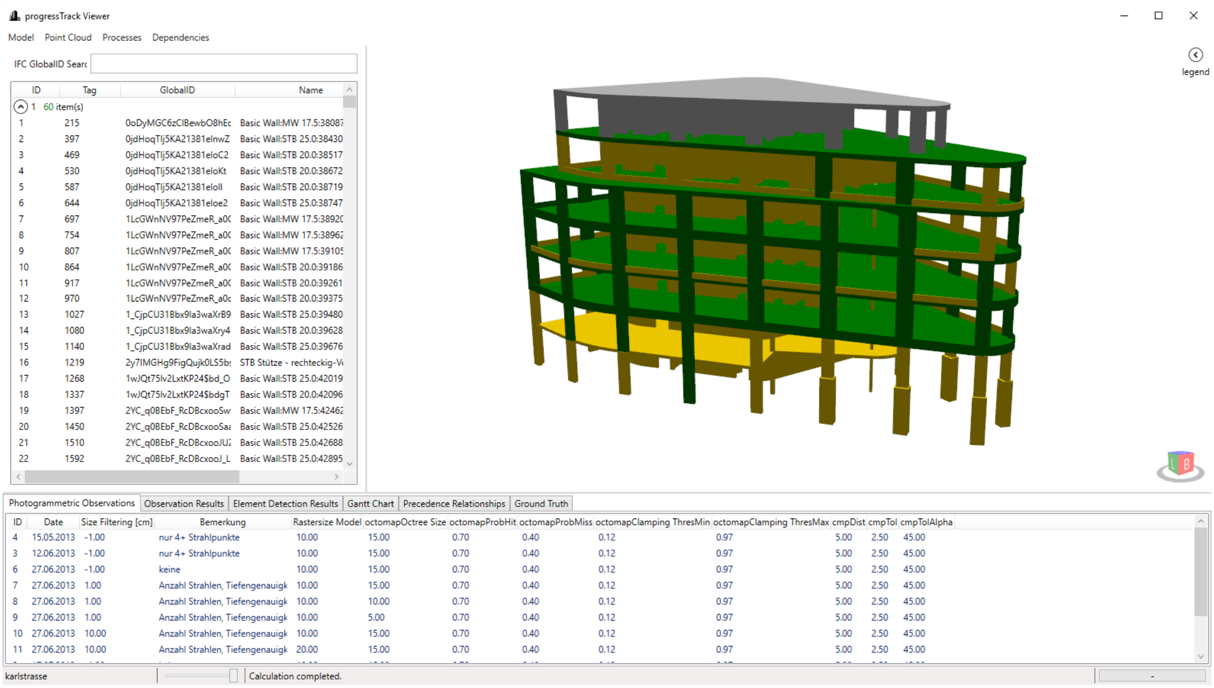

Figure 1: progressTrack Viewer: detected elements for construction site "A". Yellow elements are built, but not detected, green elements are built and detected

that were used for the case studies during this research. The building mainly consists of in-situ concrete elements that were cast using formwork on site. In the figure depicted here, one individual capturing event is selected and all detected elements are highlighted. Green coloring represents elements that have been built and are correctly detected and confirmed through the point cloud. All yellow elements are actually built but were not confirmed through the point cloud.

There are several reasons, why some of those elements were not detected:

Among of the main reasons are occlusions. During construction, large amounts of temporary structures like scaffoldings, construction tools, and construction machinery obstruct the view on the element surfaces. Limited acquisition positions further reduce the visible surfaces and hence the overall quality of the generated point clouds. As introduced in (Huhnt 2005), technological dependencies can help to formalize the schedule sequence. A precedence relationship graph (PRG) can hold this information and help to identify the described occluded elements (Braun et al. 2015b).

Another reason for weak detection rates is building elements which are currently under construction. As those elements count towards the overall progress, they must not be missed and play a crucial role in defining the exact position in the current process. Challenging parts are in general all construction methods, whose temporary geometry differs largely from the final element geometry. This accounts e.g. for reinforcements or formwork. On the one hand, formwork may obstruct the view of the element, making it impossible to be detected. On the other hand, the plane surface of a formwork for a slab might 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. Since information on construction methods are already provided by the BIM, the knowledge can be incorporated into the overall detection process and thus refine the detection results.

2. Related work

Process monitoring has become a heavily researched topic recently. Capturing the as-built construction status is mainly achieved by laser scanners or cameras using photogrammetric methods. For the comparison with the as-planned state (BIM 3D geometry), three methods are currently established:

i) Comparison of the as-built point clouds with points from the transformed as-planned geometry.
These methods compare point clouds that are acquired by laser scanners (Bosché 2010; Turkan 2012) or photogrammetric methods and derived point clouds from as-planned surfaces (Kim et al. 2013). This is mainly done by Iterative Closest Point (ICP) algorithms.

ii) Feature detection in the acquired images from the as-built state. Using feature detection algorithms like SIFT and RANSAC, construction elements are directly identified from the acquired images (Golparvar-fard et al. 2012).

iii) Matching the as-built point cloud onto the as-planned geometry surfaces. this approach matches relevant points from the point cloud directly onto triangulated surfaces of the as-planned model (Tuttas et al. 2015).

Monitoring with laser scanners or cameras proved to be helpful according to these studies. It is possible to identify individual elements for each use case. In fact, most publications focus on identifying one particular element. All of these approaches lack the possibility to clearly identify building elements under construction. A first attempt to solve the problem of elements under construction is published by (Han et al. 2015). However, Han focusses on visibility issues. E.g. when an anchor bolt for a column is invisible as it is embedded into the concrete, it still must be present since the column on top of it requires the anchor bolt for structural reasons.

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 (Tauscher 2011). He chooses an object-oriented approach to categorizing 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 (Huhnt 2005) a mathematical formalism is introduced that is based on the quantity theory of the determination of technological dependencies as a basis for automated construction progress scheduling. In (Enge 2010) 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 is dependencies. Technological dependencies represent which element is depending on another element, meaning, that it cannot be built after the first element is finished. These dependencies can be defined by precedence relationships (Wu et al. 2010). A solution to store these dependencies in graphs is discussed in (Szczesny et al. 2012). The approach in relation to progress monitoring is presented in (Braun et al. 2015a).

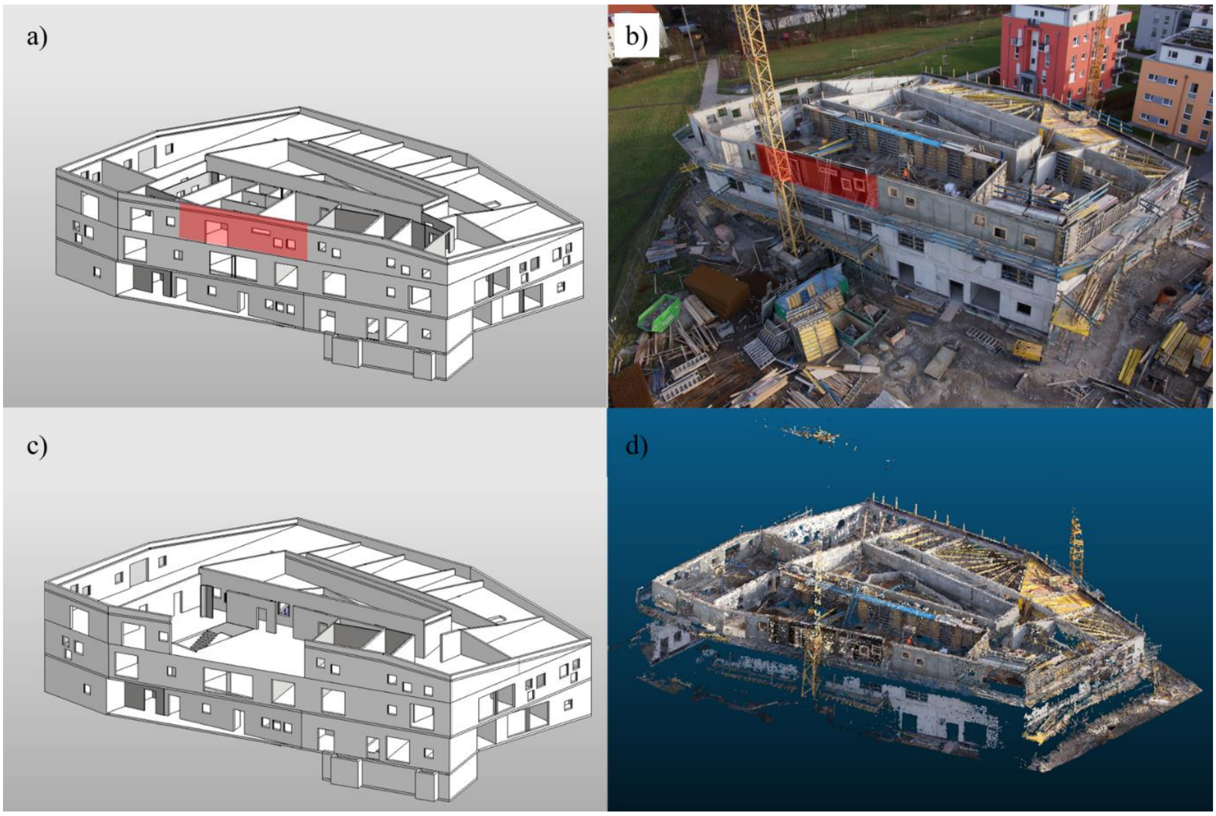

Figure 2: Process modeling problem depicted by a) as-planned modeling, b) as-built photograph, c) as-build modeling, d) as-built point cloud on construction site "C".

3. Challenges

The main goal of this research is to identify suitable construction methods for building elements that can be detected during the comparison process. The focus lies on German construction sites and methods with solid constructions based on in-situ concrete using formwork. However, this does not limit this concept to one particular country as the general construction procedure is similar in almost all sites using concrete elements.

The detection of built elements reveals different challenges:

3.1 Occlusions

As stated, the as-built progress is represented by a 3D point cloud that holds n points with their respective coordinates and corresponding detected color information. The amount n depends on many factors such as lighting conditions, feature detection from different points of view and largely from the amount and resolution of the pictures taken. A point cloud from one timestamp on our construction test site "C" can be seen in Figure *2* d). Scaffoldings and formwork are clearly visible, also various holes in the point cloud that exist due to occlusions or insufficient image quality for a reconstruction. In general, this point cloud is not perfect, but in the expected quality from a construction site that has changing visibility conditions due to working equipment and so on.

3.2 As-planned modeling vs. as-built construction

The as-planned model is represented by a 4D building information model (Figure *2* a)). Each construction element is linked to its belonging process which makes it possible to make statements about the desired construction state at a given timestamp from an as-built point cloud. The corresponding geometry holds 3D information just as the point cloud and since model and point cloud are aligned to the same coordinates, an initial detection algorithm could start the comparison.

However, the as-planned model does not necessarily equal the actual as-built process. To clarify this variance, Figure *2* depicts the BIM from test site "C", a corresponding aerial image taken by a UAV and the generated point cloud (a), b) and d)). The red marked part of the wall on the second is floor currently under construction (as seen in b) and d)), meaning there is formwork installed but no concrete filled yet. On the other hand, the BIM (as seen in a)) has one continuous wall modeled for the same wall, that is constructed on the site in several steps. Therefore, the modeling does not represent the correct construction sequencing. This problem is also described in (Huhnt & Enge 2007; Tulke 2010).

In comparison, Figure *2* c) shows the correct corresponding as-planned model for the current timestamp, with all, subsequently following elements hidden in the view. This "as-built" model is currently modeled iteratively to match the actual construction processes.

4. Identified tasks during construction

During construction, several tasks are required to construct in situ concrete elements or similar elements. The following listing shows the identified tasks on the construction sites, monitored during this research.

4.1 Varying dimensions during construction

With the PRG introduced in Section 5.1, it is possible to identify elements that might possibly be under construction and thus are considered for further investigation.

In situ concrete

In concrete construction, formwork for in situ concrete is the most common construction method. Several different methods are depicted in Figure *2* b) and d). To detect formwork, all possible elements under construction (see Section 4.1) are taken into account.

In general, elements are counted as detected, when a certain amount of points with a distance of less than 2 cm is matched on the surface of the element (Tuttas et al. 2015). If the expected elements are not detected, the threshold for the maximum distance can be adjusted to take into account that the formwork with a thickness of around 0.20m might be currently in place. If this iteration brings positive results, the element can be marked as "under construction".

Composite elements

Modern construction technologies usually use thermal insulation systems for reduced cooling and heating requirements during usage of the finished building. These composite elements consist of several layers, e.g. concrete and rock wool thermal insulation. Depending on the exact element type, these compounds are delivered as precast elements or are manufactured in situ. The latter one is a common and often used method.

In construction modeling, these elements are modeled as one single element consisting of several layers. Due to the thickness of the insulation of around 0.20m, such a wall is not detected, when only the concrete layer is present in the BIM model. Usually, all concrete parts of a building are completed before the thermal insulation is attached, resulting in a very low detection rate. In order to solve this issue, also, single layers of the elements are considered for detection.

4.2 Color detection

In general, formwork for walls and columns consists of a wooden, smooth plate on the concrete side and a steel structure for stability on the backside. This steel structure is often painted yellow, red or orange and differs largely from the gray concrete. Formwork for slabs usually consists of elevated wooden plates that have the same color range as the steel structure mentioned. This color difference can be measured and help to further improve the detection quality of formwork.

The HSV color space provided useful data for the color detection (Sural & Pramanik 2002). HSV stands for hue, saturation and value. With the HSV color space, it is possible to detect color as perceived by humans but also saturation and brightness (value). Each value has a range from 0 to 1.

4.3 Formwork for horizontal elements

Besides the color information mentioned in Section 4.3, slabs and other horizontal elements have another characteristic to identify them under construction. Automated monitoring methods for large construction sites usually observe the site from outside or above. Hence, objects are usually only visible from the side or above. Thus, a slab who's downwards facing surface is detected during the matching seems unusual. This case usually takes effect when the formwork for the element is installed, but the concrete is still missing.

4.4 Reinforcement

The detection of reinforcement depends on the quality of the point cloud itself. In our case, the results vary and make it difficult to identify these thin structures.

5. Concept

The following concept presents possible solutions to tackle the mentioned challenges by incorporation additional information on construction techniques into the comparison algorithms.

5.1 Process sequencing

Automated progress monitoring with photogrammetric methods or laser scanning always captures one particular moment at the current observation time. It is not possible to automatically determine the exact point in a process plan at which the construction progress is currently located.

For an automated handling of dependencies, a precedence relationship graph (PRG) is introduced (Braun et al. 2015a). This graph formalizes technological dependencies between individual elements. One possible graph for the depicted Gantt chart is shown in Figure 3. The correct graph is depending on the real model and not clearly recognizable from the Gantt diagram.

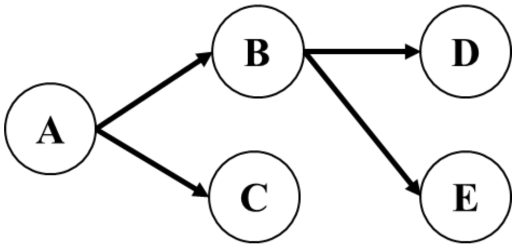

Figure 3: possible precedence relationship graph for the sample in Figure 3

Figure 4 depicts an as-planned Gantt chart visualizing five tasks *A* to *E* where *B and C* as well as *D and E* can run in parallel but are depending on their respective preceding tasks. In this simplified schema, one task represents one building element.

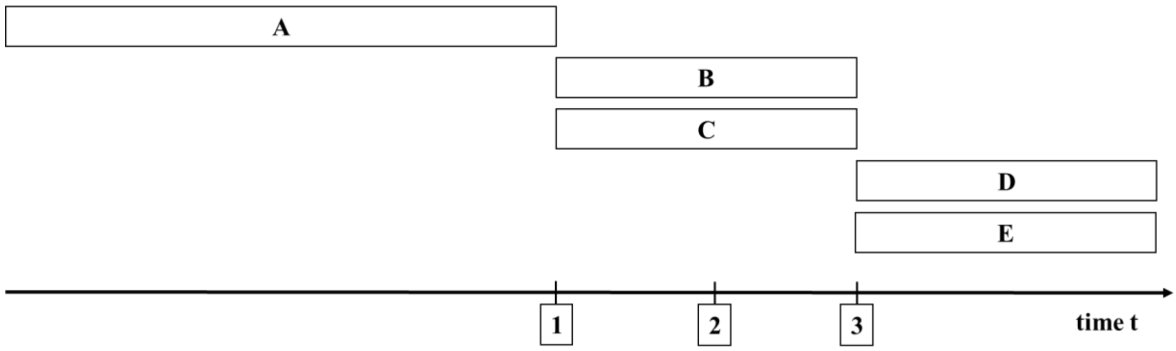

Figure 4: Gantt chart depicting uncertainties for process dependencies and belonging observation time steps

The numbers *1* to *3* symbolize three as-built data acquisitions. For the case that all processes are on time, it is difficult to determine a difference between observation *1* and *2* since the exact construction method is unknown and in most scenarios, construction workers run parallel tasks slightly asynchronous, meaning there might be some work done on task *B* whereas none on task *C*. This gets even more difficult when delays occur, resulting in rearranged process plans.

The PRG will be used to identify objects that are possibly under construction right now. A possible delay of task *A* could result in a detection of parts of the constructed element belonging to task *A* and *B* on observation *2* but no detection of the element belonging to task *C*. As a conclusion, this graph makes it possible to make further assumptions on following tasks when one particular element is detected and forms the basis for the following steps of this concept.

5.2 Workflow

With the PRG introduced in Section 5.1, it is possible to identify elements that might possibly be under construction and thus are considered for further investigation.

The basic flowchart depicted in Figure 5 shows the proposed workflow for the enhanced detection. In general, elements, that are expected to be built, but are not verified by the current detection, run through an extended detection algorithm.

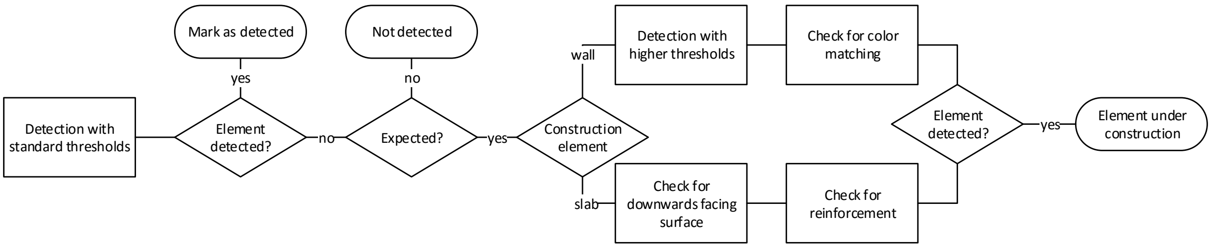

Figure 5: basic flowchart, depicting the workflow for the detection of elements under construction

Depending on the material and type of element, different steps follow. As elaborated, walls and other vertically erected elements are considered for an extended threshold in order to identify possible formwork. Additionally, a color matching for bright red or orange colors is carried out.

In comparison, horizontally aligned elements are considered for a detailed check regarding the detected surfaces. For the case that downwards faced surfaces are detected, but upwards facing surfaces not, the element might be under construction and the formwork has been detected instead of the element itself.

This leads to a more detailed detection result as even elements that are close to be finished are considered.

6. Case Study

To validate the introduced concept, three different construction sites were monitored with different observation methods (Braun et al. 2015b; Tuttas et al. 2016).

6.1 Varying dimensions

Figure 6 depicts a part of a snippet of a point cloud, generated from one time step during observation. It is overlaid with the corresponding 3D geometry, visualized in green color, to symbolize the as-planned as well as the as-built status. Based on this example, the general workflow for elements under construction is shown. As depicted, the front wall is already finished and the concrete surface is visible. The wall in the second row is currently under construction and the formwork is present and registered in the point cloud.

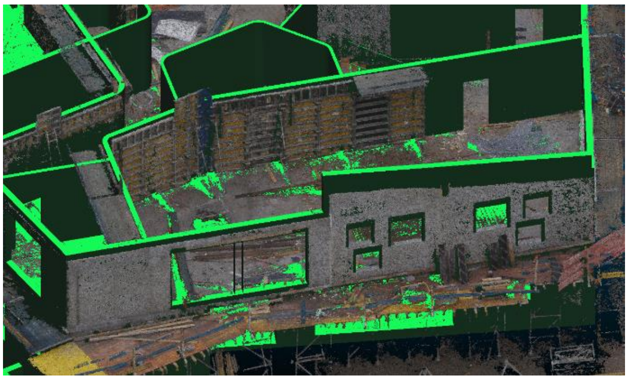

Figure 6: Point cloud of a finished, plain wall and formwork overlaid with the corresponding 3D geometry

During detection, it is expected, that the first row of walls will be detected. Due to the threshold of max. 1 cm, the second row should not be detected due to the formwork. Figure 7 a) shows the expected result, with an additionally set threshold of 1000 points per square meter (green color). Triangles marked in yellow have matching points but do not qualify for the set thresholds while elements marked red have no qualifying points at all.

The walls in the second row are expected to be in progress. As presented in the concept in Section 5.2 the detection is therefore carried out with a larger threshold. In this case, the accepted point to surface distance is increased to 10 cm which leads to the depicted results in Figure *7* b).

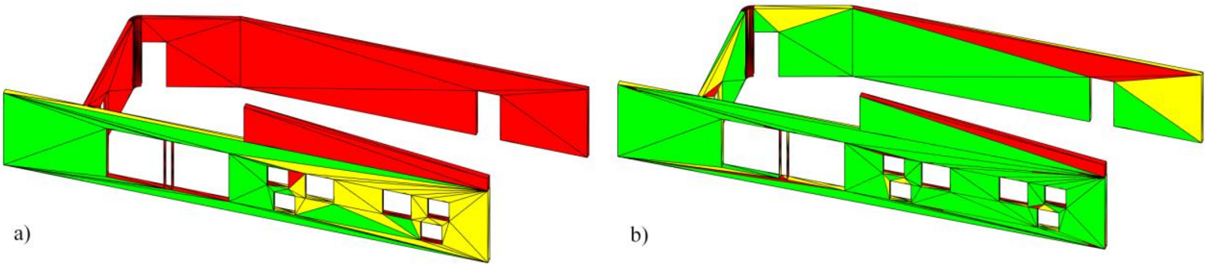

Figure 7: detected triangles during the time step shown in Figure 6. a) with distance 1cm and ϱ > 1000 pts/m², b) with distance 10cm and ϱ > 1000pts/m²

The increased threshold leads to the expected higher point density on the wall under construction, as the formwork is considered, too. According to the introduced workflow, the wall is now marked as "under construction", leading to a further detailed automated progress monitoring.

6.2 Color detection for formwork and reinforcement

As elaborated in Section 4.2, taking colors into account can improve the detection of formwork or reinforcements due to their significantly varying colors in comparison to the grey colors of the concrete. In order to proof this statement, color values of different elements were compared.

Table *1* shows the calculated mean values for different elements under different lighting conditions.

Table 1: Case study: HSV values for concrete surfaces and formwork

Type	Hue	Saturation	Value
Concrete wall	0.5973	0.0947	0.5690
Concrete wall 2	0.9109	0.0568	0.7040
Formwork 1	0.3880	0.2188	0.3979
Formwork 2	0.1141	0.2850	0.6638
Formwork 3	0.1294	0.7171	0.7078

All points relevant to an element and their color information are taken into account to calculate the mean HSV values. The results show, that the brightness (value) varies largely which is due to the lighting conditions itself. Therefore, this value has no significance. However, the hue values for formwork fall into the correct range for warm, red colors, whereas the concrete walls are based on "colder" colors. Additionally, the saturation differs for at least factor 2.3. This leads to the conclusion, that automated color interpretation is possible and applicable in this context.

6.3 Horizontal elements

Downward facing surfaces are identified by the normal values of their belonging triangulated elements. A normal with negative z-coordinates in a coordinate system with an upwards pointing z-axis has a downwards facing surface.

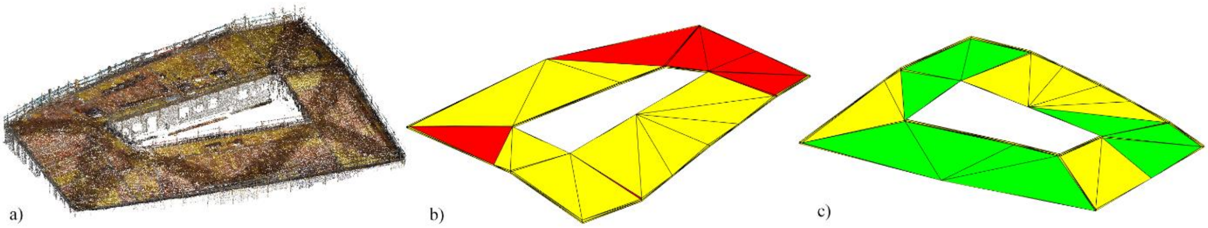

Figure 8: a) point cloud of roof under construction b) detected triangles (top view) c) detected triangles (bottom view)

Figure *8* a) shows the part of a point cloud during construction monitoring. In this case, the roof of one of our test sites is shown. It is currently under construction with the formwork in place. Additionally, parts of the reinforcement are already in place. Figure *8* b) shows the triangulated top surface of the corresponding roof. As visible, only few triangles have matching points that are not sufficient for marking the overall element as "detected". Figure *8* c) shows the downwards facing surface of the roof, that has a significantly higher point density. In this case the available points, representing reinforcement and formwork, matched the corresponding triangles of the roof.

Embedded in the proposed concept, the roof would not be detected as "built" due to the too low point density over the complete surface. However, the downwards facing elements have a sufficient density when considered individually. Thus, the element can be marked as "under construction".

7. Summary

Automated progress monitoring facilitates the need to keep track of construction progress. However, not all elements can be detected with current methods. The presented concept proved helpful to identify elements under construction. Color detection and/or a higher threshold for elements with possible formwork in place can identify additional elements that were not considered as built before. Of course, these methods should not be applied independently from the overall matching process. The methods were tested on three different construction sites.

However, the list of possible construction methods is not complete. Further knowledge on construction methods will help to evolve the system. Especially varying or different construction methods need to be observed and implemented into this concept to help refine the process and detect the construction process for even more elements.

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