Process- and computer vision-based detection of as-built components on construction sites

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Abstract -

Automated progress monitoring becomes more and more common in the construction industry. Recent approaches often use new methods like Unmanned aerial vehicles (UAVs) for a capturing large construction sites. However, the used methods often lack accuracy due to occluded elements and/or reconstruction inaccuracies from using photogrammetric methods. This paper presents a novel approach for further improvement of element detection rates. 4D BIM semantic information is used, to generate precise "as-planned" geometric models. These models are used to render a building from all points of view during the monitoring phase. Based on this information, a more accurate and reliable estimation of all detected elements can be achieved.

Keywords -

Progress monitoring; photogrammetry; BIM; UAV;

1 Introduction

Large construction projects require a variety of different manufacturing companies of several trades on site (e.g. masonry, concrete and metal works, HVAC). An important goal for the main contractor is to keep track of accomplished tasks by subcontractors in order to maintain the general time schedule. In construction, process supervision and monitoring is still a mostly analogue and manual task. To prove that the work has been completed 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 amount 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 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. Therefor it is possible to make statements about cost and the estimated project finalization. Possible deviations from the schedule can be detected and following tasks rearranged accordingly.

This technological advancement allows new methods in construction monitoring. As described in [3] 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 by taking pictures of all building elements. When enough images from different points of view are available, a 3D point cloud can be reconstructed with the help of photogrammetric methods. This point cloud represents one particular time-stamp of the construction progress (as-built) and is then compared to the geometry of the BIM (as-planned).

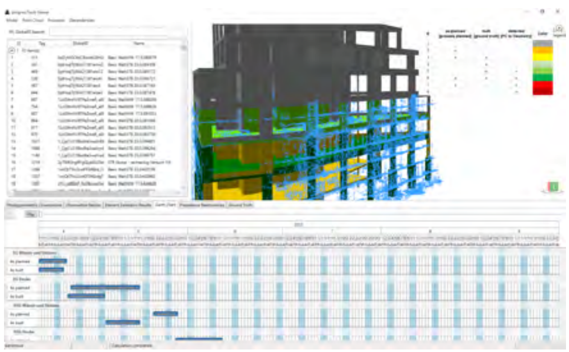

Figure 1. progressTrack: 4D BIM viewer incorporating detection states, process information and point clouds from observations

Figure 1 shows the C#-based WPF software tool, developed in the scope of this research. The tool visualizes a building information model and all corresponding semantic data. Additionally, the observation results can be selected and are supported by the possible overlay of the corresponding point clouds.

2 Related work

Several methods for BIM-based progress monitoring have been developed in recent years [15]. Basic methods make use of rather minor technical advancements like email and tablet computers into the monitoring process. These methods still require manual work, but already contribute to the shift towards a digital process. More advanced methods try to track individual building components by means of radio-frequency identification (RFID) tags or similar methods (e.g. QR codes).

Current state-of-the-art procedures apply 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 [2] and [1], 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-Closest-Point-Algorithm (ICP). Within this system, the as-planned model is converted into 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. [20] and [19] 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. [13] 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. [21] introduce a measure 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. [16] give an overview and comparison of image-based approaches for monitoring construction progress. [11] use a single camera approach and compare images taken during a certain period of time 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. [12] 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.

For finding the correct scale of the point cloud, stereo-camera systems can be used, as done in [18, 5, 6]. [17] propose using a coloured cube of known size as a target, which can be automatically measured to determine the scale. In [7] 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. [9] and [8] 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 geometry, 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.

3 Problem statement

Monitoring of construction sites with photogrammetric methods has become a working solution in many research areas. Currently a number of companies (e.g. Pix4D, DroneDeploy) already provide commercial all-in-one solutions for end users that allows to generate 3D meshes and point clouds from UAV-based site observations. All these methods give good solutions for finished construction sites or clearly visible elements of interest.

However, the authors noticed that monitoring of construction sites poses several problems. Photogrammetric methods are sensitive to low structured surfaces or windows. Because of the used method, each element needs to be visible from multiple (at least two) different points of view. Thus, elements inside of a building cannot be reconstructed as they aren't visible from an UAV flying outside of the building. Monitoring inside of a building is currently still under heavy research [14] and not available in an automated manner as orientation and observation in such mutable areas like construction sites is hard to tackle. These problems lead to holes or misaligned points in the final point cloud, that hinder correct and precise detection of building elements.

Figure 2. Occluded construction elements in generated point cloud caused by scaffolding, formworks, existing elements and missing information during the reconstruction process

As can be seen in Figure 2, another problem are elements that are occluded by temporary construction elements. Especially scaffoldings and formwork occlude the view on walls or slabs, making it harder for algorithms to clearly detect the current state of construction progress.

Since many construction elements that are correctly built and in place are occluded by other elements and hence out of view for a monitoring system outside of the building, the overall detection rates severely drop, despite the fact that most visible elements were detected correctly. Current methods do not take these problems into account and make only limited use of BIM related information such as type of construction or the general structure of a building.

As proposed in [4], the element detection based on point clouds is possible by calculating the distances between the generated point cloud and the surfaces of all building elements, derived from the BIM. After applying various optimization algorithms such as color filtering and octree based region filtering, still not all elements can be detected due to the before mentioned occlusions. Thus, the authors propose a method that includes process-based rendering of all visible elements at time of observation. In order to achieve this, all elements are rendered from all points of observation for each individual observation. After applying computer vision methods, it is possible to determine, which elements are visible at an observation. This helps to evaluate the as-built vs. as-planned comparison in regard to its efficiency and in the end results in more realistic detection rates, that take only visible elements into account.

4 Detecting visible elements

For the detection of all visible elements, the building information model needs to be rendered from all points of observation for every single observation.

4.1 Camera positions

As proposed, the point cloud is produced using photogrammetric methods. In this process, pictures are taken for example by UAVs (Unmanned aerial vehicles) from different points of view. These pictures can then be used to generate a 3D point cloud if all elements are visible from a sufficient amount of viewpoints. During the reconstruction process, the camera positions around the construction site are estimated. This is illustrated in Fig. 3. This estimation is refined during the dense reconstruction and can get more accurate by using geodetic reference points on site.

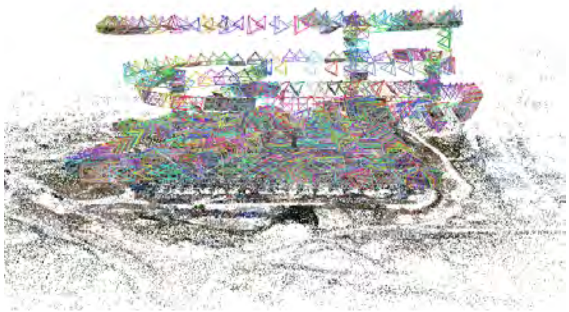

Figure 3. Estimated camera positions during point cloud generation using VisualSFM

These camera positions are required for the proposed method, as the detection accuracy will be refined by detecting all elements that are visible from these positions.

4.2 4D process data

Building information modelling can be used to combine geometry of construction elements with semantic data such as material information but also process schedules. In the scope of this research, the corresponding process schedule is connected to all elements. This allows to identify all elements that are expected to be built at each observation time stamp.

As visible in Fig. 4, the software tool used in this research is capable of integrating the building model, as well as process data and construction elements such as scaffoldings and formwork.

This data is required to define the sets of elements that are used for the visibility analysis described in this paper. Since the process schedule may change during construction, it is crucial to update the schedule permanently based on the gathered observation data.

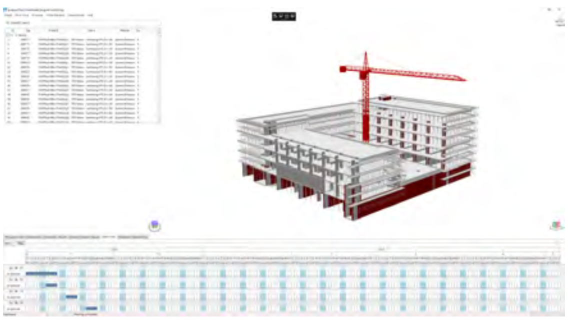

Figure 4. 4D building information model including all additional construction materials like scaffoldings and formwork

4.3 Re-projection

Based on the gathered information, it is possible to do a visibility detection using the camera positions as point of view and the process information to define the set of construction elements that are meant to be built.

To achieve this, the building model coordinate system needs to be transformed into the camera coordinate system or vice versa. Several parameters are needed for this transformation.

On the one hand, the intrinsic camera matrix for the distorted images that projects 3D points in the camera coordinate frame to 2D pixel coordinates using the focal lengths (F_x, F_y) and the principal point (x_0, y_0) is required. It can be described by the matrix K as defined in equation 1.

$$K = \begin{bmatrix} F_x & s_k & x_0 \\ 0 & F_y & y_0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

Additionally, the rotation matrix for each image as defined in equation 2 is needed.

$$R = \begin{bmatrix} r_1 1 & r_1 2 & r_1 3 \\ r_2 1 & r_2 2 & r_2 3 \\ r_3 1 & r_3 2 & r_3 3 \end{bmatrix} \tag{2}$$

Using the model coordinates of all triangulated construction elements, it is possible to calculate the re-projection of each element into the camera coordinate system and therefore overlay the model projection and the corresponding picture taken from the point of observation with equation 3.

$$t = K * R * point; \tag{3}$$

The resulting 2D coordinates that are rendered into the picture are calculated by using the vector t and getting the x and y coordinates by calculating $x = t[0]/t[2]$ and $y = t[1]/t[2]$. This is done for each point belonging to the triangulated geometry representation of all construction elements.

As visible in Fig. 5 for an explanatory column, the re-projection works as expected and helps to identify the respective construction element in the recorded picture. The mentioned calculations need to include an optional transformation and rotation if the model is geo-referenced and thus the two coordinate systems differ largely.

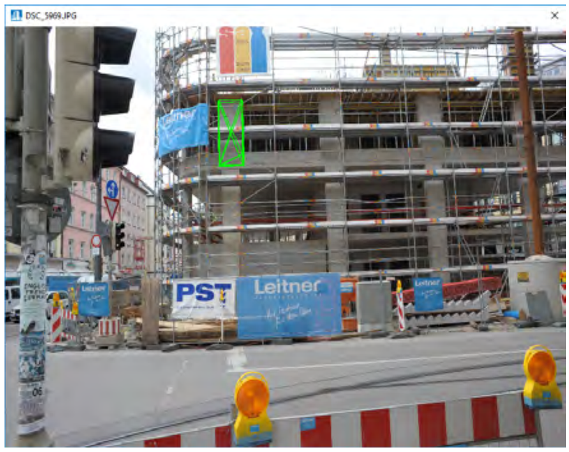

Figure 5. Reprojected triangulated column into a corresponding picture

4.4 Render model based on camera position

The algorithm introduced in section 4.3 enables the element-wise rendering of all construction elements in the respective coordinate system. In order to get a rendered image of all visible construction elements, the following steps are carried out:

1. Iterate over all pictures in observation
2. Iterate over all construction elements
3. Iterate over all points, representing the construction element
4. Get new, reprojected coordinates for all points, including distances to camera. Assign an identifier (e.g. unique RGB color) to each element
5. Iterate over all pixels/coordinates of picture and order points according to their distance to the camera

Whilst all geometric information is available, three problems need to be solved for an accurate rendering of all construction elements:

1. For triangulated elements, only the boundaries are known, however, the complete surface needs to be rendered correctly.
2. The rendered surface needs to be connected to the corresponding element since this information is crucial for a proper visibility analysis

3. Elements may blend over from the viewpoint in some circumstances. This needs to be addressed to get a correct rendering.

The first issue is solved by using basic inside/outside tests for points inside a bounding box around each individual triangle. This is combined with min/max tests to verify that all points are inside the given coordinate system of the current picture. The second issue is addressed by assigning an individual color in the RGB color range to every construction element. This allows to identify each element after the rendering is finished.

The third issue is solved by applying the Painter's algorithm [10] to each pixel in the given picture. In the given challenge, the distance to the point of view is stored for the current construction element and the color information is replaced in case an element has a smaller distance to the point of view and is also visible in the same pixel of the picture.

The applied algorithms result in a rendering as seen in Fig. 6.

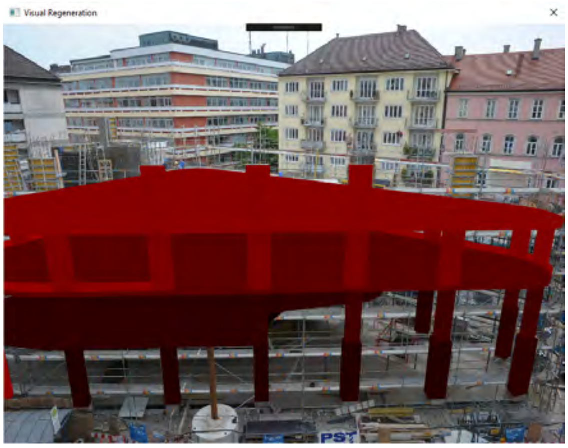

Figure 6. Using re-projection methodology for model rendering based on the Painter's Algorithm and 4D semantic information

After applying this technique to all observations and all camera positions, a distinct list of all visible construction elements can be generated by iterating over all pixels of each rendered image. The color of each pixel is assigned to an construction element and since the painters' algorithm is applied, only the element is visible, that has the lowest distance to the point of observation. Therefore, all visible, non-occluded elements can be determined with this method. This method allows for an automated construction element detection with more realistic detection rates.

5 Case study

The developed methodology has been applied to several construction sites.

As depicted in Fig. 2, most observations lack details at some point and have largely occluded areas due to the observation methods. In very disadvantageous observations the detection rate can drop down to 50% of the overall built construction elements. With the help of the presented methods, these rates can be explained since most of the undetected elements were not visible from the observation points. To quantify the efficiency of an algorithm for as-planned vs. as-built detection, it is very important to have a valid ground truth to allow a reasonable evaluation of the used methods. This approach helps to correctly quantify the used methods.

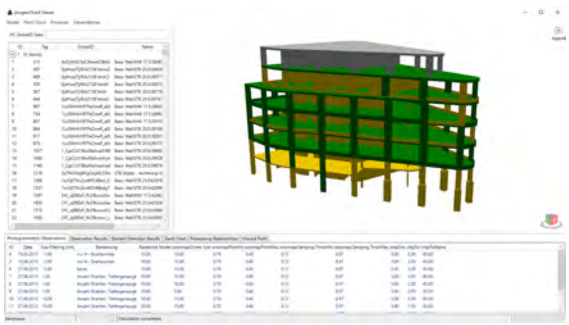

Figure 7. Detected construction elements from one observation. Green elements were successfully detected, yellow elements were not detected but are built.

This is clearly visible in Fig. 7. The green elements were detected correctly. The yellow elements, however, are actually built but were not detected. This is due to the fact that the inner walls were not visible from a sufficient number of viewpoints. Thus there was not enough points in the corresponding point cloud that allowed to validate the existence of the elements. However, these elements were identified as not visible by means of the method introduced in this paper. This helped to get a more realistic impression of the efficiency of the used detection methods.

6 Summary and Outlook

To obtain more realistic detection rates for photogrammetric monitoring methods, the paper addressed the question of visibility of individual building components. To this end the paper introduced a vision-based method which is based on rendering the building information model from all points of view of the photogrammetric capturing campaign. Since the finished building information model with installed facade elements would provide wrong information regarding element visibility during construction, only elements are rendered, that are supposed to be present at time of observation. This is achieved by using semantic and process information from the 4D building information model. The procedure's output is a list of all visible elements of a given point in time. This set of elements helps to further refine detection results based on photogrammetric methods.

Since the introduced methods do not help to identify all temporary construction elements, further research in this field is necessary. The authors are proposing to use the re-projected element positions and the relating pictures and apply machine learning methods to these parts of the picture. This could help to identify further elements such as scaffoldings or formwork, that might not be modeled in current design processes.

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