IMAGE AND BIM FUSION DATABASE FOR VISUAL CONSTRUCTION PROGRESS MONITORING

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ABSTRACT

The Architecture, Engineering and Construction (AEC) industry's use of Building Information Modeling (BIM) has significantly increased over the past decade. Theoretically, this enables a fully digitalized construction approach where the executed constructional activities are crosschecked with the 4D as-design BIM model and its incorporated action schedule. However, in practice, this process is typically hampered by a lack of sufficient digital data representing the current state of the construction site. The proposed approach in this work aids in this challenge by providing a framework that not only fully automatically processes but also analyzes (daily) recorded construction images in terms of depicted BIM structures, hence fusing both formerly entirely separate worlds (real world vs. BIM environment). Moreover, an interactive platform is developed that allows users to digitally inspect the construction site in a comprehensible, yet efficient way. The backbone architecture uses an SQLite database that allows to efficiently store all recorded site information present in the imagery. Simultaneously, taking this approach also enables an opposite information flow back to the user in the shape of database queries. The developed framework is believed to increase the efficiency of constructional activity and progress monitoring, and, in general, yields a better oversight on the performed works. In a similar fashion as to what BIM meant in the digitalization process of the design stage of a construction undertaking, the presented framework could function as a comparable paradigm on the physical building and monitoring aspect.

Keywords: Images, BIM, Progress Monitoring, Database, Construction Monitoring

1. INTRODUCTION

One of the numerous tasks of construction site managers and project engineers is monitoring the ongoing building progress and compliance between the executed works and the as-design BIM model. Currently, this is performed on a mainly visual basis where the responsible person interprets the present construction scene and compares it to the BIM model, equally so interpreted. It is clear that, when following this type of approach, this person's interpretation competence of both real-world and virtual scene is paramount, yet very prone to errors (Edum-Fotwe and McCaffer, 2000, Dainty et al., 2005, Fard, 2006). This easily leads to failure costs, or insufficient or inadequate corrective actions, for instance when not detecting anomalies and building errors or only in a (too) late stage.

It is known that the construction sector is rather reluctant in adopting novel technologies (Golparvar-Fard et al., 2009). Therefore, it is crucial that new frameworks are either very user-friendly and comprehensible for novice users or function very similar to the current approaches they try to digitalize. The presented framework is developed in such a way that it responds to both these prerequisites. First of all, it uses pictures. Also in the currently conventional building procedure it is very common to report on the constructional activities via pictures (in emails, informal conversations, progress reports and so on). They are abundantly used for their simplicity and capability to inform decision makers (Zollmann et al., 2014) and can be considered one of the most low-end instruments to adequately capture and visualize surrounding scenes. Through the image-based approach, the shift to a digital monitoring approach is perceived more easily digestible by less digitally adept individuals. Secondly, the now digitalized workflow remains virtually identical to its manual counterpart. The construction monitoring action can now be performed through inspecting pictures of the construction reality and picture-like renderings of the BIM environment. It is clear that the pure monitoring workflow remains equally intuitive as the decisive action still relies on visual interpretation of the scene to determine discrepancies between the real and BIM environments (Golparvar-Fard et al., 2009), yet in a heavily digitally assisted fashion now. Because of the partial digital shift, it is expected that decisions can be made more well-informed and will be significantly less error-prone to human subjectivity and interpretation competence, such as also mentioned in (Han and Golparvar-Fard, 2017).

Capturing pictures has become ever so easy at present. This work aims to harvest this merely exploited source of information in a construction context and use it to its full potential. On every construction scene the site manager performs a daily inspection round to verify the status of the made progress, to inspect the performed works and so on. This constitutes the ideal occasion to simultaneously perform a daily recording session of the site, in particular through omnidirectional or action cameras. The required additional efforts for construction site managers to actively record site data can be kept at minimum this way, especially compared to what the data's feedback potential could yield the managers in return. The collection of daily recorded image sequences forms the take-off point for the framework presented in this work.

In the remainder of this work, a framework is presented that automatically processes these image sequences, stores the data properly and feeds the data back to the user in an augmented and more informing shape. The paper continues with Section 2, in which related works on storing and managing visual monitoring data are presented. Subsequently, the proposed framework's methodology and implementation details are unraveled in Section 3 and 4 respectively. Finally, Section 5 provides the discussion of the achieved results and an outlook on future further development opportunities, while the conclusions are drawn in section 6.

2. RELATED WORK

In literature there is consensus on the fact that although an abundant number of images is captured on construction sites, their potential is heavily underexploited (Brilakis and Soibelman, 2005, Han and Golparvar-Fard, 2017). Furthermore, if the sheer amount of captured data is not properly managed and stored, it tends to become entirely useless very swiftly. The two most crucial image parameters in proper image management can be considered the image recording date and location. As can be deducted from the exploratory study of Han et al. on the use of big visual data in the construction industry, no appropriate or advanced methods currently exist to store site pictures in a well-organized fashion nor are easy sharing possibilities of images and databases commonly available (Han and Golparvar-Fard, 2017).

To compose a well-established database, it is crucial to retrieve a sufficient amount of information from the images and possibly ensuing photogrammetric processing stages. Only in that case, image management systems serve purpose and can be employed in monitoring tasks. One way to do so is through labeling or describing the images (i.e. their content) (Brilakis and Soibelman, 2005). Whereas for textual documents queries based on content can be considered well developed, for images this contrastingly still is an important topic of research. Examples of the former (i.e. text-based queries) include the work of Yu and Hsu, where relevant CAD plans are retrieved through the text they contain (Yu and Hsu, 2013). For the latter (i.e. image-based queries), only few exemplary works exist that typically analyze the depicted shapes, colors and lines to try to determine the material usage and finally the picture content to compose a proper database (Brilakis and Soibelman, 2005, Brilakis and Soibelman, 2008, Soibelman et al., 2008, Dimitrov and Golparvar-Fard, 2014). An approach that holds the middle between the two is presented in the work of Xiao et al. where the image content is textually described via deep learning image captioning methods (Xiao et al., 2022). Other approaches such as for instance picture-to-picture comparisons to retrieve relevant images from an image database are well-studied (Gevers and Smeulders, 2000), yet can be considered less useful in this research context.

In numerous works the cross-over between the real and virtual world is made (Park et al., 2013, Gheisari et al., 2016, Golparvar- Fard et al., 2015, Kopsida and Brilakis, 2020, Rahimian et al., 2020, Alizadehsalehi and Yitmen, 2023), yet they tend to focus on other construction related activities (defect management, providing site insight, automated progress estimation and site inspections to name a few), rather than keeping track of the pictures and storing them in a database. Only the work of Rahimian et al. can be considered somewhat comparable to this as the content of images is determined while actively using the BIM model as a second information provider (Rahimian et al., 2020). Yet, a Convolutional Neural Network (CNN) trained on interpreting depth images is used to segment the images into its content parts rather than directly using the BIM model such as in this work.

The common factor in all aforementioned works clearly is that one of the most important aspects, if not the most, in composing an image database, i.e. the image recording location, is absent. This prohibits geometrically linking the recorded imagery to the BIM model that contains a vast amount of additional site info, thus obstructing the creation of well-founded and informing image databases. Only if approaches employing reference frameworks are used (Tuttas et al., 2017, Vincke and Vergauwen, 2020) or if the image data is tied to the BIM environment using coregistration techniques in post-processing (Bosché, 2012, Kim et al., 2013, Bueno et al., 2018), databases such as in this work can be composed. To the authors' knowledge, no works exist however, that similarly focus on the aspect of properly managing recorded construction imagery in databases. In some other research domains, approaches to systematically and intelligently store

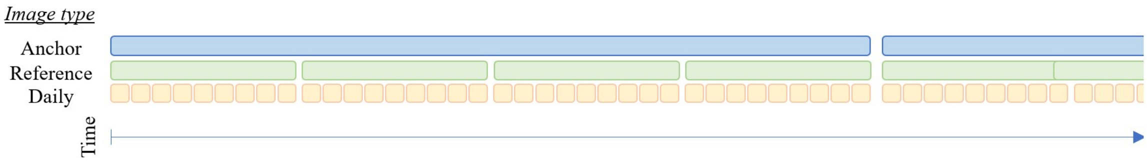


Figure 1: Graphical representation of how frequently the different defined types of images are recorded and processed.

captured data into databases are more common. This is particularly the case for the facility management and building operation sector where Internet of Things (IoT) devices are equipped for constant building monitoring, generating vast amounts of location-known data (Kang et al., 2018, Shipman and Gillott, 2019).

3. METHODOLOGY

The former sections clearly unveil that equally advanced instruments are required for the monitoring aspect of construction works, just as BIM can be considered the instrument causing a digital paradigm shift in the prior design stages (Navon and Sacks, 2007, Kopsida et al., 2015). With that aim, a support framework is presented in this work that aids construction managers in their monitoring task.

As mentioned, the centerpiece of the proposed approach is a series of daily recorded construction site image sequences. However, it is also required that auxiliary image data is available, performing a different role. A subdivision is hence made in the image data according to the role the images perform in the overall process: three data types are defined (*Daily*, *Reference* and *Anchor*). An illustration on the recording periodicity of the different image types is shown in Figure 1.

- The *Daily* image series are the main target of the presented approach. These images are typically recorded with highly portable cameras when traversing the site, yet not following the typical recording patterns required for successful photogrammetric processing. Therefore, as a standalone dataset, it frequently is rather hard to successfully process this type of imagery: the reconstruction accuracy tends to drop quickly (new daily images are tied to older daily images and so on, possibly each time aggravating the accuracy and inducing some drift) and it often is the case that chunks of the recorded site are missing (e.g. because of stepping through a doorway, yielding insufficient overlap between images in order to successfully process them). Furthermore, when periodically adding new daily images to the same photogrammetric reconstruction project, it becomes very inconsistent (e.g. if different daily images portray the same recorded building elements in a variety of states all at once).

- The *Reference* images overcome aforementioned reconstruction issues if only daily images were to be used. These pictures are recorded with later photogrammetric reconstructions in mind. This type of dataset can either entail a full site photogrammetric recording using higher resolution Digital Single Lens Reflex (DSLR) images for instance or can entail Unmanned Aerial Vehicle (UAV) imagery providing the overview and interconnection on the site or a combination of both. Moreover, the reference images provide the much-desired *reset* once in a while to avoid the drift caused by error propagation or the inconsistency issues when using daily images from longer time spans. As presented in earlier work (Vincke and Vergauwen, 2020), each reference image dataset can function as support framework to which the subsequently recorded series of daily images can be matched. A new reference image dataset is required each time the site has changed too much concerning visual appearance. In that case, it would become impossible to correctly match the newest daily images to the outdated reference images. The latter images are equally so recorded on a regular basis (e.g. fortnightly or monthly), yet much less regular than the daily images.

- The *Anchor* images perform an entirely different role. Rather than focusing on the site, they mainly portray the unchanging surroundings. As presented in (Vincke and Vergauwen, 2020), this enables that the georegistration should only be performed once at the very beginning of the construction works (except in the case radical changes occur in the site surroundings, hence the gap in Figure 1 for the anchor images). The anchor images safeguard the compliance in coordinates between all subsequent images and the BIM environment as each reference image dataset is registered to the anchor dataset, hence it inherits the correct coordinate system and thus it is able to transfer the coordinates to all daily images.

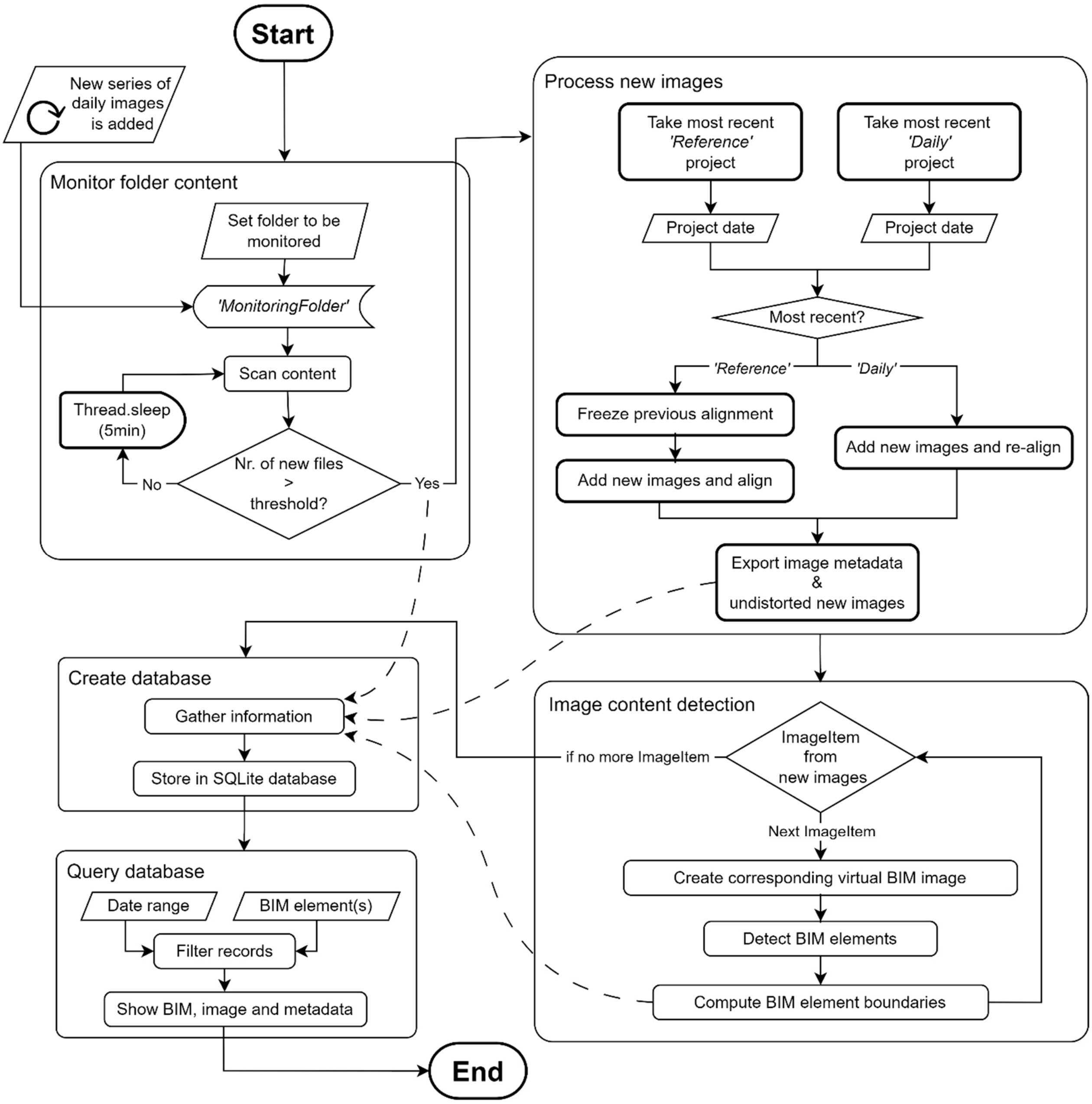


Figure 2: Overview flowchart that displays the different steps in the overall methodology of the presented framework enabling the creation of a BIM and image fused database.

With the different roles images can perform described, the following part discusses the actual framework to process, manage, store and comprehensively feed the daily image series back to the user. A summarizing overview is given in Figure 2 in the shape of a flowchart. The following subsections describe the framework in all its facets in depth.

3.1 Monitoring folder content

The user is presented with a tool to select a folder that is constantly monitored for content changes. The underlying idea is that the person recording site footage dumps the (daily) recorded imagery in that folder. If a sufficient amount of newly added images is reached, an event flag is raised for these pictures to be processed. Simultaneously, the data is also automatically moved to a predefined folder structure to keep all images stored in an orderly fashion.

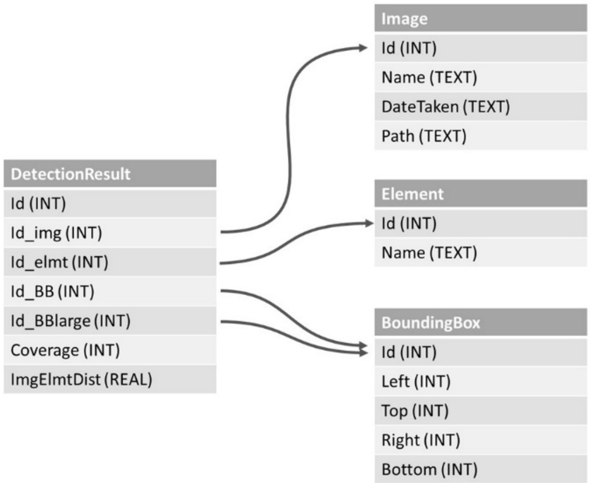


Figure 3: Internal structure of the SQLite backbone database.

3.2 Processing images

The flagged new daily images are processed in this step. In case a new reference project is available to which no daily images were added yet, the formerly performed reference image registration is frozen, prior to adding the new daily images (completely analogue to the approach presented in earlier work (Vincke and Vergauwen, 2020)). In all other cases the photogrammetric project of the former processing round is taken as base project to which the new pictures are added. All daily images (so the new but also the previous ones) are then re-aligned to the reference images. It is particularly chosen for to re-align *all* daily images in order to avoid quickly protruding error propagation effects. Because it is expectable that the recording trajectories vary from day to day, daily images are recorded from locations spread out more over the site over time, hence forming stronger connections and constraints in the processing phase. Following the presented approach (using intermediate level reference images and re-aligning all daily images of a certain reference epoch), middle ground is held between the full exploitation of the mass of daily images and the occurrence of severe image alignment inconsistencies (due to significant differences in site appearance over larger time spans).

It should be mentioned that it is not required that the full photogrammetric pipeline is performed. The process can already be halted after the image alignment phase. This yields sufficient information for the subsequent steps in the developed framework. The final step consists of exporting the image metadata containing all image parameters and saving the undistorted version of all daily images using the calculated distortion parameters.

3.3 Image content detection

The former step yields sufficient information to recreate an identical virtual camera view in the BIM environment (such as presented in earlier work (Vincke and Vergauwen, 2022)). This process is performed repeatedly to detect the content of each daily image. The content determination can be achieved through two different interchangeable approaches. The first one uses ray tracing. Using the image characteristics, a tensor of rays is calculated and projected into the BIM scene. For each individual ray, it is tested if it hits any BIM element. Looping over all rays (i.e. all pixels) the image content is uncovered. A second approach takes the opposite route: it starts from the 3D environment and projects it to the 2D image plane. When applying a particular color code to all BIM elements and assessing all pixels, the images' content can be computed once more.

3.4 Database creation

The information present in the images and computed in the former steps is gathered and stored in an SQLite database. It should be seen as a large collection of detection results of BIM elements in the various images. The internal layout is depicted in Figure 3. It can be noted that two bounding boxes are stored per detection result. This entails the most strict rectangular bounding box and the enlarged version where a margin is added at each side of the strict box such that some extra image info of the surroundings of the element is included (or in case the element is wrongly located, that it still is visible in the image after cropping with the bounding box, as long as it is within a certain limited distance from its intended building location). Moreover, the coverage (i.e. the number of pixels that portray the detected BIM element) and image-to-element distance, both calculated in the previous step of the framework, are stored in the detection result table as well.

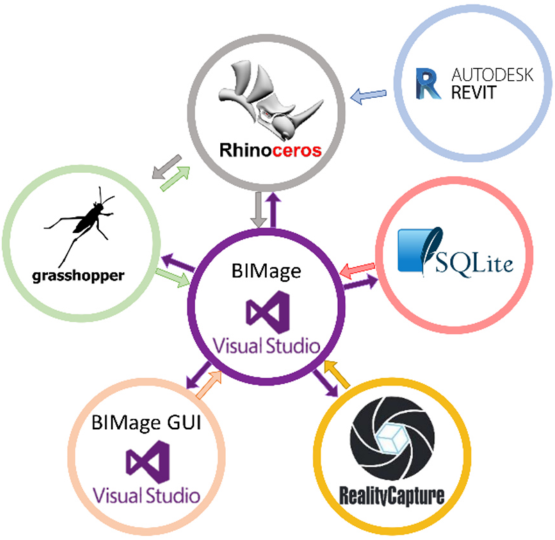


Figure 4: Structure of the framework parts, showing the interconnections between the different entities and how they interact with one another.

Figure 5: Screenshot of what the monitoring process icon and RealityCapture headless program look like. This illustrates the non-intrusive character of both background processes.

For the image, it should be noted that not the file path to the original image is stored, but rather to the undistorted version of it. The original image is discarded from this point onward, to avoid possible future misinterpretations or wrong analyses due to distortion effects that are present in the original images, yet completely absent in the rendered virtual BIM images.

3.5 Database querying

The last step of the framework consists of feeding the gathered info back to the user in a well-organized way. This is achieved through user queries, where the end user can for instance request the series of images in which a particular set of BIM elements is portrayed. Furthermore, the result list can be narrowed by including a date range. These are just some exemplary tools that were added to the graphical user interface to showcase the method's potential.

Once the database query is performed, the results are shown through a combination of a table of the appropriate detection records and an image visualizer. This can be considered the final result of the framework and enables fully digital site inspections, yet in a similar way to current visual on-site procedures.

4. IMPLEMENTATION

The framework builds upon several functions of the Rhinocommon and Grasshopper APIs, both provided through the Rhinoceros® software (Robert McNeel & associates, 2023a). The take-off point on the BIM-side input for the framework is a 3D model in the Rhinoceros environment. In our particular case when developing the framework, a Revit® (Autodesk Inc., 2023) BIM model was used. The conversion from Revit to Rhinoceros can be performed through Rhino.Inside® (Robert McNeel & associates, 2023b), a plugin for Revit by McNeel that also develops the Rhinoceros software. Models developed in other BIM software packages can be imported through Rhinoceros plugins that support IFC (Industry Foundation Classes) files. Another software package that is relied upon in the framework is RealityCapture® (Capturing Reality, 2023). It performs all photogrammetric processing. Finally, the functionalities of SQLite are used for the database part (Hipp, 2023). The proposed framework (called *BIMage*) is developed using the C# coding language and consists of a back-end part that acts as the central node in the framework. It performs several calculations and transfers the different data and commands back and forth between the different software entities. Lastly, also a frontend GUI (called *BIMage GUI*) is developed to elevate the framework into an interactive visual monitoring tool. The symbiosis and interconnections between all framework parts is depicted in Figure 4.

In practice the different components of the proposed framework are worked out in line with the methodology steps.

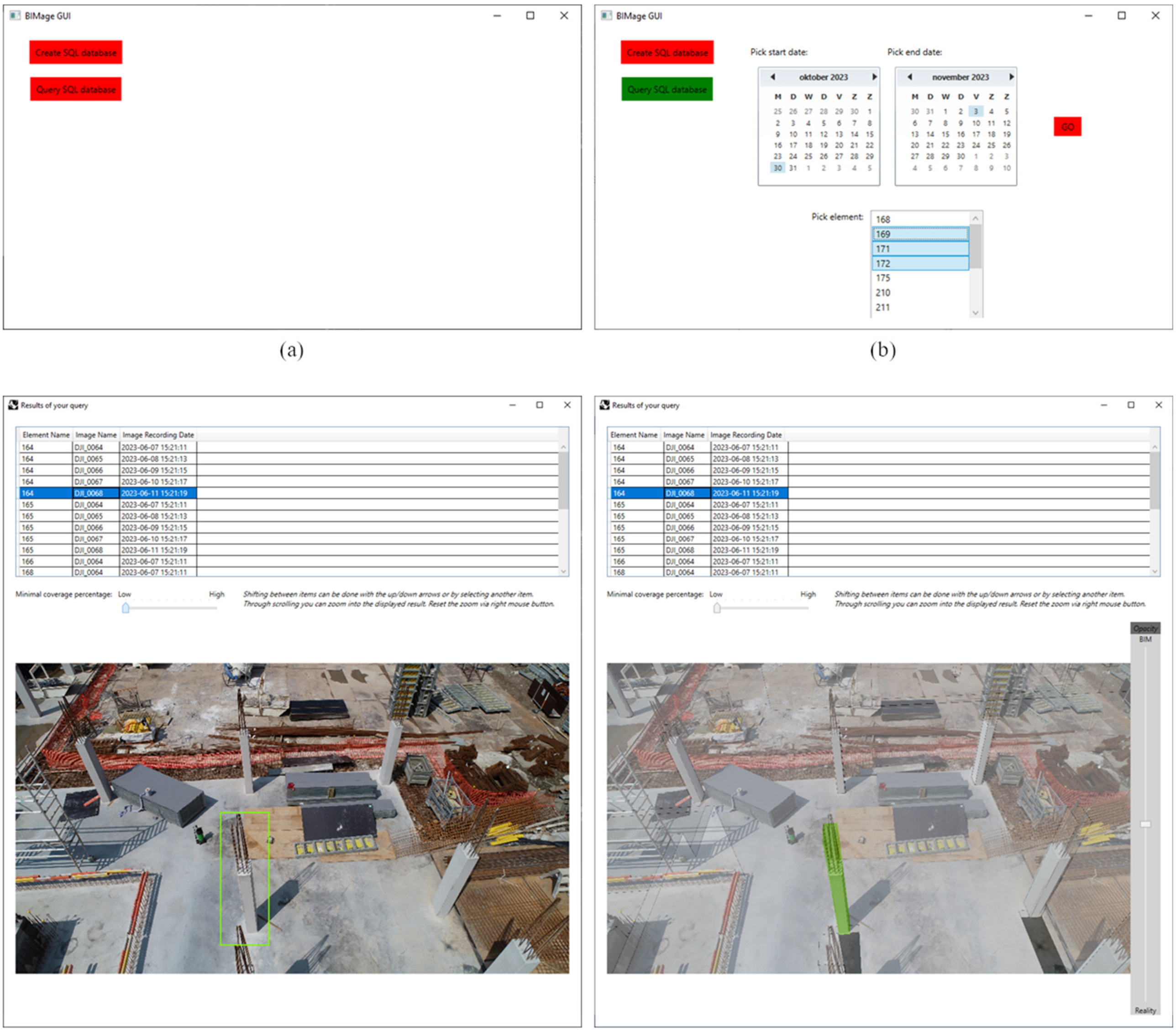
Prior to being able to analyze the daily images, a preparatory step needs to be taken. As described, BIM models, typically designed in software other than Rhinoceros (in our case Revit), are automatically imported into the Rhinoceros environment through a Grasshopper script containing Rhino.Inside components. This conversion to Rhinoceros is only required to be performed once (unless updates to the BIM model occur). All following analyses can take off from the saved Rhinoceros file.

All the framework's functionality is built into a single main Grasshopper script, yet it can be split into two subprocesses: new image monitoring and processing on the one hand, which is a continuously running background process, and on the other hand a user-initiated process with a user interface to instantiate the image database, possibly followed by database queries.

Image monitoring & processing From the moment the main Grasshopper script opens, the monitoring process is initiated (if not already running). The process is designed as a headless background program with solely a system tray icon to avoid disturbing the user, yet enabling a process stop. Additionally, the monitored folder can also be opened, allowing for swiftly adding the new daily images (Figure 5). If a sufficient number of new images is encountered, a different component is fired that is in charge of processing these. The selection of RealityCapture as photogrammetric software package necessitates the creation of batch script files for it to be able to run in a completely automated manner (an API is currently not available). Simultaneously, this also allows for RealityCapture to run as a headless instance, again not disturbing the end user that is typically not familiar with this type of software (Figure 5). A base batch file script is automatically created when starting up the image processing component. The base script is subsequently adapted such that the series of new daily images is added to the correct former photogrammetric project, as well as that it is processed in a correct way. When the processing is finalized, metadata files for each image file are automatically exported (or updated in case older daily images are present in the project) and the undistorted version of the daily images is exported as well. The former two processes keep running even after closing Rhinoceros and Grasshopper.

Database creation & querying The second part of the framework is only initiated at will of the user. It can be initiated through opening the same main Grasshopper script, which makes a user interface (BIMage GUI) pop up automatically (Figure 6a). Two buttons let the user either create a database or query the database. When selecting the *Create SQL database* option, a background Grasshopper/ Rhinoceros process is fired in which the files containing all images' metadata are retrieved. Subsequently, the content of each image is determined through the creation of virtual BIM counterpart images with a color code applied to all elements. Current graphics cards' excellent capabilities to swiftly render 3D objects are exploited this way. A ray tracing module was also developed, yet was found to be far less computationally efficient. By sliding over the colored BIM rendering in a pixel-wise fashion, grouping the pixels of the same color and coupling back to the dictionary in which the color coding is stored, the content of that rendering, and thus also the recorded image, can be determined. Moreover, this also enables the calculation of a bounding box and its enlarged version. In the following step, all detected content and the relevant other parameters are gathered and stored in an SQLite database. The former process is entirely automated and the database follows the exact structure as depicted in Figure 3.
Once a database is created, the user can query it. It should be noted, however, that it is not required to *always* create a database prior to querying. Earlier created databases can serve equally well, especially when browsing through older site data. A new database is only required when the need to inspect the newest image data is present. The current implementation of the querying capabilities in the framework is purely illustrative, yet already very powerful and informative for the end user. At present, the user is prompted to select an inspection date range and the BIM element(s) of interest (Figure 6b). Back-end, the database is subsequently queried for all records that satisfy the user prompt. In the last stage, the user is requested to choose one of the two inspection modes. The first option is the simplest one. When a record of the query result is selected by the user, the record's bounding box parameters are used to draw the appropriate rectangle on the record's image[1] (Figure 6c). This allows the user to visually inspect the site to for instance assess the achieved progress against the construction schedule. The second option is more advanced in such a way that the BIM model is overlaid on the recorded footage. Per returned record, a new BIM rendering is made on the fly using the appropriate rendering parameters stored in the record. Additionally, the specific BIM element is also transferred back to Rhinoceros. Per query record, a custom BIM view can be rendered this way, with the record's BIM element highlighted for clearer visualization and inspection. Next, the rendered virtual BIM image is overlaid on the recorded image and a slider is provided to change the opacity of the BIM foreground image (Figure 6d). This allows the user to visually inspect the site both in terms of achieved progress as well as quality control in an even more informed way compared to the currently common procedures. It should be noted that for both query visualizing options, functionality to pan and zoom in on the image is also included, enabling close inspections and better monitoring assessments and decisions.

[1] To keep the database lightweight, only file paths are stored and not the actual images.



(a) (b) (c) (d)

Figure 6: Screenshots of the developed user interface of the presented framework. a) Application start-up view b) Application view when querying the database c) Query result list with slightly augmented (green bounding box) recorded imagery d) Query result list with overlay viewer that displays both the recorded image as well as its virtual BIM counterpart rendering.

5. DISCUSSION

At present, the developed tool set has only undergone initial testing on a simple construction site. Therefore, the noticed effects on increased efficiency of constructional activity and progress monitoring are still premature. Nevertheless, the presented framework can be considered a promising tool, yielding good oversight on the performed works and current achieved construction status. It can be used for a vastly diverse set of tasks, including the typical monitoring of performed progress and assessment of achieved quality, yet also for other tasks such as verifying the usage of correct materials, assessing (in)correct wall openings and investigating the absence of rock pockets in concrete structures, monitoring the site safety and much more. Overall, the framework can be seen as an enhanced instrument for site documentation and construction activity tracking.

Despite the framework's potential, a point of critique can be raised as well: the user remains the most crucial factor in the monitoring and ensuing decision-making process. Therefore, the argument might be raised that the influence of tools like these on lowering failure costs is rather trivial as also this framework remains to rely heavily on the (interpreting) skill set of the user to monitor the construction works. Yet, the counterargument that should be raised here is that analyzing the built against the designed environment has become far easier. Especially the direct overlay of BIM onto reality makes interpretation mistakes much less likely, resulting in more appropriate ensuing actions.

Finally, the presented work can be considered an ideal base for further developments, especially concerning documentation and reporting functionalities. As progress remains to be made over time to automate estimations of the achieved construction progress and quality assessments of the performed works, the presented framework can be expanded. Analysis results can be included in the database and users can be enabled to query such parameters as well (e.g. a query that requests all images in a certain date range, but only of finished building elements). Secondly, tighter integration with the BIM environment remains possible as well (e.g. the user selects a BIM element in the BIM environment and can start the query process from there).

6. CONCLUSION

The existence and use of advanced digital tools that aid to streamline, modernize, automate and simplify the task of construction monitoring can still be considered trivial at present. In this light, a framework is presented that digitalizes the current monitoring workflow. Through automated processing of daily captured imagery, the present site conditions can be digitally represented swiftly. The link with BIM is foreseen through a common reference system, hence enabling cross-world (digital vs. real) comparisons and integration. Moreover, that link also allows for computing the theoretical content of each recorded image, which in its turn makes a plethora of ensuing analyses possible. In the presented work, a fusion of data originating from the real-world imagery on the one hand and from the digital BIM environment on the other hand is realized and used to compose a smart database of site images. Due to the digitally preserved data, user queries can be swiftly executed, enabling digitally assisted site inspection and monitoring. The presented framework is esteemed to lower the risk for human interpretation errors because of the digitalized workflow. Moreover, the approach remains comprehensible and similar to current manual practices, hence attributing to its adoptability by the construction sector, known to be rather conservative in terms of innovation implementation.

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