GEO-REGISTERING CONSECUTIVE DATASETS BY MEANS OF A REFERENCE DATASET, ELIMINATING GROUND CONTROL POINT INDICATION

Stan Vincke* and Maarten Vergauwen

Dept. of Civil Engineering, TC Construction - Geomatics
KU Leuven - Faculty of Engineering Technology
Ghent, Belgium
(stan.vincke,maarten.vergauwen)@kuleuven.be

Commission V, WG 7

KEY WORDS: Geo-registration, Co-registration, Construction, Ground Control Points, Remote Sensing

ABSTRACT:

The architecture, engineering and construction (AEC) industry's interest in more advanced ways of regular monitoring of construction site activities and the achieved building progress has been rising recently. This requires frequent recordings of the area. This is only feasible if the profound observations only require limited time, both for the actual capturing on-site as well as processing of the recorded data. Moreover, for monitoring purposes, it is vital that all datasets use a single, unique reference system. This allows for an easy comparison of various observations to determine both building progress as well as possible construction deviations or errors.

In this work, a framework is proposed that facilitates a faster and more efficient way of co-registering or geo-registering consecutive datasets. It comprises three major stages, starting with the capturing of the surroundings of the construction site. By thoroughly adding numerous ground control points (GCPs) in a second phase, the processed result of this input data can be considered as a reference dataset. In a third stage, this known component is used as additional input for the processing of subsequently captured datasets. Using overlapping areas, the new observations can be immediately transferred to the correct reference system. This eliminates the indication of GCPs in subsequent datasets, which is known to be time-consuming and error-prone.

Although in this work the focus of the proposed framework lies on a photogrammetric recording approach, it also is applicable for laser scanning. Its potential is showcased on a real-world apartment construction site in Ghent, Belgium. In the test case, the presented approach is shown to be efficient, with comparable accuracies as other current methods, however, requiring less time and effort.

1. INTRODUCTION

In the AEC industry and the associated research community, a multitude of different terms for referring to various phenomenons related to registration are used. The most common terms are geo-registration and georeferencing, but also registration and referencing, as well as co-registration, absolute or relative registration and alignment are frequently encountered.

Therefore, for the legibility of this work, the following terms for the various phenomenons are consistently used:

When referring to determining correspondences between different data entities within one dataset, the term alignment is used. Subsequently, also the term co-registration is used. This refers to the determination of transformation parameters between two separate datasets, which each - independently - were formed by aligning their data entities. At last, when referring to the localisation of a dataset in a general reference system we use the term (geo-)registration. The prefix *geo-* is included if the dataset is placed in a worldly or regional reference system and is abandoned when referring to localisation of a dataset in a local reference system.

The recent incorporation of a more BIM-oriented workflow in the AEC industry necessitates regular comparisons of the current building situation and the as-designed BIM. Furthermore the aim for an easier progress monitoring workflow amplifies the demand for accurate methods to compare two datasets of a construction site, recorded several days or weeks apart. Therefore, the presence of a uniform geo-registration system is vital. In this we present a framework that serves as a tool for the registration of consecutive datasets of construction sites by using the recorded data of the site's surroundings (figure 1). As a result the tedious and often manual indication of GCPs in subsequently captured datasets can be eliminated.

A geo-registration framework is paramount for a number of reasons. Adding control points to a project is beneficial or even paramount, certainly for larger projects. Due to the known location of the GCPs, it is possible to correct drift. Furthermore, when using photogrammetry to reconstruct the scene in 3D, GCPs are inevitable since the model lacks the correct scale without them. Also for visualisation purposes, geo-registered datasets are necessary. If multiple datasets are visualised simultaneously, it is vital that common elements are shown on the same location. Geo-registered datasets are also essential for deviation analysis. Discrepancies between datasets only make sense if those datasets are recorded using a common reference system.

If GCPs are not available, the co-registration of the datasets remains an option. This can be performed either manually or automatically. Manual registration suffers from the indication of weak, insufficient, inaccurate or incorrect correspondences. A (semi-)automatic registration, typically using Iterative Closest Point (ICP) techniques (Besl and McKay, 1992), frequently delivers poor results due to several reasons. First at all the highly cluttered nature of construction sites poses a challenging environment. Also construction elements can pose difficulties. The ICP algorithm can consider two separate closely located wall surfaces as a single surface, making them erroneously coincide. In contrast, it also is possible that the corresponding wall surface lies out of the ICP algorithm's work range. Therefore we present a framework that eliminates the use of ICP algorithms hence avoid-

---

*Corresponding author

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLII-5-W2-85-2019 | © Authors 2019. CC BY 4.0 License.

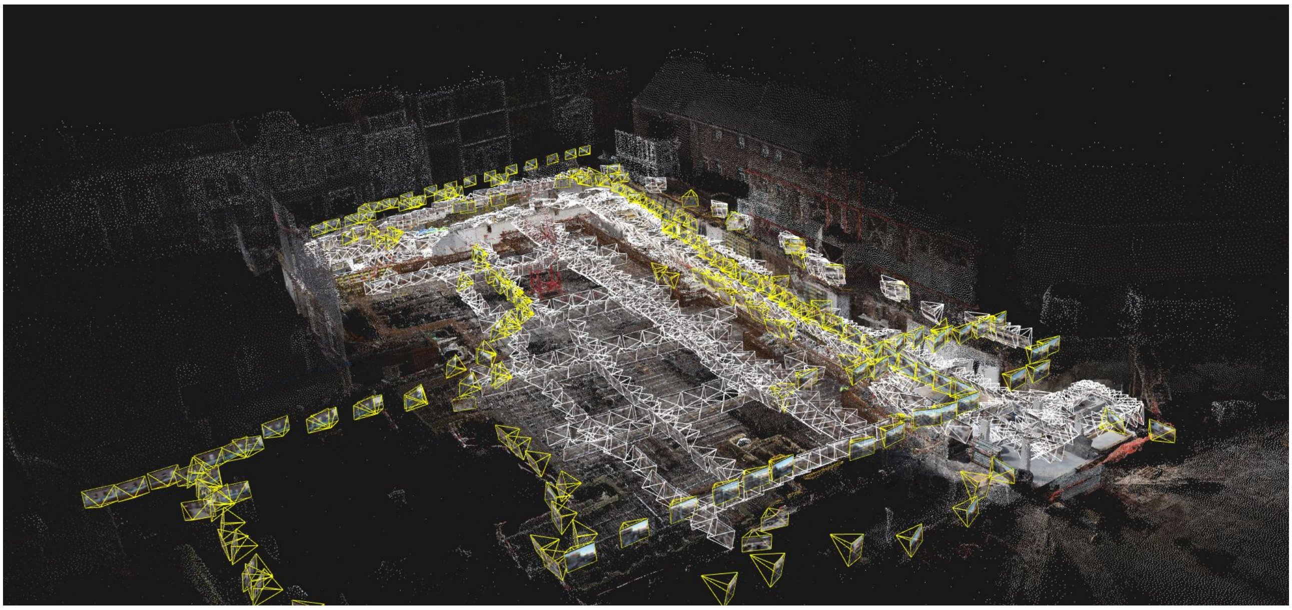

Figure 1: The yellow pictures form part of the geo-registered reference dataset, serving as the basis for the registration of the newly captured white pictures. Although the recordings of the new dataset mainly focus on the construction site itself, the surroundings are clearly depicted by the vertices originating solely from the new dataset (i.e. the white pictures).

ing the associated problems. Although the indication of the GCPs is performed manually, it is only required to happen once: only at the creation of the reference dataset. Opposed to manually indicating correspondences for a relative registration of datasets, the indicated points in the reference datasets are well defined and easily recognisable, hence reducing the risk of errors.

The remainder of this work is structured as follows. In section 2. related works on the co- and geo-registration of different datasets in the construction industry are discussed. Subsequently, the methodology of the proposed geo-registration framework is presented in section 3. The experiments and the discussion of the achieved results are presented in section 4. and 5. respectively and finally, the conclusions are presented in section 6.

2. RELATED WORK

Being able to accurately (geo-)register multiple datasets in the AEC industry is of large importance.

In an early work of Bosché et al. (Bosche and Haas, 2008) the advantageous opportunities that geo-registration offer are discussed. They present their work on automating the retrieval process of modelled objects from laser scanning data. By geo-registering both the 3D CAD model as well as the captured data, the retrieval process substantially simplifies since the a priori position of the search object now becomes (approximately) known. Tuttas et al. use control points extracted from the BIM model's reference system such that both the recorded dataset and the BIM model automatically share a common reference system (Tuttas et al., 2014). They correctly state that if multiple datasets are geo-registered, they automatically share a common reference system, hence making a co-registration obsolete. A similar approach was used in the work of Golparvar-Fard et al. for the progress monitoring on a construction site, where they assess the applicability of using fixed cameras to record the construction site (Golparvar-Fard et al., 2009b). In a first step the pictures of the first dataset are geo-registered. All of the data entities of subsequent datasets, however, are not required to be aligned, since all subsequent pictures share the same location and orientation as the ones in the geo-registered dataset because of the fixed positions. In their experiments however, proof was found that the fixed cameras still underwent small displacements due to external factors such as vibrations and wind, resulting in a new alignment for each new dataset such as for non-fixed camera imagery, making the proposed framework less viable.

To enable comparing multiple datasets, registered using a common reference system, the most common used method is the one of co-registration. Numerous works on this research topic have been presented.

The most rudimentary method to co-register datasets is presented by Westoby et al., who compare the techniques of laser scanning and structure for motion (Westoby et al., 2012). They manually indicate several targets in the scene to align multiple laser scans. Also for the co-registration of the laser scanning and photogrammetric dataset, this approach is used by indicating the corresponding control targets' centroids in both sets of data. Similarly, also Zhang et al. use such method for construction progress control (Zhang and Arditi, 2013).

One of the most common methods that is used for a more automated way of co-registering consists of two stages. In a first stage, the datasets are coarsely registered. Subsequently it is possible to register the datasets more correctly using an ICP (Besl and McKay, 1992) or derivative algorithm.

In the early work of Golparvar-Fard et al., which focusses on progress monitoring at construction sites, the at that time most common approach for the coarse registration of datasets is discussed (Golparvar-Fard et al., 2009a). Similar to the complete manual co-registration workflow as aforementioned works of Westoby et al. and Zhang et al., a global transformation based on the indication of several common points between the datasets is applied to the 3D model, obtained through structure from motion such as described by (Dellaert et al., 2000).

Since the coarse registration was most frequently executed manually, the focus was mainly on optimising the initial ICP algorithm. In the work of Kaneko et al. an advanced algorithm is proposed that ensures a correct three-dimensional matching of two datasets (Kaneko et al., 2003). Gruen and Akca present a method called Least Squares 3D Surface Matching or LS3D for the co-registration of point cloud datasets based on minimisation of the euclidian distance between surfaces rather than points, based on the earlier presented work of Chen et al., which were among the first to present such method (Chen and Medioni, 1991). In the work of Du et al. a further enhanced algorithm is proposed that also considers the different scales of the datasets (Du et al., 2007). In the works of Bosché et al. a similar optimisation of the ICP algorithm is researched further (Bosché, 2010, Bosché, 2012).

In some cases a coarse registration is obsolete. This is for instance the case in the work of Pucko et al. on progress monitoring (Pučko et al., 2018). The construction site is captured by a multitude of inexpensive low precision scanning devices. These scanners scan at specific time intervals, resulting in multiple partial point cloud frames. Due to the limited interval time, the deviation between these partial point cloud frames falls within range for a correct ICP alignment solution.

After the numerous optimisations of the ICP algorithm the focus shifted more towards automating the coarse registration process, that up till then mostly was executed manually by the indication of corresponding points (Brilakis et al., 2010). As correctly stated by Bosché et al., the ICP algorithm is only capable of optimising the intermediate coarse co-registration result as long as this step has been executed *well enough* (Bosché, 2012). This implies that the result of the coarse registration should fall within the limited deviation range that ICP algorithms are able to correctly handle. Rusu et al. were among the first to research this matter (Rusu et al., 2008, Rusu et al., 2009). In their works they present an algorithm and an updated faster version, that uses point feature histograms for an initial alignment of various point cloud datasets, after which an algorithm such as ICP can optimise these results. Similarly, Kim et al. present several works on optimised coarse registration procedures based on principal component analysis (Kim et al., 2011, Kim et al., 2013a, Kim et al., 2013b). Subsequent to the coarse registration, the initial result is optimised by the ICP algorithm in combination with the Levenberg-Marquardt algorithm presented by Fitzgibbon et al. (Fitzgibbon, 2003).

Several works use ICP solutions to minimise the deviation between co-registered datasets for progress monitoring purposes. An example is the work of Son et al., in which progress is determined by comparing multiple partial stereo vision camera datasets with the planned 3D model (Son and Kim, 2010). Both for the alignment of the partial datasets as well as the registration of the final dataset with the 3D model, ICP solutions are used.

Other approaches do not rely on a combination of coarse and fine registration process for co-registration. Gonzalez et al. were among the first to present a framework for the alignment of data entities originating from different sources, namely laser scanning range images and digital camera images (González-aguilera et al., 2009). If two such datasets can each be separately aligned and the link (or several links) is found between data entities of dataset A and B, consequently these can be co-registered and hence form a new dataset $A \cup B$. Eo et al. (Eo et al., 2012) discuss another technique that allows co-registration without any prior knowledge of the relative pose of two or more datasets. By using SIFT for feature detection and matching in the laser scan's intensity and range images, the laser scans can be aligned. Furthermore, when all scans are connected pairwise, a global optimisation is executed. Therefore, rather than relying on ICP algorithm solutions, they use the Generalised Procrustes Analysis (GPA) method, earlier presented in the work of Crosilla and Beinat (Crosilla and Beinat, 2002). The work of Kropp et al. focusses on progress monitoring, but for indoor scenes (Kropp et al., 2018). This means that they mainly focus on the finishing works of the building, rather than the construction of structural components. This enables them to effectively use the as-design BIM as crucial input for the pose estimation of the various images, extracted from a walk-trough video. As a result, the alignment of the various images is registered in the same reference system as the as-design model hence enabling an easy comparison of datasets and accordingly the determination of indoor progress.

The monitoring of progress on construction sites, requires that the site is captured on a regular basis. Several works have been published that handle the continuous registration of consecutive recordings.

Golparvar-Fard et al. present similar approaches to our proposed framework (Golparvar-fard et al., 2011, Golparvar-Fard et al., 2015). The resulting point cloud obtained with photogrammetry is co-registered with the as-planned model in the same way as described previously, namely based on correspondences. However, for the registration of all subsequent point clouds they propose using the enhanced ICP algorithm of Du et al. (Du et al., 2007). This way, as in our method, the geo-registration is only executed once. However, this approach only considers the new dataset as a rigid and indivisible object to transform. This way the drift that possibly occurs in these subsequent datasets is not corrected. Furthermore, if alignment errors occur in the initial processing of the new dataset's entities, these are still present in the transformed dataset. In contrast, the registered dataset in our work is used as valuable input for the registration of the newly captured data. This ensures that these entities are registered correctly, with the reference dataset as a crucial backbone.

The most recent and most closely related work to ours, is that of Aicardi et al. (Aicardi et al., 2016). They present a similar approach as ours for the registration of subsequent imagery datasets using reference images previously registered in an initial reference dataset. However, their work mainly focusses on aerial imagery, obtained via an Unmanned Aerial Vehicle (UAV). As a result, the images are not only all oriented in the same direction, but also their position is already approximately known by the georeferencing parameters in the Exif-data, obtained via the GNSS-module in the UAV. For construction site and progress monitoring purposes terrestrial data entities are necessary. However, the recording locations of such data entities are almost never known, not even approximately. Furthermore, the exclusive use of terrestrial recordings results in a higher amount of necessary data entities to record the site. This requirement is justified though, because larger detail is required for progress monitoring and deviation analyses. As a result however, the abundance of data entities further complicates an easy alignment. Therefore, the use of a previously aligned reference dataset is crucial, often offering the only possibility to link two partially aligned subsets of data. For instance if multiple rooms are recorded, these form enclosed regions only linkable via the surroundings, visible through wall openings for future doors and windows. Therefore, in case of terrestrial recordings, a reference dataset is crucial as it is actively used for the alignment, while in their presented work the sole purpose is its use as an instrument for the (geo-)registration.

3. METHODOLOGY

In this paper a framework is presented for geo-registering consecutive datasets of a construction site. It consists of three major steps, namely the 3D acquisition of the surroundings of the construction site, the processing of these data and finally the processing of new, subsequent datasets using the information in the reference dataset (figure 2). These three stages are discussed in depth in the following subsections with according numbers to the phases in the methodology.

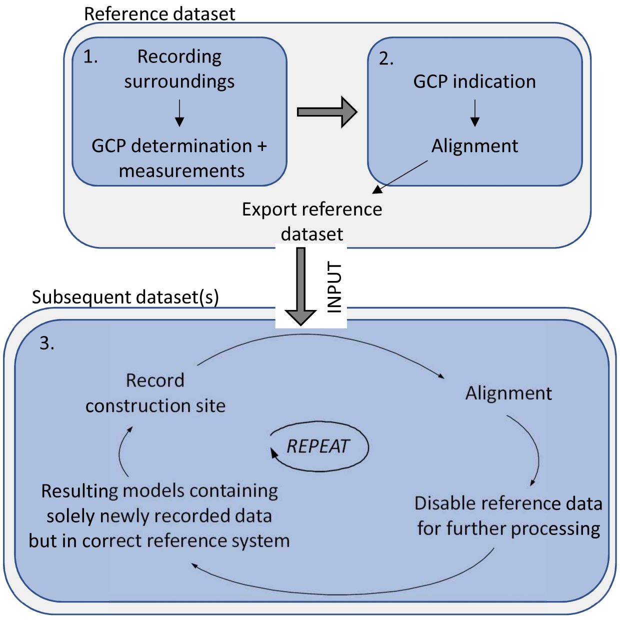

Figure 2: Methodology diagram

3.1 Recording reference data

As mentioned before, GCPs of construction site projects are typically not located on the actual site, but on surrounding recognisable structures and buildings because these remain stable and standing. The fundamental idea behind our proposed approach is to create a registered project, only containing data of the surroundings. This project can then serve as valuable input and as a reference system for the registration of subsequent datasets of the actual construction site. Therefore, in a first step, the surrounding area of the site is captured profoundly by remote sensing techniques. In our case, photographs and photogrammetry are used, but an approach using laser scanning can also be envisaged. Subsequent to the recordings, appropriate and clearly visible GCPs are selected. Their relative location is precisely determined using a total station. The two optional subsequent steps are the co- and geo-registration of the reference system. Determining the location of the GCPs in respectively, the coordinate system of the other dataset or a national coordinate system, allows for calculating the transformation parameters. The co- or geo-registration can hence be completed by applying the computed transformation.

3.2 Processing the reference dataset

The recorded data of the surroundings are processed in a second phase. Because this dataset will serve as a reference for all subsequent ones, its accuracy is of paramount importance, hence making this step the most critical one of the proposed approach. This is why the chosen GCPs are indicated as precisely and in as many data entities (images/scans) as possible. This approach lays the groundwork for a very tight and highly accurate network of data entities. After further processing, the reference dataset of the surroundings of the construction site is established, serving as a fast and easy geo-registration tool in subsequent datasets of the construction site.

3.3 Processing subsequent datasets

The subsequent datasets are used for monitoring and analysis purposes and therefore only focus on the scene itself. Nevertheless, parts of the surroundings are always present. These parts serve as the crucial link between the reference dataset and the newly captured datasets. In a next phase, the new data is imported into the reference project. This way, in every subsequent step, the new data will not only be processed on its own, but also in conjunction with the formerly captured and geo-registered reference dataset. This ensures that the new dataset both incorporates the reference system ánd inherits the metric quality of the reference dataset, which is considered as an integral dataset of which the location of the data entities are considered as completely fixed. For the further processing of the new dataset, namely the dense matching, meshing and colouring and texturing of the model, the data entities of the reference dataset can be disabled considering they mainly contain useless information of the surroundings on the construction site.

4. EXPERIMENTS

The experiments were conducted on a large apartment construction site in Ghent, Belgium. In line with the described methodology, the three phases of the experiments are presented in the following paragraphs.

4.1 Recording reference data

Due to the large size of the construction site (80 x 80 metres), the reference project constitutes of 296 images of the site's surroundings. A correct alignment of this dataset is paramount since all subsequent datasets will be matched with this reference dataset. Therefore the images are carefully recorded spread over the construction site to form a network as strong as possible. For the registration of the reference project 23 ground control points on surrounding walls and structures, unaffected by the construction works, are chosen. These are spread out as much as possible, such that the project is registered as precisely as possible. Subsequently, the relative position of the GCPs is recorded accurately by a total station. These steps ensure that the reference dataset can be aligned and registered correctly.

In a next phase, the GCP dataset is co-registered with the as-design BIM model. For deviation analysis and progress monitoring purposes, it is crucial that the subsequent recorded construction site datasets share the same reference system as the BIM model. By calculating the transformation parameters based on correspondences, the GCP network is registered to the BIM model reference system.

Subsequently, it optionally is possible to advance from a co-registered to a geo-registered reference dataset by similarly calculating the transformation of the locally measured GCPs to the GCP locations according to the national coordinate system by means of GNSS measurements. However, in this work the last step was not executed since this yields no additional advantages over the current approach for our envisaged purposes.

4.2 Processing the reference dataset

In the second step of the proposed framework, the 296 recorded images of the surroundings are processed in combination with the measurements of the GCPs to form the aligned and registered reference dataset for subsequent recordings. For processing we use the photogrammetric RealityCapture software. Because of the reference dataset's importance, each GCP is indicated in all the images that portray it. This results in a total of 340 indications of the 23 GCPs in the 296 images.

Subsequently, the alignment of the images was executed, taking into account the GCP locations. For processing subsequent datasets in the third major step of the proposed framework, the resulting reference dataset is exported as a RealityCapture alignment component. This dataset contains the ground control points, the reference images and their location and orientation parameters, calculated in the alignment, and the resulting sparse point

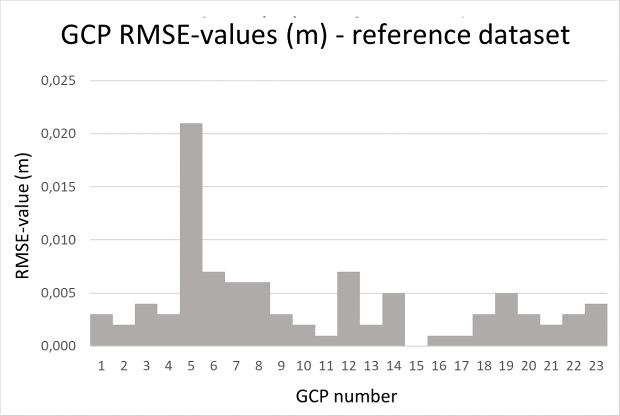

Figure 3: Column chart showing the RMSE-values of the comparison of the GCP locations determined by total station and their location after registration. Except for one outlier, GCP 5, the RMSE-values are lower than 7 mm.

cloud.

4.3 Processing subsequent datasets

In the next phase of the framework, subsequent datasets are co-registered with the reference dataset based on the image data of the surroundings. Although focussing only on the construction site itself, the surroundings are partially reconstructed as well. A total of approximately 430.000 points form part of surrounding structures, on a total of approximately 4,9 million points.

The first step consists of importing the 1326 images of the newly captured dataset, and the reference project, i.e. the RealityCapture alignment component, into a new project. As the reference dataset was previously correctly aligned and registered, all its data entities are considered as known in location and orientation and hence are locked. This way, when aligning all entities of the complete dataset, the new images are aligned to the reference images, thus taking over the coordinate system of the reference project. For further processing, the reference images no longer have purpose and are therefore disabled for the dense point cloud generation, meshing, colouring and texturing. This results in an end product, such as a dense point cloud or a mesh, originating solely from the new imagery, but registered in the correct reference system.

We applied the proposed method to a subsequent dataset, captured two weeks after recording the reference dataset.

5. DISCUSSION

Both for the reference dataset and for the subsequent dataset, a Quality Analysis (QA) is executed and discussed in this section. This is followed by an enumeration of possible advantages of the proposed framework over current approaches. Furthermore, future possibilities for enhancing this work are examined.

QA Reference dataset
The column chart in figure 3 shows the deviations between the measured and calculated position of the GCPs. They all fall below an acceptable 7 mm, except for GCP 5, which can be considered as an outlier. The incidence angle between the indications of the outlier GCP in the various images is fairly low, hence providing an explanation of the inaccurate point position.

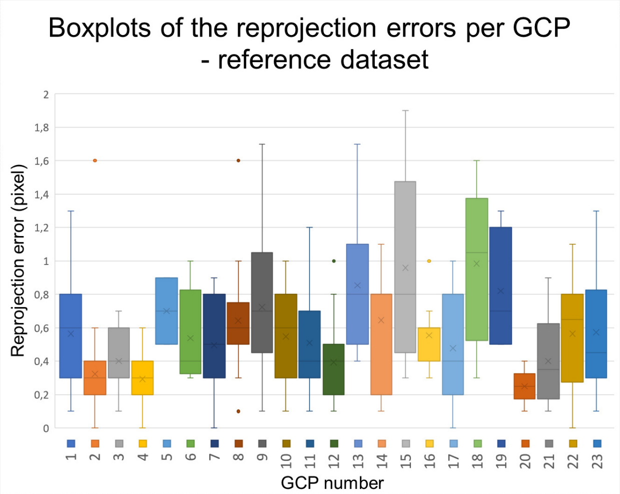

Figure 4: Boxplots giving an overview of the well indicated GCP locations in the pictures. The medians of the various GCPs range from 0,25 to 1,05 px.

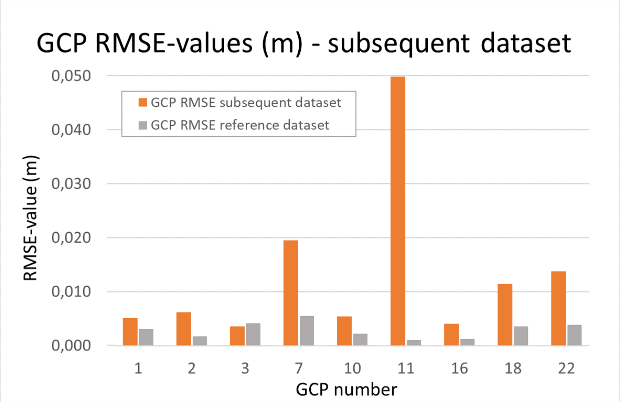

Figure 5: Column chart showing the RMSE-values of a subset of GCP locations. The error is calculated between the actual GCP position and the position in the subsequent dataset. For comparison, the according RMSE-values of the GCPs in the reference dataset are shown in grey.

For further analysis, also the reprojection error of all GCP indications is considered. The results are shown in boxplots for each GCP in figure 4. The figure shows acceptable results for the indication of the GCP locations in the images, with an overall median of 0,5 pixels and a standard deviation of 0,36 pixels.

QA Subsequent dataset
Figure 5 shows the column chart of the resulting RMSE-values. On average, the GCPs in the subsequent dataset have an RMSE-value of 1,3 cm. In contrast, the overall average RMSE value of the reference dataset for this subset of GCPs is 0,3 cm. The reason why only a subset of GCPs is considered for the QA, is that these points were the only visible GCPs in this specific subsequent dataset. Several remarks can be made about these results. First of all, despite the accuracy loss, the proposed approach has a major valuable advantage: precious time is saved for referencing all subsequent datasets. Furthermore, the lower RMSE-value is only obtained after meticulously indicating the GCP locations in every possible image. To apply the indication approach of the reference dataset to all subsequent datasets is not possible or at least enormously time-consuming. Consequently, subsequent datasets will presumably be less accurate since less GCPs will be indicated or GCPs are indicated in less images. However, this was not tested in this work.

Advantages of the presented approach
The use of GCPs for accurate (geo-)registration is strongly advisable. The proposed framework also makes use of them. However,

the time-consuming indication part only happens once during the entire project, namely at the creation of the common reference dataset. This heavily reduces the complexity and the necessary time compared to manual methods for the indication of GCPs in all the different datasets. Furthermore, there are also benefits over a (semi-)automatic GCP indication process. Since the common reference dataset is used repeatedly, the regular construction site datasets are registered in the exact same way. In contrast, when using image recognition algorithms for the indication of GCP targets, minor deviations occur, hence making every registration slightly different.

The proposed framework also yields several other advantages over the current approaches. Construction sites evolve constantly and thus frequently occlude original GCPs located in the building area. Therefore we decided to create a large amount of GCPs outside the construction site. The chosen GCPs are typically easily distinguishable points on surrounding buildings, landmarks or structures. This yields the advantage that the GCPs remain visible throughout the entire construction phase. Moreover, since the actual GCPs are only used once in the whole process, it is not necessary to materialise them. A correct processing of subsequent datasets namely does not depend on it: subsequent imagery is aligned with the reference imagery and thus makes GCPs in the further process obsolete.

Since the actual geo-registration only happens once, more effort can and should be put into the initial alignment workflow. By indicating the GCPs in as many data entities as possible, the reference dataset becomes more accurate. Furthermore, a larger number of GCPs is advisable because of the reference dataset's importance. However, only relatively low time investments are required for creating and measuring additional control points versus the overall accuracy profit they yield. The resulting reference dataset contains thousands of additional points and leads to more accurately referenced datasets of the construction site, since the registration not only takes into account the GCPs but also the rest of the available information present in the data entities. As a result, during the regular recordings it is no longer required to focus on capturing the GCPs in as many data entities as possible. Even while only focussing on recording the construction site itself, the surroundings are reconstructed sufficiently for co-registration purposes.

The versatility of the presented approach not only makes it usable for recording approaches using photogrammetry, where this work focusses on, but also for laser scanning capturing approaches. Furthermore, the backwards compatibility of the proposed framework enables for the geo-registration of earlier recorded datasets, even if they were recorded before the creation of the reference dataset or before the GCPs were chosen.

Future work

Although in this work the focus was on a photogrammetric approach, it also is viable for laser scanning. This can be included in future work. Furthermore, the work can be extended to other photogrammetric software packages, which mostly also offer the opportunity to create partial projects or subprojects and export and import them. Another possibility to enhance our work is to apply the approach to more subsequent datasets as well as analysing the result obtained through the proposed framework in comparison with a manually registered subsequent dataset.

Also opportunities exist for automating the proposed method even further. By materialising the GCPs through aid of markers, detection could be automated as several software packages provide such functionality. This way the tedious manual indication of GCPs can be avoided. Furthermore, by incorporating materialised control points in the workflow, the GCP indication accuracies might rise. On the downside however, is that this way the GCPs must be accessible in order to materialise them, which is not always possible and also not necessary in the followed approach.

6. CONCLUSION

Frequently recording the site is of high importance in the AEC industry. This provides us with the possibility to accurately monitor the achieved progress on construction sites. Therefore, a framework is required that provides the opportunity to process the recorded data in an automated and fast, but accurate way. Furthermore, the captured datasets preferably share the same unique reference system as the as-design BIM model. This enables easier an accurate analyses for deviations and progress.

In this work such framework is proposed for the co-registration or geo-registration of consecutive datasets. The presented approach is advantageous over the current manual or (semi-)automatic methods insofar that the need to indicate ground control points in subsequent datasets is eliminated. The GCPs only need to be indicated once for accurately establishing a reference dataset that can be used repeatedly for the registration of all subsequent datasets. This approach hence saves a lot of time, compared to the current methods.

The applicability and accuracy is proven in the conducted experiments. Using the proposed approach, an average RMSE-value of 1,3 cm was obtained. This is the average deviation between the GCP locations after the registration of a subsequent dataset and their locations measured by total station, considered as ground truth.

7. ACKNOWLEDGEMENTS

This project has received funding from the FWO research foundation (under FWO PhD SB fellowship 1S11218N) and the Geomatics research group of the Department of Civil Engineering, TC Construction at the KU Leuven in Belgium. We would also like to thank Willemen Group for giving access to their construction site.

REFERENCES

Aicardi, I., Nex, F., Gerke, M. and Lingua, A. M., 2016. An Image-Based Approach for the Co-Registration of Multi-Temporal UAV Image Datasets. *Remote Sensing* 8(9), pp. 1–20.

Besl, P. and McKay, N., 1992. A Method for Registration of 3-D Shapes. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 14number 2, pp. 239–256.

Bosché, F., 2010. Automated recognition of 3D CAD model objects in laser scans and calculation of as-built dimensions for dimensional compliance control in construction. *Advanced Engineering Informatics* 24(1), pp. 107–118.

Bosché, F., 2012. Plane-based registration of construction laser scans with 3D/4D building models. *Advanced Engineering Informatics* 26(1), pp. 90–102.

Bosche, F. and Haas, C. T., 2008. Automated retrieval of 3D CAD model objects in construction range images. *Automation in Construction* 17(4), pp. 499–512.

Brilakis, I., Lourakis, M., Sacks, R., Savarese, S., Christodoulou, S., Teizer, J. and Makhmalbaf, A., 2010. Toward automated generation of parametric BIMs based on hybrid video and laser scanning data. *Advanced Engineering Informatics* 24(4), pp. 456–465.

Chen, Y. and Medioni, G., 1991. Object modeling by registration of multiple range images. In: *Proceedings of the 1991 IEEE International Conference on Robotics and Automation ICRA*, pp. 2724–2729.

Crosilla, F. and Beinat, A., 2002. Use of generalised Procrustes analysis for the photogrammetric block adjustment by independent models. *ISPRS Journal of Photogrammetry and Remote Sensing* 56(3), pp. 195–209.

Dellaert, F., Seitz, S. M., Thorpe, C. E. and Thrun, S., 2000. Structure from motion without correspondence. In: *Proceedings IEEE Conference on Computer Vision and Pattern Recognition. CVPR 2000 (Cat. No.PR00662)*, Vol. 2, pp. 557–564.

Du, S., Zheng, N., Ying, S., You, Q. and Wu, Y., 2007. An Extension of the ICP Algorithm Considering Scale Factor. In: *2007 IEEE International Conference on Image Processing*, Vol. 5, pp. 193–196.

Eo, Y. D., Pyeon, M. W., Kim, S. W., Kim, J. R. and Han, D. Y., 2012. Coregistration of terrestrial lidar points by adaptive scale-invariant feature transformation with constrained geometry. *Automation in Construction* 25, pp. 49–58.

Fitzgibbon, A. W., 2003. Robust registration of 2D and 3D point sets. *Image and Vision Computing* 21(13-14), pp. 1145–1153.

Golparvar-fard, M., Asce, M., Peña-mora, F., Asce, M. and Savarese, S., 2011. Integrated Sequential As-Built and As-Planned Representation with D 4 AR Tools in Support of Decision-Making Tasks in the AEC / FM Industry. *Journal of Construction Engineering and Management* 137(December), pp. 1099–1116.

Golparvar-Fard, M., Peña Mora, F. and Savarese, S., 2009a. D4AR-A 4-dimensional augmented reality model for automating construction progress monitoring data collection, processing and communication. *Journal of Information Technology in Construction* 14, pp. 129–153.

Golparvar-Fard, M., Peña-Mora, F. and Savarese, S., 2015. Automated Progress Monitoring Using Unordered Daily Construction Photographs and IFC-Based Building Information Models. *Journal of Computing in Civil Engineering* 29(1), pp. 04014025.

Golparvar-Fard, M., Peña-Mora, F., Arboleda, C. A. and Lee, S., 2009b. Visualization of Construction Progress Monitoring with 4D Simulation Model Overlaid on Time-Lapsed Photographs. *Journal of Computing in Civil Engineering* 23(6), pp. 391–404.

González-aguilera, D., Rodríguez-gonzálvez, P. and Gómez-lahoz, J., 2009. An automatic procedure for co-registration of terrestrial laser scanners and digital cameras. *ISPRS Journal of Photogrammetry and Remote Sensing* 64(3), pp. 308–316.

Kaneko, S., Kondo, T. and Miyamoto, A., 2003. Robust matching of 3D contours using iterative closest point algorithm improved by M-estimation. *Pattern Recognition* 36(9), pp. 2041–2047.

Kim, C., Kim, C. and Son, H., 2013a. Automated construction progress measurement using a 4D building information model and 3D data. *Automation in Construction* 31, pp. 75–82.

Kim, C., Lee, J., Cho, M. and Kim, C., 2011. Fully Automated Registration of 3D CAD Model with Point Cloud from Construction Site. In: *Proc. 28th International Symposium on Au- tomation and Robotics in Construction, Seoul, Korea*, pp. 917–922.

Kim, C., Son, H. and Kim, C., 2013b. Fully automated registration of 3D data to a 3D CAD model for project progress monitoring. *Automation in Construction* 35, pp. 587–594.

Kropp, C., Koch, C. and König, M., 2018. Interior construction state recognition with 4D BIM registered image sequences. *Automation in Construction* 86(November 2017), pp. 11–32.

Pučko, Z., Šuman, N. and Rebolj, D., 2018. Automated continuous construction progress monitoring using multiple workplace real time 3D scans. *Advanced Engineering Informatics* 38(June), pp. 27–40.

Rusu, R. B., Blodow, N. and Beetz, M., 2009. Fast Point Feature Histograms (FPFH) for 3D registration. *2009 IEEE International Conference on Robotics and Automation* pp. 3212–3217.

Rusu, R. B., Blodow, N., Marton, Z. C. and Beetz, M., 2008. Aligning point cloud views using persistent feature histograms. In: *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 3384–3391.

Son, H. and Kim, C., 2010. 3D structural component recognition and modeling method using color and 3D data for construction progress monitoring. *Automation in Construction* 19(7), pp. 844–854.

Tuttas, S., Braun, A., Borrmann, A. and Stilla, U., 2014. Comparision of photogrammetric point clouds with BIM building elements for construction progress monitoring. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives* 40(3), pp. 341–345.

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J. and Reynolds, J. M., 2012. Structure-from-Motion ' photogrammetry : A low-cost , effective tool for geoscience applications. *Geomorphology* 179, pp. 300–314.

Zhang, C. and Arditi, D., 2013. Automated progress control using laser scanning technology. *Automation in Construction* 36, pp. 108–116.