Using Crane Cameras for Workspace Mapping and Monitoring for an Autonomous Tower Crane

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Abstract

In the context of the development of an autonomous tower crane, the ability of the crane to perceive its environment is a key aspect. To enable efficient and collision-free autonomous load transportation, an accurate and complete geometrical model of the workspace of the crane is required as basis for path planning. We introduce a concept for a crane based sensor system consisting of cameras mounted at the jib, which is used to derive the required 3D data. To evaluate the potential of this approach, we conduct a feasibility study with a focus on the accuracy of the photogrammetric 3D reconstruction of a crane's workspace. Additionally, the results are compared to reference data obtained from terrestrial laser scanning to check the completeness of the reconstruction. The results confirm that the crane camera images are suitable for the 3D reconstruction of the workspace and that the resulting data can be used as basis for autonomous load transportation.

Key Words: Autonomous Crane, Crane Cameras, Digital Elevation Model, Path Planning, Photogrammetry

1. Introduction

The construction industry is currently facing many challenges, as it not only needs to increase its productivity but also to become more sustainable at the same time. The Cluster of Excellence IntCDC (Integrative Computational Design and Construction for Architecture) tackles these issues, among other approaches, by integrating digital technologies in the planning and building processes (Knippers et al., 2021). Within this project, a cyber-physical construction platform for the automated on-site assembly of prefabricated building elements is being developed. One part of this platform is an automated tower crane that will work collaboratively with other robotic systems or humans. The automation of the crane is not only a prerequisite for such collaborative work, but it is supposed to increase the productivity at the site, as well. The latter can be achieved by the integration of the crane into a central task scheduling system and by optimizing its operations in terms of their time efficiency.

A first step towards this goal of fully autonomous load handling is the realization of autonomous load transportation between two predefined locations. To do so, the tower crane needs the ability to perceive its environment in order to be able to plan paths (Burkhardt & Sawodny, 2021) and move the load without collisions. Thus, a sensor system to perform 3D mapping and monitoring of the workspace of the crane is needed. Our goal is to develop a construction platform that can be used anywhere independently of the specific construction site, where placing sensors could be impossible, e.g. due to occlusions. That is why we aim at a sensor system attached to the crane itself. Additionally, a tower crane is an ideal sensor carrier for mapping applications, as it provides an extensive overview over the construction site.

For this reason, tower cranes are already used as sensor carriers for existing applications in research and commercial products where the mapping or monitoring of construction sites is needed. Mostly, these applications use downward facing cameras as sensors, because they capture a large part of the site at once, are cost efficient and can easily be processed with one of the many available photogrammetric software packages. One commercial product uses a single downward facing camera with a wide field of view placed at the crane's jib (Pix4D SA, 2021). The images captured during one day are processed to generate products like daily construction site overviews in form of orthomosaics or 3D models for progress monitoring. In the work of (Masood et al., 2019) 3D point clouds generated with this crane camera system are used to extract as-built point clouds of individual buildings. With the goal to monitor the progress of construction sites on a daily basis, (Tuttas et al., 2016) suggested to extend the crane camera concept to an array of cameras mounted along the jib such that they have overlapping fields of view. As a result, 3D data with higher resolution and less occluded areas can be captured. Except for 3D-model generation to capture the progress of the construction activities, other concepts use crane cameras as supporting system for the crane operator, e.g. to support blind lifts (Shapira et al., 2008) or to monitor moving objects to increase situation awareness (Chen et al., 2017).

Our investigations aim on the use of a crane-based camera system for the 3D reconstruction of the workspace for autonomous load transportation. In contrast to the previously mentioned existing applications which derive 3D models from crane camera images, the crane not only serves as a sensor carrier due to its extensive overview over the construction site, but it receives the camera data as input to the crane's control. The camera data thus enables the control to run autonomous processes such as path planning and trajectory following, because the environment with its potential obstacles can be taken into account. Compared to existing applications, this requires an increase in the temporal resolution of the derived 3D data towards real-time. Additionally, the accuracy and reliability of the data must be sufficient to ensure that the system operates securely. Taking into account the precision, with which the crane can be controlled, we require the 3D data to have an accuracy of a few centimeters.

In the following chapters, the proposed concept for workspace mapping is introduced and the corresponding crane mounted camera system is described. Subsequently, a feasibility study about the accuracy and completeness of the derived 3D data is conducted to assess the potential of our approach.

2. Materials and Methods

Our workspace mapping and monitoring system is designed as a modular system consisting of both hardware and data processing modules which can be individually adapted to the current requirements. The three main data processing modules are 3D reconstruction, collision avoidance and building element detection. The 3D reconstruction module, which is the subject of the work presented here, is responsible for the mapping of the workspace of the tower crane as base for path planning. Its output is a digital elevation model (DEM). Regarding the temporal resolution of this output, three levels of complexity with different requirements are considered. The offline approach assumes a controlled environment used only for experiments and thus does not require real-time ability of this module. On the way towards real-time ability, a quasi-online approach is being developed. It uses additional knowledge, e.g. from crane sensors, to speed up the photogrammetric processing. The most elaborated version of the 3D reconstruction module will provide an updated DEM in real-time to be used as input to an adaptive crane control.

As the main sensor system for the 3D reconstruction module, we are investigating the use of crane cameras. Our setup is similar to the one described in (Tuttas et al., 2016) and consists of five downward facing cameras mounted at the jib of a top slewing tower crane (Fig. 1). We use GigE Vision cameras with a 12 megapixel CMOS color sensor (4096x3000 pixels) with a pixel size of 3.45µm and a global shutter. To be able to reach a ground sampling distance of 1cm (pixel size projected to the ground), we choose a lens with a focal length of 16mm. The jib has a height of approximately 45m above ground and the cameras are mounted along the jib with ca. 10m distance between each other, whereas the first camera is placed close to the tower. The longer edge of the image sensor is parallel to the jib. As a result, the footprints of the cameras at the ground overlap by 75%, such that a photogrammetric 3D reconstruction of the area underneath the jib is possible with just one set of images (one image per camera, simultaneously triggered). The rotation of the crane by the incremental rotation angle α (Fig. 1) between the triggering of two sets of images generates additional image overlap in the direction of the movement. Thus, the 3D reconstruction of the whole workspace of the crane is possible. The cameras are mounted in a weather-proof housing and are powered via Power over Ethernet (PoE). They are also controlled and triggered via Ethernet from a computer on the ground, where the image processing is performed as well.

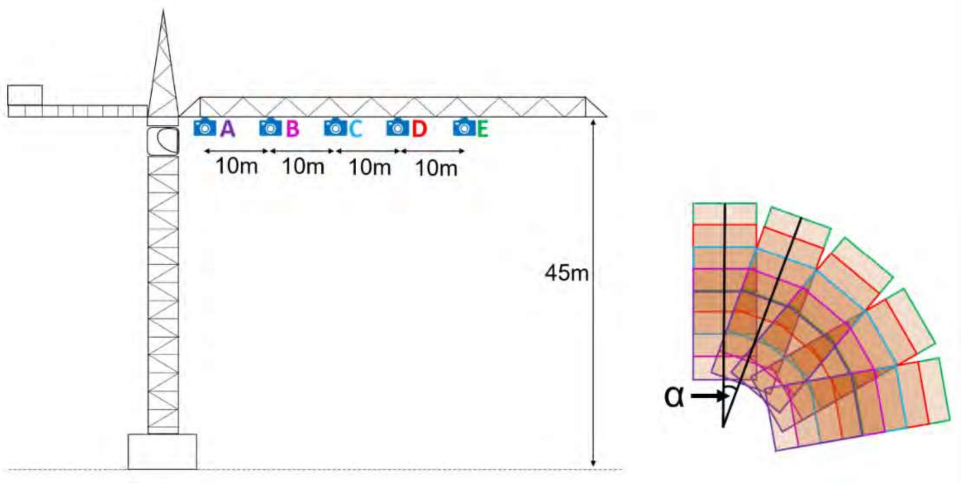

Figure 8: Setup of the crane cameras at the tower crane (left) and top view of the image footprints at the ground, which result from the rotation of the crane by the angle α between triggering two sets of images (right). The colors of the rectangles correspond to the respective cameras.

2.1 Feasibility Study

Since autonomous applications do not only have high requirements for the up-to-dateness of the data used, but also in particular for their quality, we conducted a feasibility study to evaluate the achievable quality of a DEM generated by our crane camera system. For this study, we consider the offline approach of the 3D reconstruction module, as it serves as our baseline. To assess the potential of the crane camera system, the quality of the DEM in terms of accuracy and completeness is analyzed based on an image block captured during a full rotation of the tower crane with α=5°. Figure 2 shows the test site where we performed these measurements. Its dimension is approximately 65m by 25m. To be able to georeference the data and to evaluate the accuracy of the photogrammetric reconstruction, 12 control points and 14 check points marked with photogrammetric targets are equally distributed over the whole test site (Fig. 2). Their coordinates were derived with total station measurements.

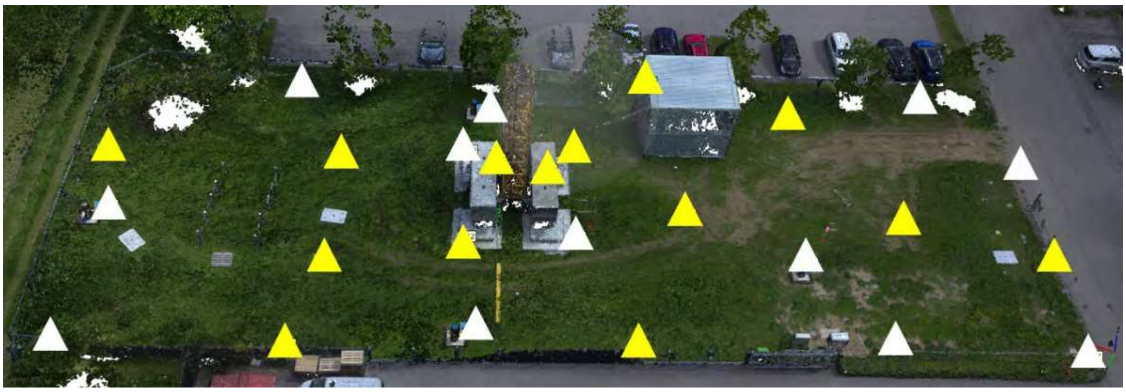

Figure 9: Photogrammetric point cloud of the test site with the tower crane. The white triangles mark positions of control points and the yellow triangles mark check points.

The pre-calibrated images are processed with the software Agisoft Metashape (Agisoft, 2021). For the evaluation of the accuracy of the resulting dense photogrammetric 3D point cloud, the root-mean-squared-error (RMSE) of the check point coordinates is considered. To be able to evaluate the completeness of the DEM, it is compared with reference data captured with terrestrial laser scanning (TLS). For this, a georeferenced DEM with a raster width of 10cm for both photogrammetric and TLS data is generated with OPALS (Pfeifer et al., 2014). The DEM contains the maximum Z value for each grid cell. As a measure for comparison, we consider their absolute difference, namely the difference in height per grid cell.

3. Results

For the described configuration, the RMSE of the check point coordinates is 2.7cm. As observable from Table 1, a similar accuracy is still reached if the amount of images is significantly reduced by increasing α from 5° up to 50°.

Table 1: RMSE at check points for different rotation angles and respective number of images for a full image block (360° rotation of the crane).

α	**5°**	**10°**	**20°**	**35°**	**50°**
Number of images	360	180	90	52	36
RMSE [cm]	2.7	2.6	2.7	2.1	2.4

The comparison of the photogrammetric DEM and the reference DEM in Figure 3 confirms that accuracies of less than 5cm are reached for the solid objects in the scene (e.g. fences, crane foundation, container), which are considered as the obstacles relevant for path planning.
Regarding the completeness of the data, the comparison with the TLS reference data in Figure 3 shows that no relevant objects are missing. Also thin objects like the fence (see Fig. 3 a, white line surrounding the site) or the cable (b) are reconstructed, if they have enough contrast to their background.

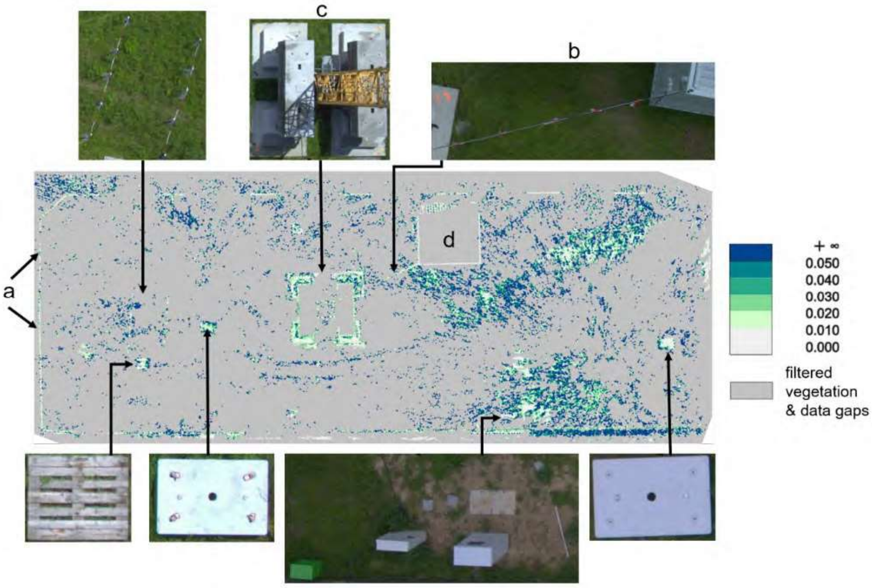

Figure 10: Evaluation of the completeness and accuracy of the DEM: Absolute difference of photogrammetric (α=5°) and reference (TLS) DEM in [m]. The snippets from crane camera images indicate the location of the solid objects present in the scene.

Bigger differences of more than 5cm (blue areas in Fig. 3) are mainly caused by vegetation, for which photogrammetric reconstruction works poorly in general, e.g. due to movement caused by wind. Because the whole test site is predominantly covered with high grass which distorts the results, cells with DEM differences of more than 10cm are filtered out for visualization purposes. The top of the crane's fundament (Fig. 3, c) and of the container (Fig. 3, d) were not in the field of view of the TLS, thus there is no data available for differencing. In contrast to the behavior of the check point accuracy shown in Table 1, the completeness of the 3D reconstruction significantly decreases when increasing α. In this case, particularly smaller objects like the fence are no longer reliably reconstructed, because they are captured in fewer images and only from increasingly varying perspectives.

4. Discussion

Using an array of crane cameras to generate a DEM of the crane's workspace as basis for the autonomous operation of the tower crane leads to promising results. Our first study shows that accuracies of a few centimeters are reached for the relevant parts of the construction site, which meets our requirements. To be able to meet the requirements of autonomous operations not only in terms of DEM quality but also regarding the temporal resolution, the 3D reconstruction module is to be further developed with the goal of real-time operation. As the results of our tests with a decreased number of images are promising regarding their accuracy, the reduction of the amount of data to be processed can play an important role to speed up the processing for the quasi-online approach. However, to be able to reach true real-time capability it is currently investigated if a similar DEM quality can be reached with 3D reconstruction results of Visual SLAM methods like for example LDSO (Gao et al., 2018). The results presented in this paper are the baseline for these investigations. Finally, the crane camera based 3D reconstruction module will be integrated in the crane control system. It will provide the DEM as input for the path planning algorithm and thus enable collision-free autonomous load transportation.

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