LEAN AND BIM-BASED FLIGHT PLANNING FOR AUTOMATED DATA ACQUISITION OF BRIDGE STRUCTURES WITH LIDAR UAV DURING CONSTRUCTION PHASE

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Abstract

In the execution phase, the acquisition of information is crucial. A key challenge in BIM-based flight planning with unmanned aerial vehicles (UAV) is designing, simulating, verifying, possibly optimizing and executing the model-based acquisition based on a 4D-BIM. The presented "lean data acquisition process" (LDAP) triggers the acquisition event-based and demand-oriented (Pull principle) for relevant activities and exclusively acquires the associated components. Then, the LDAP comprises model-based planning (Plan), realistic simulation (Do), validation and uniform evaluation (Check) as well as adjustment (Act). This ensures that only relevant data and information from the construction process are acquired.

Introduction

Problem Statement

The "Masterplan BIM Bundesfernstraßen" (BMDV, 2021) of the Federal Ministry of Transport and Digital and Infrastructure (*Bundesministerium für Digitales und Verkehr*, BMDV) of the German Federal Republic presents the regulatory framework for the application of the BIM methodology on a nationwide basis for public highway infrastructure projects in Germany. In the BIM methodology, the life cycle of a BIM stretches from the design phase through the execution phase to the operation and maintenance phase (Glock, 2018). First extensive practical experience is currently being gathered for the design phase in infrastructure construction (Liebich et al., 2018) and will be standardized, e.g., by further development of the IFC (Industry Foundation Classes) format for the infrastructure (buildingSMART, 2022). The BIM methodology is currently still being tested in infrastructure and civil engineering in execution (Schneider & Tschickardt, 2021) and maintenance phases. In the construction phase, and particularly in infrastructure construction, there is a high frequency of decision making, as construction processes are complex and heterogeneous due to one-off production. In both lifecycle phases, it is crucial to constantly enrich and update the BIM with current information about the site condition of the bridge structure during the construction and operation phases. Automated data acquisition during the construction phase is indispensable to generate the necessary information to support rapid decision making, e.g., within construction management.

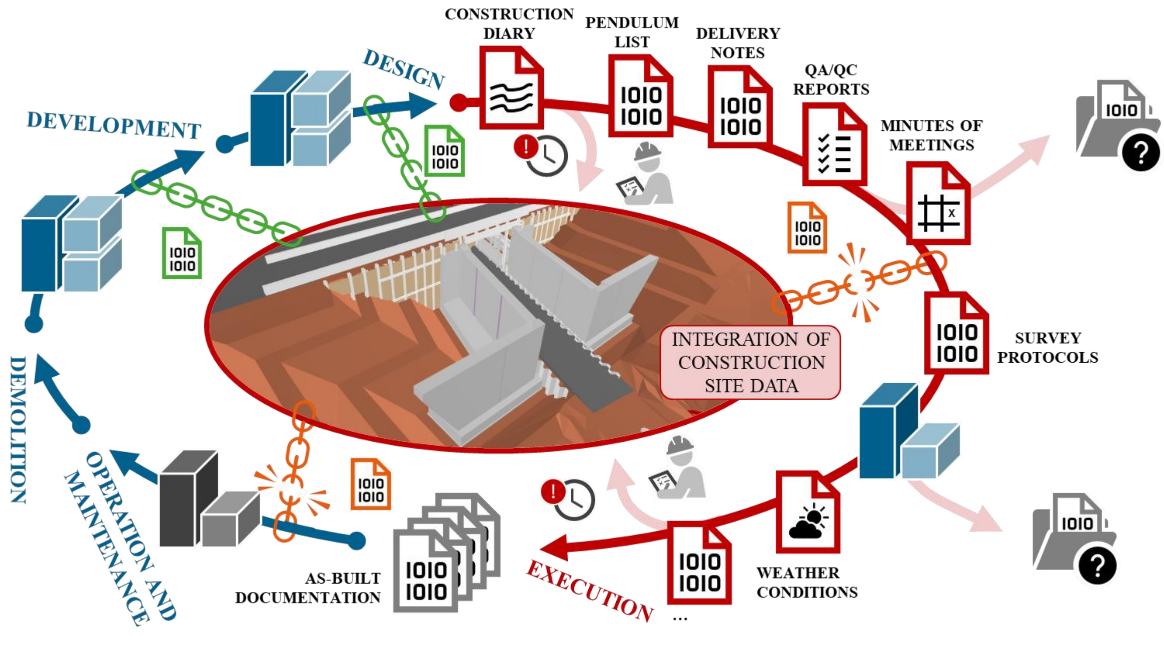

Figure 1: Missing data and information during the information life cycle of a bridge structure

Figure 1 displays the problem statement regarding the missing data and information during the information life cycle of a bridge structure, especially in the construction phase. The data and information are mostly linked to the BIM throughout the development and design phase. In contrast, data acquisition and documentation of the construction progress are still carried out in a predominantly manual, laborious, and error-prone process. Information such as construction diaries, pendulum lists, delivery notes, quality assurance/quality control (QA/QC) reports, minutes of meetings, weather conditions, survey protocols and others are generated daily at a construction site. This data and information are acquired by various possible databases. Some will be handwritten, some will be already within a machine-readable tool (i.e., Excel) and some will be lost due to human errors. First approaches of research based on automated data acquisition instigate the use of photogrammetric methods and/or laser scanning (light detection and ranging, "LiDAR") and the evaluation of the required information during the execution phase. UAVs equipped with LiDAR sensors can support the documentation and reconstruction of the construction site. Significant advantages include easier access to most parts of the structure, higher coverage and accuracy, improved efficiency and increased safety by reducing the likelihood of falling hazards. Today, data acquisition is mostly done manually, whereby the quality of the acquired data and the coverage of relevant structure areas mainly depend on the person's experience (Biswas et al., 2015). A systematic design and planning of the data acquisition is not carried out properly. Planning and validating the data acquisition helps to ensure the complete acquisition of the relevant components of the structure for a specific time.

However, little research has been done yet on how data acquisition planning can be performed automatically based on the BIM (Glock et al., 2021). Semantically rich BIMs (i.e., 4D-BIM) can be used for the automation of the planning process. Furthermore, the 4D-BIM should be updated with recent information aggregated from acquired data should provide an efficient source of information in the construction phase.

Currently, the data of a manually planned acquisition and implementation lacks accuracy and degree of coverage (Zhang et al., 2016). UAV-assisted data acquisition can already support this, but to date, data acquisition planning has been labor-intensive, error-prone, and inefficient. The surveyor must manually extract information from conventional 2D drawings or unrich geometric models, identify the location of relevant components of the structure and finally create a plan for data acquisition. This leads to a reduction in cost-effectiveness, a "too much" or "too little" of data and a lack of efficiency (Biswas et al., 2015).

Furthermore, the acquisition of construction-relevant data has been handled poorly up to these days. According to a survey (Ailland, 2013) among construction managers, the period from manual data acquisition of construction-relevant data to processing is one week in 65% of the cases. The construction diaries are only kept daily by 23% of the respondents. This long period makes it even more difficult to obtain an up-to-date picture of the construction processes. Automation of construction documentation can relieve the construction management regarding the acquisition effort. Efficient data acquisition can be achieved through a preceding planning optimization process called "Planning For Scanning" (P4S) (Aryan et al., 2021). A key challenge is to first design, simulate, verify, possibly optimize, and finally execute a model-based and UAV-assisted automated data acquisition based on the 4D-BIM.

Research Objectives

The presented research aims to evaluate current standards and company reporting systems for cataloging and categorizing collectible data on the construction site. This includes the evaluation of current processes of bridge construction, to determine which processes can be assisted with UAV automated data acquisition. The second aim is to incorporate the pull principle and the continuous improvement (PDCA) being part of the lean methodology in the design, planning, and execution of data acquisition in the construction phase of bridge structures. The research intends to focus on LiDAR-generated point clouds instead of photogrammetry-based point clouds because accuracy plays a crucial part in construction site documentation. First, the research focuses primarily on the construction phase. The data acquisition will be initially triggered event-based and demand-oriented according to the pull principle, for specific scheduling processes, e.g., when a structure part or scaffolding/formwork is completed or when the inspection of a structural component is due. The respective information on due dates is derived from existing BIMs of the bridge structure for the construction process, which provide specific information as a 4D-BIM.

At the beginning of the automated model-based planning (1), relevant viewpoints, so-called "points of interest" (POI), need to be identified from the 4D-BIM. This can be done based on the vendor-neutral and technology-open data format IFC, as this is used for standardized data exchange in the construction industry or in a 4D-Software. The flight plan is the connection of the POI along an optimized path and includes the location of the take-off and landing spots, which can be defined manually. To determine the optimal flight route, various search algorithms can be used to find the most cost-effective and/or shortest route with the fewest obstacles between these POIs. The flight plan will also be validated (2) in a simulation software to exclude collisions with the bridge structure and to be able to check the quality of the acquired data in advance. The validation (3) of the synthetic data acquisition is to be carried out via quality criteria, yet to be developed, which should be generally valid and not trade-specific for a LiDAR-based UAV data acquisition. This should include, for example, sufficient accuracy (Level of Accuracy, "LOA") (Tang & Alaswad, 2012), density (Level of Detail, "LOD") (Tang & Alaswad, 2012) and surface completeness (Level of Completeness, "LOC") (Biswas et al., 2015). The adjustment (4) of an inaccurate flight plan should be performed continuously and iteratively until all quality criteria are sufficiently fulfilled.

The design of the flight plan is continuously optimized as part of a continuous improvement process with the sub-steps Plan - Do - Check - Act (PDCA). The optimization is performed by the following sub-steps:

(I) automated and model-based planning of the flight plan for data acquisition (Plan),

(II) a simulation of the data acquisition considering the typical characteristics of the sensors and UAVs as well as the local conditions (Do),

(III) a validation and uniform evaluation with key indicators of the simulation (Check), and

(IV) an adjustment of the designed data acquisition flight plan (Act).

By implementing the pull principle and continuous improvement (PDCA) of the lean methodology as part of the data acquisition planning, it can be ensured that only the data of sufficient quality is acquired in a goal-oriented manner. Also, the 4D-BIM can be updated to reflect the construction progress or the current state of the bridge structure.

The presented approach is particularly suitable for infrastructure projects, such as bridge and road construction in open space. Furthermore, structures such as football stadiums, large factory halls or offshore wind farms/production platforms, and major concrete constructions for buildings are also feasible to a specific degree. Interior construction and confined spaces, on the other hand, are not implementable, because the UAV has a certain geometrical dimension and the reception signal must be given at all times.

Background and literature review

Effective and efficient data acquisition can be achieved through a prior planning optimization process, which can be referred to as P4S (Aryan et al., 2021) as stated before. Therefore, in this chapter, lean construction basics will be introduced and furthermore the state of research in the fields of automated UAV-based acquisition as well as its planning is being analyzed.

Lean construction

A process is a sequence of consecutive actions. The current processes and framework conditions in the construction industry often lead to schedule and cost overruns as well as to construction defects that can only be eliminated at great expense. This happens even in projects that are relatively well organized and despite the great efforts of the project team. The main reason for this is the traditional linear planning process (Spieth et al., 2016). Lean construction has been one of the innovative methods to overcome the weaknesses of the conventional approach. Lean construction incorporates the following principles (Singh & Kumar, 2020): Specification of the value from the customer's point of view, Just-In-Time approach, Continuous Improvement (PDCA), Value stream-oriented approach, Flow principle and Pull principle instead of Push.

Lean construction is a philosophy based on the lean principles of Taiichi (Toyota Production System) (Saieg et al., 2018) and had been developed as lean manufacturing principles from the automotive sector and was further developed as lean construction and lean philosophy. The goal of lean construction is thus continuous improvement, waste reduction and high-quality management of projects and supply chains, as well as improved communication on the construction site and within the team. The approach is based on the idea of continuously improving the entire project and its sub-processes collaboratively in planning and execution. This needs accessible and transparent information and data management. Only then excellent processes on the construction site can be achieved.

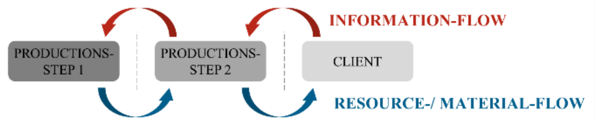

Figure 2: Pull principle (Günther & Tempelmeier, 2012)

According to (Günther & Tempelmeier, 2012) the customer triggers the production process with a demand-oriented order, so that production is customer-oriented. Production is structured according to the pull principle, so that each production step triggers production for the respective upstream step. This approach creates a demand pull. The order or demand of information is passed on from production step to production step antiparallel to the material flow (Figure 2). Figure 3 shows the PDCA cycle that can be used to successfully implement continuous improvement. It describes the sequence by which activities can be carried out and subsequently evaluated and improved. The cycle enables constant improvement of the activity by constantly going through the cycle. The application of the PDCA cycle in data acquisition planning is promising, as it ensures that data acquisition activities on the construction site are carried out efficiently and their duration is reduced to a minimum.

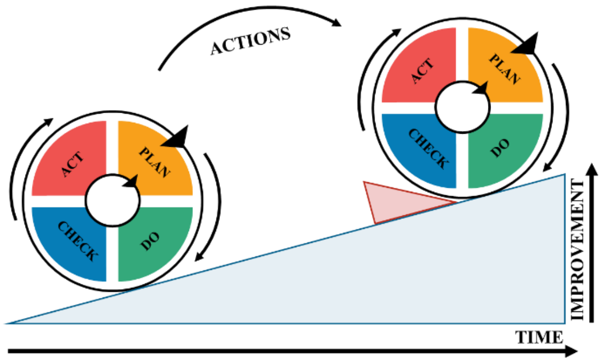

Figure 3: Continuous improvement (Spieth et al., 2016)

Automated and UAV-based data acquisition

As stated before due to the labor-intensive, error-prone, and inefficient flight planning, it is necessary to optimize the current manual data acquisition process and to automatically generate the flight plan for data acquisition based on a BIM with optimal coverage with lean principles.

The authors Aryan et al. provide an overview of previous UAV-based P4S approaches (Aryan et al., 2021). In the approach by Bolourian & Hammad the shortest path of the flight plan is computed using the genetic algorithm, obstacle avoidance using the A*-algorithm, and ray tracing calculation for the optimal coverage during acquisition

based on a 3D model. The POIs for the UAV mission are determined manually (Bolourian & Hammad, 2020).
The concept of Morgenthal et al. proposes a UAV-based bridge inspection, in which the POIs are first determined with a defined distance to the entire structure and a grid lying on the structure shell, which must be flown by the UAV. The basis is a 3D model or an initial manual flight, which was transformed into a polygon mesh (Morgenthal et al., 2019). The authors point out further research needs, especially in intelligent flight planning to consider quality criteria of the information to be generated as well as environmental and technological effects in UAV-based data acquisition. The co-author Debus & Rodehorst extend their method in that the bridge inspection is based on different levels of interest (LOI) (Debus & Rodehorst, 2021b). For each defined LOI, viewpoints are computed with the camera field of view that sufficiently covers the corresponding LOI, while the number of images is reduced to a minimum. Based on this, the authors use the "greedy algorithm" to find the selection of viewpoints that cover the entire structure. Each of the calculated viewpoints is at a defined distance from the surface of the structure. The authors do not provide any information on possible validation of the flight plan, nor on the format and interfaces to the UAV. Debus & Rodehorst introduce quality criteria for planning the flight path of image-based as-built inspection for the evaluation of flight path planning (Debus & Rodehorst, 2021a). For each quality criterion, a procedure is proposed that measures the degree of fulfillment of the quality requirements. The proposed quality criteria are promising for image- and UAV-based acquisition but need further development for LiDAR-based acquisition.
For UAV acquisition missions, the identification of POIs to be flown is crucial and their automated derivation from the BIM is a core element of this research. The first approach by Biswas et al (Biswas et al., 2015) and Biswas (Biswas, 2019) focuses on the acquired surfaces of the building components when planning single standpoints of a terrestrial laser scanner (TLS), since not only a single point must have sufficient accuracy, but also the acquisition of as many surfaces of building components as possible. Fully automatic coverage planning can be supported by BIMs according to the review of Aryan et al. (Aryan et al., 2021), although only the two methods Biswas et al. (Biswas et al., 2015) and Heidari & Varshosaz (Heidari & Varshosaz, 2016) have proposed a P4S method for covering surfaces within a BIM. Heidari & Varshosaz (Heidari & Varshosaz, 2016) discretizes surfaces of components with homogeneously distributed point sets and reduces the surface coverage problem to point coverage. In contrast, Biswas et al. (Biswas, 2019) tries to determine the actual surface coverage of the components. From the author's point of view, the use of the surface of the components is advantageous, as it allows a higher accuracy to be achieved since this can be matched with the surfaces of the BIM components. Also, surfaces can be derived from the IFC file and the BIM in the 4D-Software.
An approach for automatic indoor data acquisition using LiDAR sensors on an Unmanned Ground Vehicle (UGV) is presented in (Ibrahim et al., 2019). This approach is based on a 3D model, although 2D site plans are generated and used for the planning. Ibrahim & Golparvar-Fard build on this method and extend it for outdoor data collection using UAV and photogrammetry (Ibrahim & Golparvar-Fard, 2019). The developed approach first generates standard flight planning templates, which can subsequently be manually adjusted with a visual assessment and safety check. The application of a multi-criteria genetic algorithm enables the optimization of flight planning. The results of the executed and simulated data acquisition are not analyzed at first. Ibrahim et al. then present metrics and methods for evaluating BIM-supported data acquisition planning, which can be applied to camera-equipped UAVs or ground vehicles (Ibrahim et al., 2021). The metrics and methods of the authors consider six criteria: (1) visual coverage of components in acquired photos, (2) resolution of each captured component using the surface sampling distance (SSD) represented by each back-projected pixel, (3) alignment of the camera position with the component, (4) expected stability of the reconstruction of the components, (5) regulatory compliance (VLOS), and (6) battery power during the data acquisition. The metrics are evaluated in different experiments and can be used for the verification of BIM-based planning of data acquisition from camera-equipped systems.

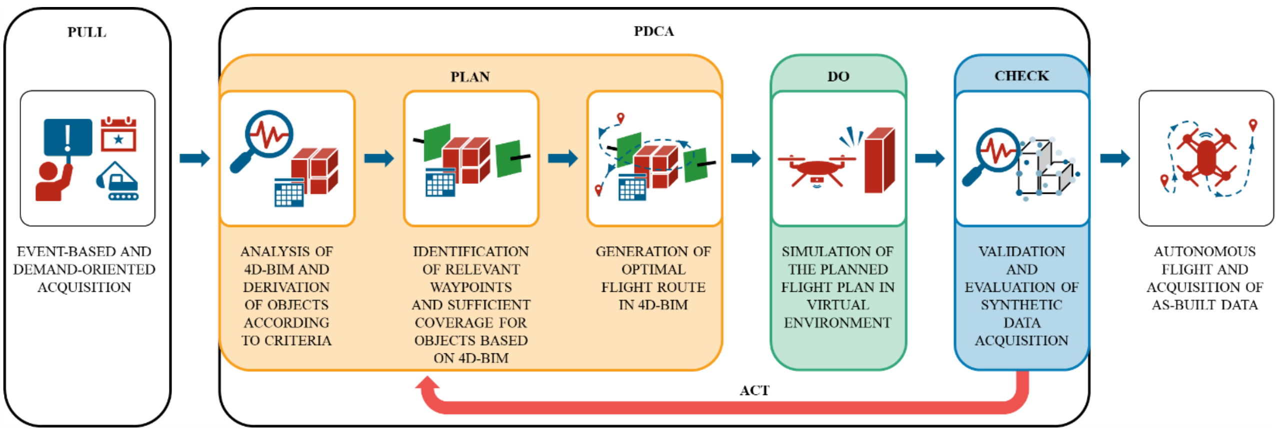

Figure 4: Concept for the lean data acquisition process (LDAP)

Freimuth & König follow a different approach and derive optimized, oriented bounding volumes of the objects contained in the BIM, the data acquisition planning is then done by a grid lying on the building hull with a corresponding safety distance (Freimuth & König, 2015). Later, approaches are investigated where the possible navigation volume is described by not occupied voxels, from which the flight path planning is derived (Freimuth et al., 2017). The concept is then further extended in (Freimuth & König, 2018) and (Freimuth & König, 2019). The UAV uses built-in cameras during the flight to detect and fly around obstacles that are not included in the BIM. Furthermore, an additional software component compares the acquired point cloud data with the BIM during the aerial flight and thus enables an automatic object-related completeness check. The approach was evaluated in simulations to be executable on real UAVs. In contrast to Freimuth & König, in the presented research the POIs are derived based on the semantic and geometric information of the 4D-BIM via the IFC interface (Krijnen, 2021) (or in a 4D-Software) and the surfaces of the components. In addition, the simulation of the acquired LiDAR-based point clouds and an analytical evaluation and completeness check of the acquired data are performed to fulfill quality criteria and to optimize the flight planning before the actual flight.

The approaches of Hamledari et al. (Hamledari et al., 2018), (Hamledari et al., 2021) build on the approach of Lin et al (Lin et al., 2013) and use a 4D-BIM in IFC as a basis already. The activities and associated components for which data acquisition is required are manually filtered in the IFC using a simple interface, e.g., in terms of completion date or responsible sub-contractor. Subsequently, the components are displayed in the freely navigable space of the floor plan to generate a series of POIs that ensure complete coverage of the identified elements. Following this, the shortest distance of the data acquisition positions was calculated. The method was tested using real aerial flight, but no simulation or verification of the proposed acquisition planning was performed. In this presented research, a simulation and evaluation of the data acquisition planning will be performed, including verification of the completeness and quality of the acquired data to guarantee data quality.

The comprehensive literature review of completed and still ongoing research projects shows that UAV-based data acquisition should be automated to determine POI and flight plan based on 4D-BIMs and to design, simulate and validate the flight plan in an automated manner. Notable advantages here include that only the necessary data is acquired and the minimization of the intervention in the operative day-to-day business. The generated flight route should be optimized considering flight duration, battery capacity, degree of coverage of the components, the UAVs movement options, expected weather conditions during the planned flight, payload and take-off weight, as well as the size of the UAV. In addition, research is needed on how POIs can be determined from 4D-BIMs in IFC (or in 4D-Software) and which methods are suitable for deriving POI and flight plans from this in an automated data acquisition planning. Furthermore, an evaluation of the flight plan with real environmental conditions is necessary to identify further influences and to integrate them into the design that has a decisive influence on the data acquisition. Currently, there is a lack of generally accepted quality criteria for UAV-based LiDAR data acquisition that can be used to check the acquired data in terms of coverage, completeness and accuracy and the flight route in terms of POI must be flown and flight duration.

Concept for model-based flight planning to automate data acquisition

An approach to automate the data acquisition planning in bridge construction is presented. An overview of the concept for the lean data acquisition process (LDAP) is provided in Figure 4.

Initiation of data acquisition

The main hypothesis of our research is that any data acquisition should serve a certain information need and use case. The initial phase of the research involves cataloging and categorizing the data and information to be acquired according to guidelines and standards as well as companies internal reporting system. This includes the evaluation of current processes of bridge construction, to determine which processes can be assisted with UAV automated data acquisition. After cataloging and categorizing, the data acquisition will then be initiated for example, by events in the construction progress, e.g., the scheduled construction of components. This procedure ensures that only relevant data is acquired during the LDAP. The LDAP involves flight planning (Plan), simulation of the data acquisition (Do), assessment of the data acquisition process (Check) and adjustment of the flight path (Act).

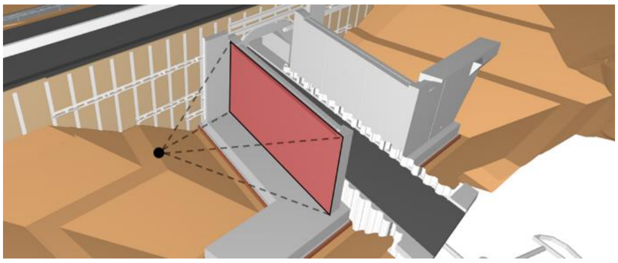

Figure 5: Derivation of POIs

Plan – Flight planning

The derivation of the flight plan for the semi-autonomous aerial survey is done from the 4D-BIM in the vendor-neutral and open data format IFC or in a 4D-Software (see Figure 4). Based on the 4D-BIM, relevant components are identified event- and demand-oriented by the associated processes analogous to (Hamledari et al., 2021) and POIs are derived for the UAV-based data acquisition. This is done by deriving the component surfaces of the relevant operations and the corresponding IFC entities (IfcTask, IfcBuldingElement, IfcCartesianPoint). The premise for the calculation of the POIs is, among others, the configurations of the laser scanner (vertical and horizontal field of view).

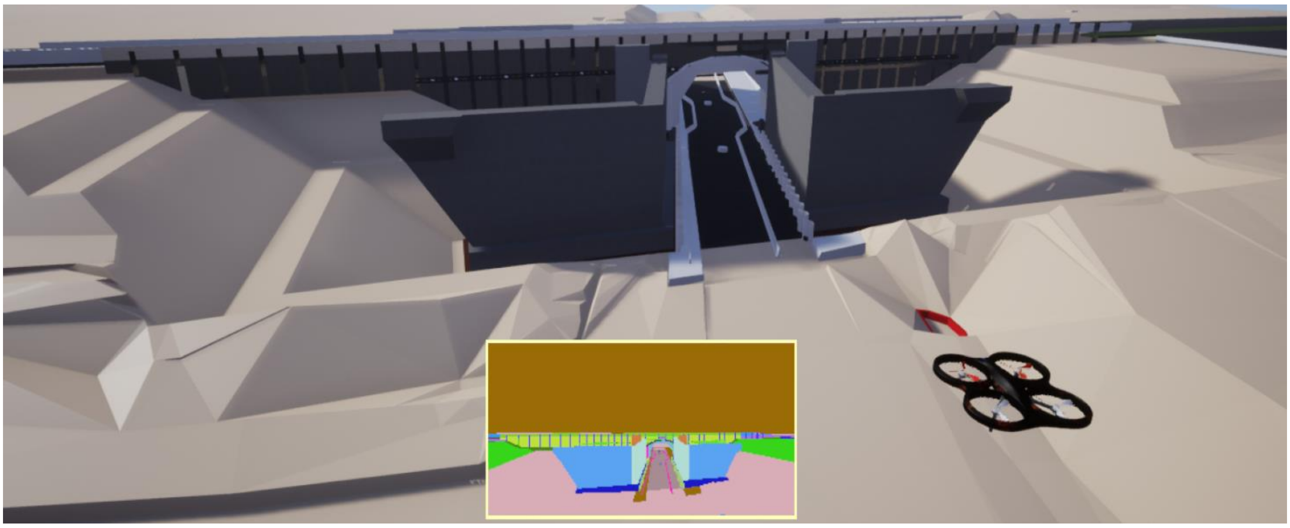

Figure 6: Simulation of UAV-based data acquisition

In this way, it can be ensured that the flight path to be flown provides optimum LiDAR coverage and quality during the data acquisition process. The flight plan will then be computed using search algorithms.

Do – Simulation of the data acquisition

A simulation of the flight plan is performed with the software AirSim (Shah et al., 2017) to validate the data acquisition mission regarding the quality of the acquired data. LiDAR sensors are carried by the simulated UAVs that follow the planned flight path and continuously acquire synthetic data. There is no need for registration of the acquired synthetic data because all points are transformed according to the position of the UAV and referenced to a common coordinate system. In addition to the real color values, the labels corresponding to the component classes are also acquired. The simulation reports contain information about the measured power consumption, the mission duration, and the captured segmented point cloud. The simulation can consider real aerodynamic behavior and possible disturbances. Disturbances occur, among others, in the form of gusts that can temporarily displace the UAV and in the form of distorted GNSS reception that leads to inaccurate position measurements.

Check – Assessment of the data acquisition

The simulation is followed by the evaluation of the aerial survey. Here, the methods of Debus & Rodehorst and Ibrahim et al. (Debus & Rodehorst, 2021a; Ibrahim et al., 2021) are used and extended concerning the acquisition technology. Statistical methods are used to determine the quality criteria (LOC, LOA and LOD) of the synthetic point cloud to ensure the correct requirements of each component. The following criteria also contribute to the evaluation of the flight plan: the objective of the data acquisition, i.e., construction progress monitoring; collision avoidance, for visibility of UAV and distance compliance check due to regulations; environmental influences, e.g., wind; and UAV data, i.e.: flight speed, positioning accuracy and GNSS coverage.

The procedure of the automatically designed, simulated, and validated data acquisition process shall be performed continuously until the desired results are achieved in the simulation. This enables the planning of an automated and LiDAR-supported UAV data acquisition. The UAV is then able to operate (partially) autonomous based on the flight plan, which exclusively acquires the components in the desired quality, sufficient accuracy, density and completeness. The comparison between the as-designed, as-simulated and as-flown flight plan can also contribute important knowledge for the optimization of future data acquisition planning.

Act – Adjustment of the flight path

An adjustment to the flight plan can be made if the evaluation of the simulation process reveals that the flight plan is inadequate in terms of flight parameters or data quality. If the flight duration exceeds the flight time limited by the battery capacity, for example, a return to the launch site for a battery exchange must be planned. In addition, weather conditions or local conditions may result in the need to adjust the flight plan. If the quality of the data in the acquisition is judged to be insufficient, e.g., in terms of coverage or density (see Figure 7), the POIs must be adjusted, and additional POIs may also have to be added. The adjusted flight plan can then be transferred to the UAV for semi-autonomous flight data acquisition.

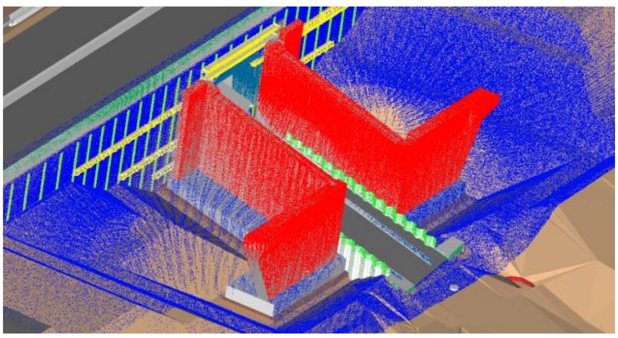

Figure 7: Synthetic data acquisition with the segmented point cloud.

Semi-autonomous flight data acquisition

Based on the LDAP, the semi-autonomous aerial survey can now be performed. Despite a careful realistic simulation of the aerial mission, unexpected obstacles may occur on the UAV's flight path. Therefore, it is necessary that the UAV itself is equipped with collision avoidance systems and can independently detect and avoid obstacles. In addition, the intervention of the UAV pilot is necessary in individual cases to resolve exceptional situations.

Conclusions and Outlook

This paper proposed a novel approach for data acquisition, the so-called LDAP (lean data acquisition process). The UAV-based data acquisition process is initially event-based and demand-oriented triggered and most importantly process-related, considering the pull principle and continuous improvement according to the PDCA cycle. The step of cataloging and categorizing collectible data and the determination of which processes can be assisted by a UAV has not been done yet. The flight plan is first automatically planned based on the 4D-BIM in the IFC format or in a 4D-Software, then realistically simulated, validated, uniformly evaluated and adjusted if needed. This concept ensures that only relevant data and information from the construction process are acquired.

The acquired data can then be used to update the 4D-BIM (especially scheduling processes) with the component-specific information. This can be done by detecting surfaces within the acquired data and matching them with the 4D-BIM to confirm whether the component is present or not. This allows an efficient process of construction progress control. Furthermore, the acquired data can be used to geometrically update the 4D-BIM, for example using IfcOpenShell (Krijnen, 2021). This ensures the generation of accurate as-built models for the operation phase.
In addition, the generated synthetic data from the simulation and the realistic flights can be used as training data for the machine learning methods (Scan2BIM) for objects detection or other purposes.

The presented novel approach is currently being implemented successively, with the focus on UAV flight planning and simulation. Further research tasks include firstly cataloging and categorizing the data and information which are generated on construction sites and could be acquired by UAVs based on the 4D-BIM. This includes the definition of quality criteria such as LOC and LOD which specific required values to fulfill subsequent processes. Secondly, the elaboration and implementation for geometrically updating and semantically enrichment of the 4D-BIM for construction progress control. The updated model provides the ideal prerequisite for the operation and maintenance phase. The approach ensures automated and quality-assured data acquisition at short cycle intervals, which is beneficial not only for project management of the construction but also for the operation and maintenance phase, as the as-built model represents the actual built situation.

Acknowledgment

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References

Ailland, K. (2013). Ereignisbasierte Abbildung von Bau-Ist-Zuständen [Dissertation, Bauhaus-Universität Weimar, Weimar].

Aryan, A., Bosché, F. & Tang, P. (2021). Planning for terrestrial laser scanning in construction: A review. Automation in Construction, 125(W2), 103551. https://doi.org/10.1016/J.AUTCON.2021.103551

Biswas, H. (2019). Automatic Planning for Scanning: Optimizing 3D Laser Scanning Operations Using BIM and TLS. International Journal of Computer Science (IAENG), 46(3), 1–9.

Biswas, H., Bosché, F. & Sun, M. (2015). Planning for Scanning Using Building Information Models: A Novel Approach with Occlusion Handling.

BMDV. (2021). Masterplan BIM - Bundesfernstraßen.

Bolourian, N. & Hammad, A. (2020). LiDAR-equipped UAV path planning considering potential locations of defects for bridge inspection. Automation in Construction, 117, 103250. https://doi.org/10.1016/j.autcon.2020.103250

buildingSMART. (2022). Industry Foundation Classes (Version 4.3) [Computer software]. https://standards.buildingsmart.org/IFC/DEV/IFC4_3/

Debus, P. & Rodehorst, V. (2021a). Evaluation of 3D UAS flight path planning algortihms. Remote Sensing and Spatial Information Sciences, XLIII-B1-2021, 157–164.

Debus, P. & Rodehorst, V. (2021b). Multi-scale Flight Path Planning for UAS Building Inspection. In Proceedings of the 18th International Conference on Computing in Civil and Building Engineering (Bd. 98, S. 1069–1085). Springer International Publishing. https://doi.org/10.1007/978-3-030-51295-8_74

Freimuth, H. & König, M. (2015). Generation of waypoints for UAV-assisted progress monitoring and acceptance of construction work. In Proceedings of the 15th International Conference on Construction Applications of Virtual Reality (CONVR).

Freimuth, H. & König, M. (2018). Planning and executing construction inspections with unmanned aerial vehicles. Automation in Construction, 96, 540–553. https://doi.org/10.1016/j.autcon.2018.10.016

Freimuth, H. & König, M. (2019). A Framework for Automated Acquisition and Processing of As-Built Data with Autonomous Unmanned Aerial Vehicles. Sensors (Basel, Switzerland), 19(20). https://doi.org/10.3390/s19204513

Freimuth, H., Müller, J. & König, M. (2017). Planning UAV-Assisted Visual Inspections of Construction Sites. Proceedings of the Joint Conference on Computing in Construction (S. 161–168).

Glock, C. (2018). Digitalisierung im konstruktiven Bauwesen. Beton- und Stahlbetonbau, 113(8), 614–622. https://doi.org/10.1002/best.201800021

Glock, C., Kaufmann, F. & Tschickardt, T. (2021). Drohnenbasierte Erfassung von as-built Modellen zur Automatisierung von Prozessen des digitalen Planens und Bauens im Brückenbau. DigiTraVe - Fachtagung über Planung, Bau, Betrieb von Brücken, Tunneln, Straßen digital (S. 367–374).

Günther, H.-O. & Tempelmeier, H. (2012). Produktion und Logistik (9. Aufl.). Springer-Lehrbuch. Springer.

Hamledari, H., Davari, S., Sajedi, S. O., Zangeneh, P., McCabe, B. & Fischer, M. (2018). UAV Mission Planning Using Swarm Intelligence and 4D BIMs in Support of Vision-Based Construction Progress Monitoring and As-Built Modeling. In Construction Research Congress 2018 (S. 43–53).

Hamledari, H., Sajedi, S., McCabe, B. & Fischer, M. (2021). Automation of Inspection Mission Planning Using 4D BIMs and in Support of Unmanned Aerial Vehicle–Based Data Collection. Journal of Construction Engineering and Management, 147(3), 4020179. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001995

Heidari, M. & Varshosaz, M. (2016). Optimal Placement of a Terrestrial Laser Scanner with an Emphasis on Reducing Occlusions. The Photogrammetric Record, 31(156), 374–393. https://doi.org/10.1111/phor.12162

Ibrahim, A. & Golparvar-Fard, M. (2019). 4D BIM Based Optimal Flight Planning for Construction Monitoring Applications Using Camera-Equipped UAVs. In Computing in Civil Engineering 2019 (S. 217–224). American Society of Civil Engineers. https://doi.org/10.1061/9780784482438.028

Ibrahim, A., Golparvar-Fard, M. & El-Rayes, K. (2021). Metrics and methods for evaluating model-driven reality capture plans. Computer-Aided Civil and Infrastructure Engineering. https://doi.org/10.1111/mice.12693

Ibrahim, A., Sabet, A. & Golparvar-Fard, M. (2019). BIM-driven mission planning and navigation for automatic indoor construction progress detection using robotic ground platform. In Computing in Construction, Proceedings of the 2019 European Conference on Computing in Construction (S. 182–189). https://doi.org/10.35490/EC3.2019.195

Krijnen, T. (2021). IfcOpenShell. http://ifcopenshell.org/

Liebich, T., Borrmann, A., Elixmann, R., Eschenbruch, K., Hausknecht, K., Häußler, M., Hochmuth, M. & König, M. (2018). Wissenschaftliche Begleitung der BMVI Pilotprojekte zur Anwendung von BIM im Infrastrukturbau: Endbericht Handlungsempfehlungen.

Lin, Y.-H., Liu, Y.-S., Gao, G., Han, X.-G., Lai, C.-Y. & Gu, M. (2013). The IFC-based path planning for 3D indoor spaces. Advanced Engineering Informatics, 27(2), 189–205. https://doi.org/10.1016/j.aei.2012.10.001

Morgenthal, G., Hallermann, N., Kersten, J., Taraben, J., Debus, P., Helmrich, M. & Rodehorst, V. (2019). Framework for automated UAS-based structural condition assessment of bridges. Automation in Construction, 97, 77–95. https://doi.org/10.1016/j.autcon.2018.10.006

Saieg, P., Sotelino, E. D., Nascimento, D. & Caiado, R. G. G. (2018). Interactions of Building Information Modeling, Lean and Sustainability on the Architectural, Engineering and Construction industry: A systematic review. Journal of Cleaner Production, 174, 788–806. https://doi.org/10.1016/j.jclepro.2017.11.030

Schneider, M. & Tschickardt, T. (2021). BIM in der Praxis Havellandautobahn A 10/A 24: Brücken-Ersatzneubau unter laufendem Betrieb: Über Schalungsplanung im Ingenieurbau beim Pilotprojekt "Verfügbarkeitsmodell A 10/A 24". In Sonderheft: BIM - Building Information Modeling 2021, 144–146.

Shah, S., Dey, D., Lovett, C. & Kapoor, A. (2017, 15. Mai). AirSim: High-Fidelity Visual and Physical Simulation for Autonomous Vehicles. http://arxiv.org/pdf/1705.05065v2

Singh, S. & Kumar, K. (2020). Review of literature of lean construction and lean tools using systematic literature review technique (2008–2018). Ain Shams Engineering Journal, 11(2), 465–471. https://doi.org/10.1016/j.asej.2019.08.012

Spieth, D., Hermes, M. & Berner, F. (2016). Wechselwirkungen zwischen Lean Construction und der Arbeitsmethode BIM am Beispiel der BIM-Anwendungsfälle Visualisierung und Bauablaufmodellierung. Bauingenieur, 91(11), 466–472.

Tang, P. & Alaswad, F. S. (2012). Sensor Modeling of Laser Scanners for Automated Scan Planning on Construction Jobsites. In Construction Research Congress 2012 (S. 1021–1031). https://doi.org/10.1061/9780784412329.103

Zhang, C., Kalasapudi, V. S. & Tang, P. (2016). Rapid data quality oriented laser scan planning for dynamic construction environments. Advanced Engineering Informatics, 30(2), 218–232. https://doi.org/10.1016/j.aei.2016.03.004