Simulating and Executing UAV-Assisted Inspections on Construction Sites

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Abstract -

Unmanned Aerial Vehicles (UAV) are an established utility for remote sensing and mapping purposes. Practical applications emerge in the form of inspecting structures that are hard to reach, deterioration analysis, construction monitoring or quantifying material in landfills. From a technological perspective most of these applications rely on the same established method, manual piloting by experts. While ongoing research is focused on developing reliable means of obstacle avoidance, sophisticated mission planning solutions can greatly increase the practicality of UAVs for inspection purposes.

We propose an inspection planning concept for highly automated inspections in BIM projects. The application, developed in the course of this research, interacts with the firmware and the simulation capabilities of the Dronekit framework, which makes for a highly integrated and sustainable UAV. The main contribution is the 3D simulation of planned flight missions with Software-In-The-Loop (SITL) technology. The inclusion of actual flight dynamics allows the operator to perceive an authentic representation of the UAV's behaviour before take-off. Furthermore, the web-based planning application renders preview images in the virtual scene which provide a realistic impression of the results to be expected. The application automatically generates the different waypoints for obtaining photographs of a Point of Interest (PoI).

Keywords -

Visual Inspection; Unmanned Aerial Vehicles; 4D Building Information Modelling; Progress Monitoring; Ground Control; Path Planning; Simulation

1 Introduction

An important aspect of Building Information Modelling (BIM) for construction is the accurate and up-to-date correlation between as-planned and as-built information. Any deviation between model and reality inhibits the expected increase in efficiency due to the need of manual adjustment of plan data and implied workloads [3]. This justifies a demand for effective progress-monitoring solutions that gather relevant data. Traditionally, such inspections are conducted by staff walking around the construction site and taking photos of modified structures. Apart from the tedious nature of repeatedly iterating several spots on larger construction sites the photographer often cannot reach an optimal perspective when taking pictures of façade elements in greater heights. Furthermore, feeding the gathered information into BIM should not imply additional work. A direct and automatic association of data and their respective building elements in BIM is therefore necessary.

Unmanned Aerial Vehicles have become reliable and affordable utilities for inspections on existing buildings and construction sites. Typically, inspections are carried out manually with a trained pilot steering the UAV around a PoI. However, autonomous capabilities increase operational safety and open up large potential for automation and frequent repetition of recurring inspection tasks. Scheduled flight missions with automatically generated flight paths and camera control leverage the operator of most of the manual work. The goal is to develop a workflow that triggers, generates, and conducts inspections with minimal human effort required.

The main contribution of this research is a case study involving a software application, which, comparable to conventional ground station applications, generates and transfers flight missions and monitors all relevant information in-flight. It advances the concept with a 3D scene representation of the building model, automatic path-planning around building structures and an interchangeable logic for either realistically simulating inspection flights or conducting actual inspections with a live data link. This work demonstrates how the invocation of flight controller logic for simulation purposes furthers the concept of a structured use of UAVs in construction.

2 State of the Art

UAVs introduced new possibilities for gathering sensor data from remote positions in various applications. Many industries, including construction, have since adopted the use of UAVs. Noteworthy applications are crop analysis in precision agriculture, documentation of excavation sites in archaeology, early detection of forest fires, support in emergency services and inspection of power lines and solar panels. The most common sensor among theses applications is a stabilised camera system for aerial images.

Infrared cameras enable surveyors identify degraded solar panels in order to maintain efficiency in small and large-scale photovoltaic plants [11, 16]. When mounted on winged UAVs for extended range, these sensors also greatly improve response times to forest fires [18]. Novel approaches, developed in the precision agriculture field, greatly rely on the automated use of UAVs and help farmers save resources and individually maintain individual orchards by assessing large areas of crops and soil on a daily basis [19]. Among other methods of gathering sensor data, the UAV-based approach is advantageous for its high usability and low data acquisition costs [4].

The adoption of UAV technology in these industries increased the demand for safe and efficient products which can be operated with little to no expertise in piloting. However, autonomous operation with the ability to automatically sense and avoid obstacles is an even more complex challenge concerning aircraft than it is in cars. Some manufacturers have recently begun selling this functionality in their prosumer class models, reports of failed manoeuvres and crashes indicate that their proprietary solutions are not yet reliable and thus unfit for industrial use [15]. Manufacturers as well as research projects in the robotics community follow different approaches to solve this problem. Light Detection and Ranging (LiDAR) offers highly accurate measurements at sufficient rates. These sensors are popular in automotive applications where measurements are taken in a very narrow vertical window as well as winged aircraft with no vertical take-off and landing capabilities. In multi-rotors however, the limited angular width and susceptibility to mechanical stress limit practicality. Furthermore, the laser beams emitted by LiDAR devices are significantly corrupted by rain and fog [12]. The vision-based approach relies on small, inexpensive solid state cameras for sensing the environment. Portable parallel computing solutions like the Nvidia Jetson TX1 allow real-time processing of stereo camera streams for depth-sensing with sufficient accuracy. However, the dependency to sufficient lighting is a drawback to this approach and additional Night Vision Imaging Systems (NVIS) and Forward Looking Infrared (FLIR) sensors increase weight and cost of the system. Concluding the technological aspect, the current state of UAV technology in terms of sensing the environment and avoiding obstacles is unclear. Apart from recent academic achievements [12, 10], commercial solutions have made an impact but their proprietary nature forbids an evaluation of the robustness of the sensing mechanism [15]. Regulatory requirements towards the operation of autonomous aircraft are yet to be defined in most jurisdictions, thus manufacturers have no obligation to meet official requirements. Authorities in the United States, embodied by the Federal Aviation Agency (FAA), have recently published new regulations for the use of civilian UAVs. However the use of autonomous functions was not specifically defined and must adhere with requirements towards piloted use, most notably the satisfaction of the line-of-sight criterion [7].

Practical applications for UAVs in construction and related industries focus on inspection, (quantitative) measurements and reconstruction of 3D geometry for further analysis in Structural Health Monitoring (SHM). Reconstruction of geometry may be carried out either by applying Structure from Motion (SfM) methods on still images or with sophisticated sensors like laser range finders or integrated solutions like the Microsoft Kinect. These data are used for deterioration analysis [9], preservation [1], or energy efficiency measuring [13]. Inspections in open, uncrowded spaces yield good results with low effort due to mostly planar path-planning and a lack of obstacles [8, 14]. In above ground construction however, the automated employment of UAVs reveals more complex challenges. Moving parts, machinery, working personnel and a constantly evolving building structure with scaffolding and other obstacles must be taken into account when planning autonomous inspections on construction sites. While the quality and accuracy of the gathered data is found to be sufficient throughout the evaluated studies and processing methods create valuable information, a BIM inspection concept should emphasise on automation and efficacy. Eschmann et al. [6] describe the challenges for such a concept as collision-avoidance, path planning and efficient data acquisition. In their experimental study the authors collected data of one façade structure for the purpose of reconstruction and automated crack detection. While 12,000 aerial images were collected in the course of four days, only several hundred were used for later processing. Provided with the right preparation methods, a similar inspection could have been carried out in a matter of hours or minutes.

3 Research Methodology and Simulation Concept

This is a constructive research to assess the potential of utilising autonomous UAVs in combination with BIM for inspection purposes on construction sites. The benefits appear in the form of

- low installation costs with little to no operating costs,
- autonomous navigation enabling a high degree of automation,
- the ability to reach vantage points on high structures or roofs and
- low additional effort required for frequent repetition intervals.

However, the following issues and requirements need to be addressed to reach a degree of efficiency that surpasses the traditional methods of repeated walkabouts and deploying lifting platforms.

- Autonomous features on UAVs are still limited. The concept should focus on available technology and future-proof new developments. Furthermore, limitations of currently available technology need to be accounted for.
- Operation of the UAV must not interfere with ongoing processes and collisions must be averted.
- The scheduling of inspections and input of collected data should be coherent with existing methods of managing building information.

To meet the demand for a systematic inspection solution, as established in Section 2, the UAV and its control workflow should empower the operator to accurately plan the inspection flight before conducting it on-site. The expected benefits of such a preparation stage are reduced execution times on site, increased awareness of the UAVs movements and better understanding of the expected data yield. The preparation of an inspection should require as little manual input and decision-making by the user as possible. Ideally, the user should be able to interactively select the objects to be inspected and then rely on the inspection software to automatically determine the correct flight mission including control of the sensor.

The automated inspection solution proposed in this work relies on locating the UAV via Global Navigation Satellite Systems (GNSS) and coordinating its flight trajectory along the object boundaries defined in the georeferenced BIM. This knowledge-based concept may be extended by active collision avoidance technology in the future, but the main achievement of this concept is the creation of an automated workflow that generates efficient flight missions and requires no further knowledge than that provided by BIM.

Fig. 1 illustrates the designated workflow between the system and the user and identifies the tasks the system needs to solve as well as the required data sources.

The application is designed to be used both in the planning stage of an inspection and while conducting it. After selecting the BIM to work in, the user is prompted to either plan a new inspection or to load existing mission data which may then be executed on the UAV. By setting time and date of the intended inspection mission, the application is able to render sunlight and shade as it will appear on-site. This helps the operator decide whether the natural lighting conditions are suited for the photographs.

The selection of a PoI then triggers the application to generate both a path of waypoints along the points of interest as well as preview pictures from various vantage

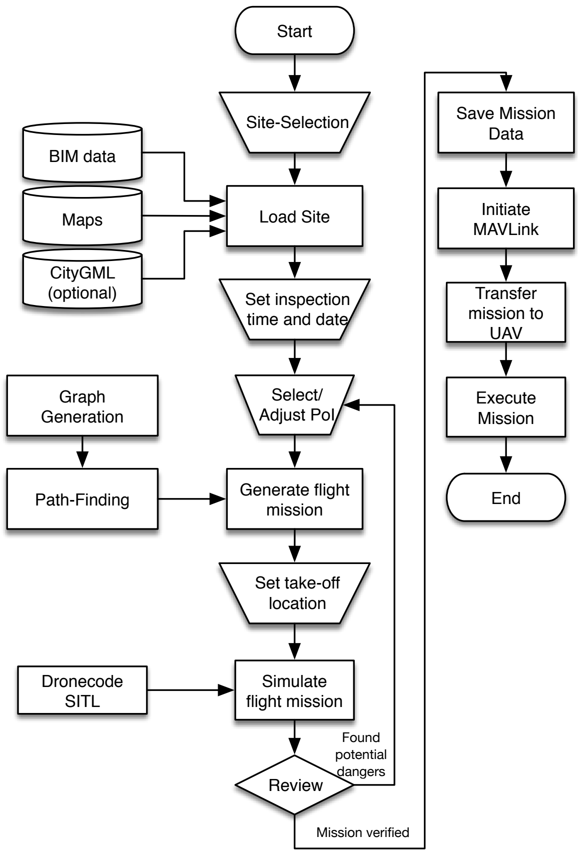


Figure 1: Application workflow

points (Fig. 2). To the operator a PoI is a structural element of the building that has undergone changes. In terms of the flight mission, the PoI is an aggregate of multiple waypoints, each providing a different perspective on the structural element. Apart from its geodetic location, each vantage point also includes camera control commands. Each vantage point requires the camera to be pointed towards the PoI in a different attitude. The stabilisation gimbals used in this project operate on two axes, pitch and roll. To cover rotation of the camera on the yaw axis, the UAV itself needs needs to rotate accordingly when reaching a vantage point. The autopilot of the UAV is capable of triggering the camera shutter, so each vantage point in a flight mission also triggers a shutter command.

The path from take-off location towards the PoI is represented as a sequence of waypoints, beginning at the take off location, leading to the PoI, and leading back to the take off position for landing. The Inspection-Planner needs to calculate a viable route between take-off and PoI, considering all physical objects on the construction site. The path planning concept is separated into three steps: segmentation of the scene, graph generation and invocation of

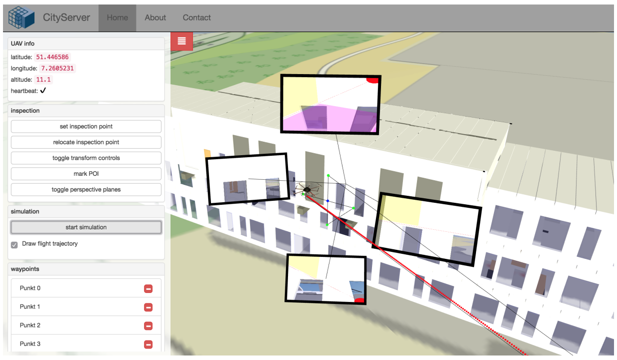


Figure 2: After selecting an element the user is presented with previews of the images the inspection will yield

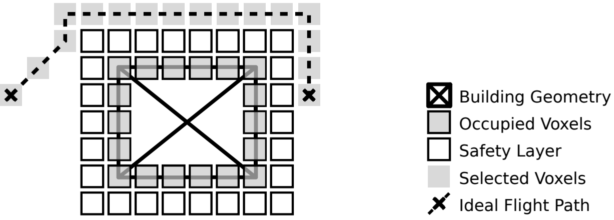


Figure 3: Schematic top-down view of the navigation mesh around a building

a graph search algorithm to determine the ideal route. For the segmentation step the concept of navigation meshes, established in robotics research, was adapted. Navigation meshes are typically an aggregate of 2D polygons that represent the areas of a robot's environment that are accessible. However, UAV navigation requires a 3D representation of navigable space, allowing the UAV to travel in vertical direction and to account for variable height of physical objects. The navigation volume is represented as a set of voxels, where no intersections with relevant geometries from the BIM occur. Each voxel inherits information about its neighbourhood of voxels and the potential waypoint it represents. To abide with the required minimum distance the UAV should maintain towards objects, a further processing step is applied. It generates an augmentation layer of voxels around bodies of occupied voxels. The augmentation step needs to create a closed hull of voxels around occupied bodies. This is achieved by using the 26-connected Moore neighbourhood of each occupied voxel. Fig. 3 shows a simplified 2D schematic of a building geometry after the navigation volume was created and with an exemplary flight path drawn between start and end point. Based on the relations between voxels, a graph is generated, with each transition between nodes representing a possible movement of the UAV from one waypoint to the corresponding one of a neighbouring voxel. Provided start and end points the node-based graph search algorithm A* is invoked. By applying penalties in the form of increased transition costs for vertical travel, the shortest path algorithm favours lateral avoidance strategies to climbing over obstacles. This benefits the legislative criterion requiring the operator to keep the UAV in line-of-sight at all times. Further modifications of this kind may be applied in further development stages of a practical path-finding strategy.

The UAV will be guided to each of these points with the information about the needed orientation for the camera to obtain the images as planned. Each of these points adheres to a predefined ruleset of how much distance the UAV should keep to any structure throughout its mission.

The BIM data source is the central component in this concept. Integrating the inspection preparation with BIM counters two of the constraining factors. It provides spatial data of possibly any structure, machinery and the digital elevation model, which is the fundamental knowledge for automatically computing the space in which the UAV may navigate in. Furthermore, the 4D BIM concept provides the temporal knowledge of processes and locations of machinery which enables the automatic generation of scheduled inspections.

BIM data, exchanged in the IFC format, is managed and provided to the inspection planner application by the open source BIMserver [2].

Spatial information about the environment of the site may be augmented by cadastre data typically available in the CityGML format or by freely accessible vectorised map tiles.

3.1 Simulation of Inspection Flights

After the selection of elements to inspect and generating the according flight mission, the user may simulate the mission. The simulation gives the operator a realistic impression of how the UAV will behave in the actual execution and allows identification of latently dangerous manoeuvres that the model cannot account for. Therefore, the simulation should be as realistic as possible, which can be achieved by executing the firmware image that is identical to the one that resides in the flash memory of the UAV's micro-controller. By defining simulation parameters that resemble the real environment it is possible to let the simulated UAV behave like the physical counterpart. This kind of simulation is built on the SITL framework established by the Dronecode Foundation [5]. By providing an interchangeable communication interface between the application, the UAV and the simulation engine, there is no need for an extra control protocol (Fig. 4). This is not only a conceptual benefit for the user trying to validate flight missions, but also a fundamental aid for future developments which focus on advanced path-finding strategies with complex constraints.

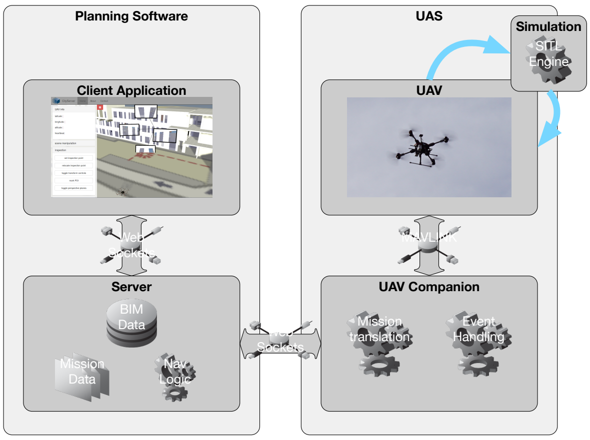


Figure 4: Simulation Schema

To further the realism of the 3D simulation and provide an informative display of the UAV's status when executing a mission, maintaining a low latency between Server and the browser-based client is mandatory. Telemetry data, received from the UAV (or the simulation) is being forwarded to the client application via WebSockets in real-time. The UAV Companion is an intermediary software between the planning software and the UAV interface, which may either be a physical link to the UAV or the interchangeable counterpart of the simulation. It may be executed directly within the server application but may also be executed independently on a Single Board Computer (SBC) such as a Raspberry Pi, which is mounted on the UAV. It is the conceptual component that translates flight missions, generated in the Planning Software to MAVLink formatted waypoints and dispatches telemetry data back to the planning software.

MAVLink [5] is a lightweight messaging protocol designed for use between Groundstation applications and UAVs and may also act as inter-communication link between multiple UAVs in swarming applications. The MAVLink protocol is highly efficient. It is a header-only library, which doesn't take up much space in the memory of highly limited micro-controllers. Moreover, its messages are small in size with simple integrity checking via CRC checksums. This makes the protocol suitable for low bandwidth long range telemetry links.

The server-bound communication link of the UAV Companion is implemented in a REST API that allows direct read/write access to the information that is to be shared. It dispatches relevant events from the UAV to the Planning Software, giving the user insight into the current flight status. Forwarded events and parameters are:

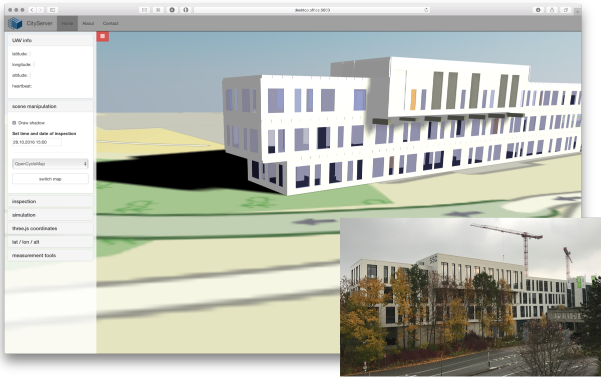
- Current position: latitude, longitude, altitude
- Attitude: in three axes, including camera attitude
- GPS: Horizontal Dilution of Precision (HDOP), number of satellites
- Battery status: Voltage (per cell), current draw, remaining capacity
- Flight mode: including arm status

In extension to providing a realistic simulation in terms of movement and control, the SITL simulation approach is also fit to investigate the potential risk induced by environmental factors. Occlusion of multiple satellites at the GPS sensor's position can significantly lower the accuracy. Another source of error is known as multipathing effects which often occur in urban canyon scenarios. In addition to line-of-sight signals, the sensor receives signals which are reflected on facade surfaces [17]. The simulation framework features adjustable parameters including those of the simulated GPS device or direct influential factors like wind gusts. It is therefore possible to test variations of such parameters to evaluate a flight mission. Provided with a probabilistic model of the influence of building structures to the GPS system, the simulation software can simulate decreased accuracy of the GPS sensor and provide insight about how much such disturbances interfere with the navigation system of the UAV. Furthermore, simulation of energy consumption provides important information about the feasibility of an inspection mission. The setup of a meaningful energy consumption simulation requires setting the right take-off weight of the UAV as well as the power consumed by the motors in combination with the propellers. These parameters should be determined by conducting calibration flights with the designated UAV that is equipped with complete payload. In return, this allows the simulation to provide meaningful insight about the expected flight duration and battery usage. Similar tests may be carried out with simulated wind gusts, adjustable in strength and direction, or increased error in the magnetometers which may be disturbed by ferrous materials.

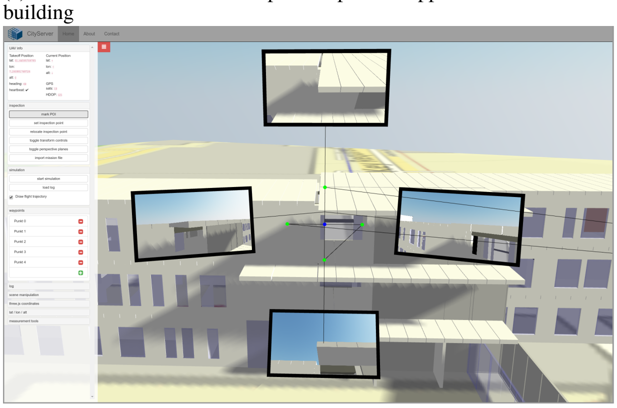
4 Case Study

A practical case study was conducted in two steps. To asses the practicability of the application with realistic model data the recently rebuilt SSC building on the campus of the Ruhr University Bochum (Fig. 5a) was recreated in a BIM and used to generate and simulate an inspection mission. In another test, the quality of the simulation method was evaluated by comparing a simulated flight and a flight test in an open field.

The SSC model mainly consists of outward facing structures, which are analysed in real-time for the path generation. After selecting the model the user selects the designated take-off location for the UAV on the map plane.

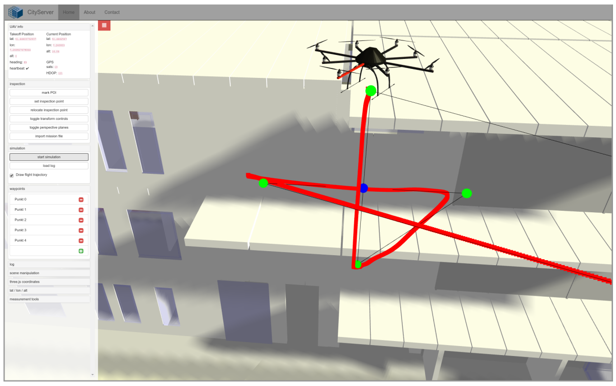


(a) The BIM loaded in the inspection planner application and the real building

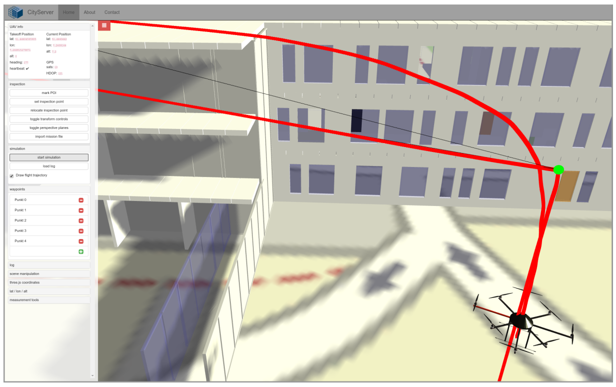


(b) The previews from the perspectives convey an understanding of the photos that will be taken

Figure 5: Creating an inspection mission



(a) Four waypoints (green) mark the different perspectives for photos around the PoI



(b) The simulated UAV starts descending while reaching the land location

Figure 6: An ongoing simulation run of the created mission

Subsequently the user selects the PoI by clicking on the corresponding facade structure. The application then generates the flight mission and previews of the photos that will be taken around the PoI (Fig. 5b). In case the previews do not meet the operator's expectations, they may be adjusted directly in the scene and the mission will be regenerated in place. The automatically generated mission is then simulated for verification. Figures 6a and 6b show the ongoing simulation run of the exemplary inspection mission. The flight path is visualised as a chain of waypoints (green) and straight connection lines (black), which do not accurately represent the movement of the UAV. By initiating the underlying simulation engine, a virtual representation of the UAV executes the flight mission and draws a line of its trajectory (red) in the scene.

In order to evaluate the realism of the simulation, a test flight with an automated flight mission was conducted in an open field. A building model was geo-referenced on a predefined spot on a field near the campus. A PoI was selected on the roof structure of the model and the generated mission was then executed in the integrated simulation. After checking the simulation a real test flight using a 3DR IRIS+ UAV was conducted under unfavourable weather conditions. Clouded sky influenced the GNSS sensor's reception and wind gusts of level 6 in the Beaufort scale made an impact on the stabilisation mechanism of the flight control. The UAV's flight control stores a log of all relevant flight parameters throughout a flight in its flash chip, including all sensory data and navigation status. The SITL simulation provides the similar log data. This evaluation focuses on the perceived location of the real and the simulated vehicle. Fig. 7 shows the logged positions of both runs, red being the simulated trajectory, blue being the flight test. While both trajectories look similar, it gets clear, that the simulation did not exactly foresee the flight dynamics. This is due to the fact that the simulation was not provided with alternating gusts but a constant wind speed and the simulated GPS sensor was run with constant reception quality. A closer look on the log data provides further insight. The two plots in Fig. 8 show a direct comparison of simulation of flight data by measured latitude and longitude in WGS84 notation. The error bars reflect the vagueness of the measured position of the test flight and were derived from the Horizontal Dilution of Precision (HDOP), reported by the GPS sensor. The HDOP is an estimate of the signal quality, dependent on multiple

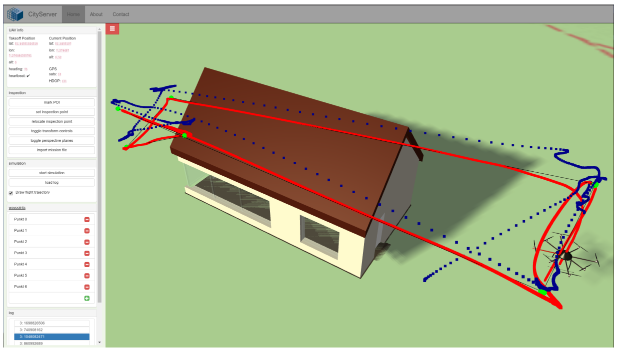
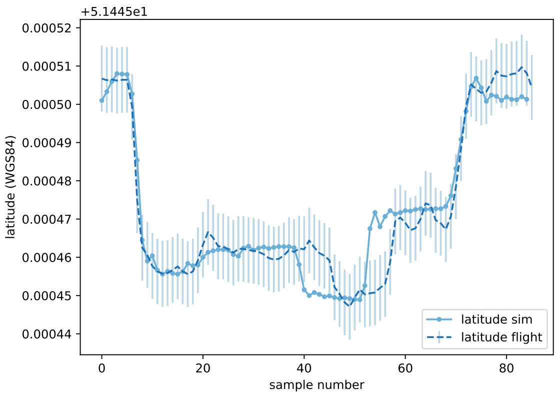
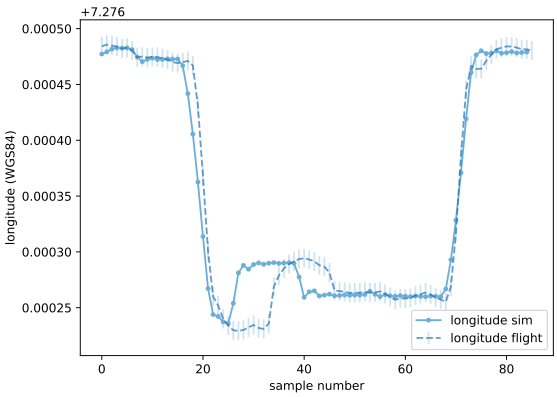


Figure 7: The recorded flight trajectories of the simulation (red) and the field test (blue)



(a) Logged latitude measurements



(b) Logged longitude measurements

Figure 8: Measured locations of the test flight with HDOP error margin and the simulated flight

conditions, such as visibility of satellites, electromagnetic disturbances and multipathing effects. It reports a possible deviation in meters for each logged measurement. The simulation, including its mechanism for producing a vague perception of position in space, is expected to exhibit a similar behaviour that ideally lies within the error margin of the real flight. While the simulated trajectory mostly lies within the error margin, short aberrations can be explained by the fact that the simulation was quicker in marking waypoints as reached and therefore was able to move on to the next one earlier. These observations are important steps towards a reliable automated inspection method and show how a realistic simulation supports the development of more complex navigation strategies.

5 Conclusion and Outlook

This work is part of an ongoing research effort to investigate the practicability of employing UAVs for inspection purposes in construction environments. The bottom-line concept of generating flight missions based on BIM data and open source robotics software is implemented in an exemplary application. The main contribution of this work is an integrated concept for preparing and conducting automated inspections with UAVs. Furthermore, by using realistic simulation techniques, the operator is provided with meaningful predictions of the aerodynamics and energy consumption of the UAV. Regarding the further refinement of the path-planning strategy, the simulation greatly accelerates testing and is therefore also considered a meaningful support measure for future works.

While the preloaded knowledge from the model may account for any possible obstacle in the working environment, a maximum degree of safety can be achieved with active collision avoidance functionality. The industry is heavily invested in solving this problem, but reliable solutions are yet to be found. Regarding future developments, active collision avoidance may complement the presented solution at any stage, but the fundamental concept of generating ideal flight paths in a known model environment stays relevant as collision avoidance does not replace this knowledge. Further efforts will be made in a study on active avoidance of low GPS reception in the proximity of buildings. Monitoring the signal quality, the inspection planner application may actively steer the UAV into open space, away from the building façade, to regain better reception. This method has the potential to greatly minimise the risk of malfunctions.

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