Practical Considerations and Case Study for Implementing Autonomous UAV Video Collection of Construction Activities

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Abstract –

Various methods have been proposed in recent years to extract valuable insights from images and videos of construction activities to improve project management. Previous studies have proposed automated video collection using camera-equipped multirotor unmanned aerial vehicles (CE-MUAVs) to enable the collection of construction videos with the ability to fit the camera's field of view (FOV) automatically to the specific areas where the activities are happening. However, multiple practical considerations should be addressed before implementing autonomous UAV video collection of construction activities to fulfill the technical, safety, and data quality requirements, while respecting the legal regulations. This paper aims to identify these considerations and to develop a workflow for implementing an effective video collection of construction activities using autonomous CE-MUAVs. A test on an actual construction site is conducted to validate the applicability of the workflow.

Keywords –

Construction activity; Video Collection; Path planning; 4D Simulation; UAV.

1 Introduction

With the emergence of advanced computer vision (CV) techniques, it is possible to automatically extract rich semantics and high-level knowledge from digital images and videos, enabling more comprehensive and efficient analysis for different construction management applications [1], including activity monitoring [2], progress monitoring [3, 4], and health and safety monitoring [5–7]. However, the complexity and high costs associated with video collection have significantly constrained the widespread adoption of these methods. Collecting high-quality videos of specific areas of interest on construction sites, where activities happen, according to the project schedule remains challenging with conventional approaches, such as stationary cameras, handheld devices, equipment-mounted cameras, and wearable systems [1].

Over the past decade, considerable attention has been paid to automated video collection using camera-equipped multirotor unmanned aerial vehicles (CE-MUAV), which provides mobility to the camera to fit its field of view (FOV) automatically to the important parts of the construction site while ensuring high efficiency and reasonable cost [8–10]. Previous studies have proposed generating collision-free UAV paths based on a BIM model to support visual inspection tasks of buildings [11, 12]. Other studies proposed methods for sampling the viewpoints to achieve full visual coverage of the structure considering the sensor (i.e., camera or laser scanner) specifications, such as FOV, focal length, and sensor size [13, 14]. Then, routing algorithms are applied to generate the optimal path through the sampled viewpoints. In addition, Ibrahim et al. [15] proposed a method of UAV path planning for progress monitoring during the construction phase considering the schedule using waypoints. However, current implementations of CE-MUAVs primarily focus on scanning static objects in outdoor and indoor environments for purposes like 3D reconstruction and inspection. On the other hand, limited research is available about collecting videos of construction activities using autonomous UAVs.

To address this research gap, the authors previously proposed a method to perform simulation-based optimization of path planning for CE-MUAVs considering multiple construction activities according to the as-planned micro-schedule [16]. This method identifies the top-ranking viewpoints (VPs) to collect high-quality videos about the construction activities in the micro-schedule with good coverage of the workspace while minimizing the distance to the workspace. In addition, the method generates optimized paths that minimize the travel duration between the top-ranking VPs while avoiding collisions. While effective in a virtual environment, this approach has yet to be tested in real-world scenarios. However, multiple practical considerations should be addressed before implementing autonomous UAV video collection of construction activities to fulfill the technical, safety, and data quality requirements, while respecting the legal regulations. This paper aims to identify these considerations and to develop a workflow for implementing an effective video collection of construction activities using autonomous

CE-MUAVs. A test on an actual construction site is conducted to validate the applicability of the workflow.

2 Simulation-Based Optimization of Path Planning for CE-MUAV

Figure 1 shows the method of simulation-based optimization of path planning for CE-MUAVs proposed in the previous work of the authors [16]. This method identifies the top-ranking viewpoints (VPs) to collect high-quality videos of construction activities based on the micro-schedule with good coverage of the workspaces, while minimizing the distance to these workspaces. In addition, the method generates an optimized path that enables the UAV to collect videos based on the identified VPs while minimizing travel time and avoiding collisions. It has been demonstrated that aerial videos captured while the UAV is hovering offer distinct advantages, as they enable the capture of finer scene details and intricacies [17]. It is assumed that the CE-MUAV will collect videos during traveling and hovering states. However, the focus is on spending more time to collect videos while hovering. There are three main modules in the simulation-based path planning: (1) Preparation of the simulation environment; (2) VPs optimization; and (3) Path planning for the UAV to minimize the travel duration.

In the *simulation environment preparation module*, the workspaces for a certain period are identified from the as-planned 4D simulation of the project. Then, the solution variables of the UAV are identified according to the selected model of the UAV. The search spaces for different workspaces are then defined considering the safety risks in the construction site, the CV requirements (e.g., range of camera, tilt angle), and the compliance with legal regulations, which will be further explained in Section 3. At last, cubic cells are generated within the workspaces for calculating the camera coverage.

In the *VPs optimization module*, the top-ranking VPs for each workspace, where the FOV of the hovering camera can provide good coverage while minimizing the distance, are identified by integrating a multi-objective genetic algorithm (MOGA) with simulation. Two objective functions are defined: maximizing coverage and minimizing the camera-to-workspace distance. For each workspace, multiple top-ranking VPs will be identified. With these VPs, the *path optimization module* solves the generalized traveling salesman problem (GTSP) to optimize the cycle path with the least travel duration to collect videos from one of the top-ranking VPs for each workspace. It is worth noting that in this paper, the Theta* algorithm is utilized to generate a more efficient collision-free path to travel between the VPs compared with the A* algorithm used in our previous paper [16]. This optimized cycle path consists of multiple waypoints, each specifying the location and pan angle of the UAV and the tilt angle of the camera. At last, the hovering duration at each VP of the optimized cycle path is defined according to the importance level of the task in different workspaces.

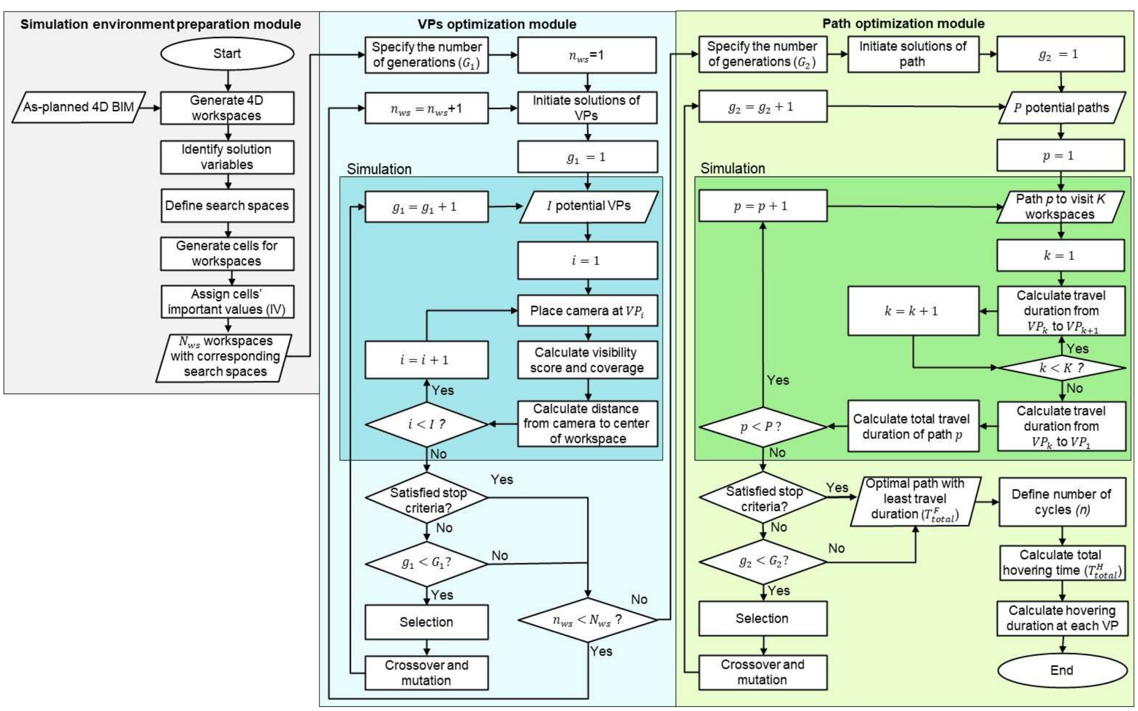

Figure 1. Simulation-Based Optimization of Path Planning for CE-MUAV

3 Practical Considerations for Implementation

Multiple practical considerations must be addressed before implementing autonomous UAV video collection of outdoor construction activities in actual projects using the optimized path generated by the proposed method in Section 2.

3.1 Technical requirements

To ensure effective implementation, several technical requirements must be addressed. Here, the technical requirements can be considered in two aspects, the hardware requirements and software requirements. The hardware requirements mainly refer to the requirements in selecting an appropriate UAV that is capable of performing the task. First, the UAV should support pre-planned flight operations and offer an application programming interface (API) to enable importing the optimized flight path from the simulation console. The UAV should also have a reliable antenna for Global Navigation Satellite System (GNSS) or alternative systems to maintain accurate flight paths. The operational range and battery life must be sufficient to complete the video collection tasks. In addition, the UAV should be equipped with a camera capable of collecting high-quality video to meet the data requirements for CV, which are explained in Section 3.4. Moreover, sufficient onboard storage for videos is essential. Automated data transmission using 5G communication to a remote console or database is highly preferable, as it enhances efficiency by eliminating manual data retrieval.

On the other hand, appropriate software tools should be selected. For example, to develop a detailed construction 4D simulation model, Naviswork [18] was used in the author's previous work [16]. This model was then imported into Unity 3D game engine [19], which has a realistic physics engine for simulating the UAV operations. In addition, converting waypoints from simulation coordinates into UAV-readable data is necessary. The implementation process involves three coordinate systems: (a) coordinate system of the construction 4D simulation, (b) coordinate system of the simulation for path planning, and (c) coordinate system for UAV navigation. Typically, models are developed in a local coordinate system specific to the software tools [20]. To incorporate the geospatial context of the coordinate system of (a) and (b), a geographic information system (GIS) can be used to show the positions in a projected coordinate system (PCS) [21]. However, UAV navigation uses a geographic coordinate system (GCS). For example, DJI UAV navigation [22] uses a geodetic coordinate system. Therefore, to navigate the UAV, it is necessary to have a tool to translate the coordinates of the waypoints of the optimized path from the PCS to GCS.

3.2 Safety requirements

The integration of UAVs in construction may encounter several safety risks [23–25], highlighting the need for careful operation planning and UAV selection to ensure safe and effective operations. The major risk is collisions with workers or objects on construction sites. During the planning phase, risk assessment should be performed to identify all potential collision risks based on the site layout. In the *simulation environment preparation module*, safety buffers should be assigned to workspaces and high-risk areas. In addition, selecting UAV models equipped with active collision avoidance can further mitigate these risks [29]. UAVs may also encounter motor malfunctions or communication loss, necessitating a detailed emergency contingency plan to address such scenarios before deployment. Moreover, the selection of a UAV model should consider risk mitigation features, such as pre-flight fault detection, automatic return-to-home functionality in case of loss of connection, and a reliable and secure communication system to prevent unauthorized access or interference to the UAV. Furthermore, UAVs may pose safety risks to workers on-site due to distractions [24]. Selecting light-weight UAV models that generate less noise can help reduce this issue.

3.3 Compliance with legal regulations

UAV deployment must comply with the legal requirements. The UAV should be properly registered in accordance with local laws and regulations. The operators must undergo training and obtain the necessary licenses or certifications before conducting operations. If the operation takes place in controlled airspace, the necessary certificates and permits must be obtained as required by regulations. In addition, detailed documentation of the operational risk assessment, precautions for risk mitigation, and an emergency contingency plan may be required by the responsible department (e.g., Transport Canada) when applying for special flight operations [26].

In *simulation environment preparation module*, zones where the project team does not have permission to operate the UAV, such as areas near surrounding buildings, should be clearly defined to prevent unauthorized intrusion. The compliance of such regulations should be verified through virtual verification after generating the optimized path and confirmed again during on-site verification before deployment.

Moreover, the selection of UAV model should take into account the ease of obtaining operational permissions. For instance, basic operations that do not require a special flight operations certificate apply to UAVs weighing less than 25 kg in Canada [27]. It is worth noting that exceptions may apply to micro-UAVs weighing under 250 g in some countries [26], which may reduce the complex process of obtaining permission to fly. Operating a micro-UAV does not require a pilot license or certificate if the operator ensures safe operations with good practices and compliance with all applicable requirements and regulations.

Furthermore, during the operation, the UAV use must respect the privacy of workers and other individuals captured in the video. The project team should obtain consent from workers before deployment. In addition, the team is responsible for developing secure data communication and storage methods to protect the privacy of the collected data.

3.4 CV requirements

The video collection process must meet specific CV requirements to ensure the captured frames are suitable. A proper tilt angle should be maintained to clearly show the pose of workers and equipment. In addition, CV methods (either object detection or activity recognition) are usually susceptible to aerial imagery with the small size of objects and variable tilt angle of view [17, 28, 29]. Therefore, the distance from the camera to the objects should be less than a certain maximum value to avoid the low resolution of objects in the frame while maintaining the coverage of the designated workspace. This CV requirement is fulfilled through the *VPs optimization module*, as explained in Section 2. In addition, a stable FOV with minor vibration and motion blur improves the quality of CV results. It has been suggested that aerial videos captured while the UAV is hovering offer distinct advantages, as they enable the capture of finer scene details and intricacies [17]. Moreover, hovering time should be sufficient for gathering essential data from the optimal VPs.

Table 1 lists the considerations of the requirements in different processes during the implementation. It should be mentioned that these requirements are often interconnected.

4 Implementation Workflow

The proposed method for implementing optimized video collection of construction activities using CE-MUAVs based on optimized path planning is shown in Figure 2. The implementation can be divided into three phases under three different coordinate systems as mentioned in Section 3.1. In the model preparation phase, a high LOD as-planned 4D simulation is developed. Then, the as-planned 4D model is integrated with the GIS data to show the geospatial context of the project. By reviewing the 4D simulation, risk assessment is performed and requirements are identified according to the key considerations as mentioned in Section 3. Based on these requirements, the type of UAV is selected. Then, the 4D simulation model is transferred to the simulation platform for UAV path planning.

Table 1. Practical considerations during implementation

Implementation step	**Technical requirements**	**Safety requirements**	**Legal regulations compliance**	**CV requirements**
UAV model selection	-UAV and sensor specifications -Pre-planned flight function -Reliable antenna and navigation system	- Robust accident prevention functionalities - Malfunctions handling - Light-weight UAV to avoid distractions - Secure communication method	- Weight of the UAV	- UAV performance to avoid vibrations and motion blur - Camera specifications
Simulation modelling and path optimization	-Simulation tool -Tool to translate coordinates of waypoints -Operational range and battery life	-Safety buffer to avoid collision risks	-Unauthorized flight zones	-Defining reasonable search space
Pre-flight planning		-Risk assessment -Contingency plan -Precautionary measures	-Operation certificate and flight permit -Privacy protection	

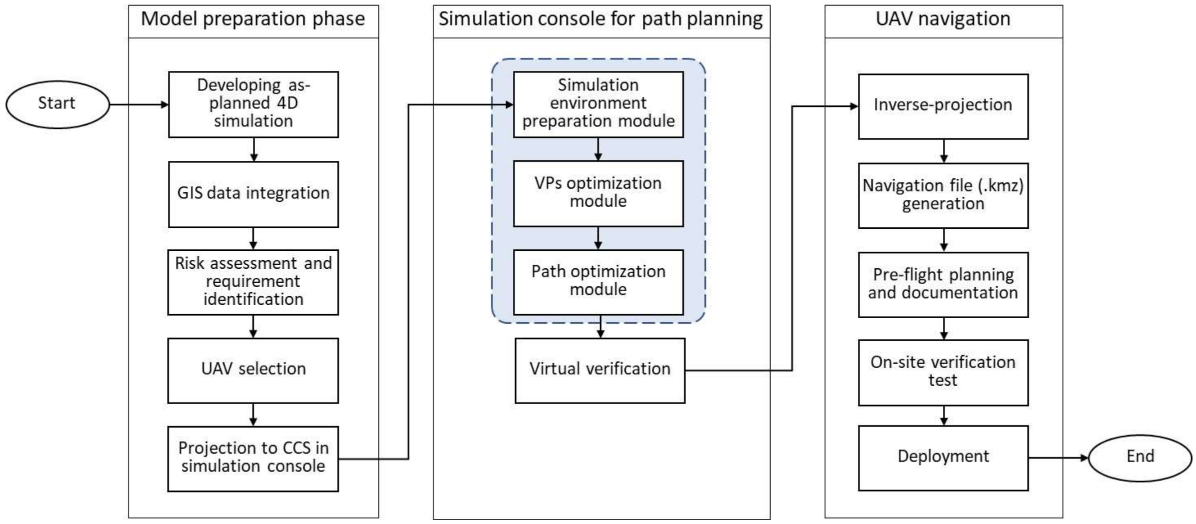

Figure 2. Implementation workflow of Autonomous UAV Video collection based on optimized path planning

Simulation-based path planning of CE-MUAVs is performed to find the optimized path for automated and effective data collection of construction activities using 4D as-planned simulation as explained in Section 2. In the *simulation environment preparation module*, the search spaces, safety buffer, and unauthorized flight zones should be defined considering the safety requirements, compliance with legal regulations, and the CV requirements as mentioned in Section 3. At the end of this phase, virtual verification is conducted to verify the efficiency and effectiveness of video collection along the optimized path. This is achieved by running a simulation in which the virtual UAV follows the same path within the virtual environment. The verification process involves reviewing the UAV's trajectory to eliminate the safety risks and analyzing the camera's FOV during hovering to ensure comprehensive coverage of the workspace.

To navigate the UAV, the waypoints of the optimized path in the simulation system are inverse-projected from PCS to the GCS as mentioned in Section 3.1. Using the waypoints in the GCS, a navigation file for the UAV is generated. One commonly used format for the navigation file is the .kmz format. Before deploying the UAV with the navigation file, pre-flight planning is carried out to outline precautionary measures and emergency contingency procedures. Once these plans are documented, an on-site verification test is conducted to ensure the UAV follows the optimized path and hovers VPs to collect videos of the expected workspaces of tasks. The on-site test should also verify that the operation is free of safety risks. In addition, it should ensure compliance with legal regulations during the deployment (e.g., preventing the collection of videos that infringe on workers' privacy). To minimize disruptions, this test should be conducted during off-peak hours, with the UAV moving slowly to allow immediate stops if any risks arise. Once verification is complete, the operation plan with the optimized path will be deployed to collect videos.

5 Case study

A field test was conducted on a construction site to validate the applicability and effectiveness of the proposed workflow. The test focused on activities carried out during a short period of a park construction project, which includes an outdoor skating rink and a pavilion. Figure 3 shows the workflow implementation in this case study.

As shown in the bird-view of the GIS integrated site layout (Figure 3(a)), the construction site is divided into two parts by a road. The left part is the main construction area, where two tasks were underway: the workspace for pouring concrete for the pavilion (WS3) and excavating and leveling the area designated for the skating rink (WS2). The right part contains a loading area used for storing the excavated soil (WS1). As shown in Figure 3(a), this construction site is surrounded by three buildings, each with a height of more than 25 meters, resulting in potential collision risks. Therefore, safety buffers are assigned to these buildings. Additionally, a safety buffer was maintained along the road, creating a danger zone with a height of 10 meters.

5.1 CE-MUAV selection and variable identification

The UAV used in this case study is the DJI Mini 4

Pro [30], which features a maximum speed of 12 m/s and a maximum ascent/descent speed of 5 m/s in "Normal Mode". Weighing 249 g with its standard battery, this UAV simplifies regulatory compliance in most North American jurisdictions as mentioned in Section 3.3, making it ideal for construction projects. Its compact and lightweight design minimizes safety risks while maintaining excellent maneuverability. Furthermore, its omnidirectional obstacle sensing system significantly reduces the risk of collisions, enhancing operational safety. The maximum flight time is 30 minutes with the standard battery.

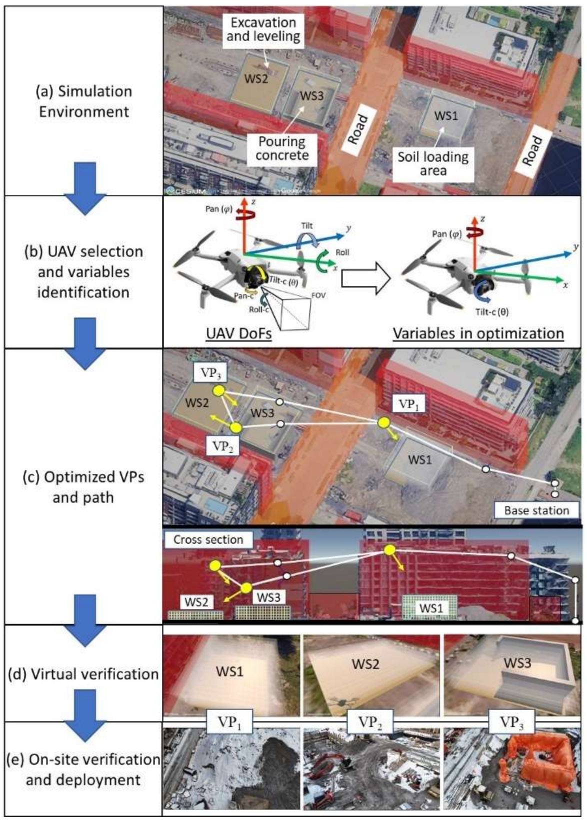

Figure 3. Workflow implementation in the case study

The UAV supports pre-planned flight operations under GNSS and provides an API [22] for importing mission files from a computer. Its camera captures 4K videos in MP4 format at up to 100 fps and offers a diagonal field of view (FOV) of 82.1° and a horizontal FOV of 74.3°, ensuring high-quality video collection for construction monitoring.

The variables for the viewpoint (VP) optimization module are defined based on this UAV model. As illustrated in Figure 3(b), the UAV provides ten degrees of freedom (DoFs). Six of these are associated with the UAV's pose (x, y, z, pan, tilt, and roll), while the camera, mounted on a 3-axis mechanical gimbal, introduces four additional DoFs (pan-c, tilt-c, roll-c, and FOV). However, the API does not allow the control of the tilt and roll angles of the UAV, as well as the pan and roll angles of the camera. In addition, the camera's FOV is fixed at its default value. Thus, the variables considered in the optimization process are the UAV's position (x, y, z), its pan angle (φ), and the tilt angle of the camera (θ).

5.2 Prototype development

A prototype system was developed using Unity3D game engine [19] to create a simulation platform for VPs optimization and path planning. As mentioned in Section 3.1, a method for translating the waypoints of the optimized path in the local coordinate of the path simulation platform to the UAV-readable waypoints under GCS is required. The 3D geospatial platform add-in for Unity named Cesium [31] is used for this purpose. The prototype system is run on a computer with i7-6800k CPU, 64 GB of random access memory (RAM), and two GTX 1070 GPUs.

5.3 Results

The results from the simulation-based path planning platform are multiple top-ranking VPs identified for each workspace. Using these top-ranking VPs, the path optimization module generates an optimized flight path as shown in Figure 3(c). The time required to travel between different waypoints is calculated. In this case study, the expected number of cycles per operation is 30, and the operation safety factor α for calculating the total operation time is set to 0.9. The traveling time between VPs (T_{total}^{F}), the total hovering time(T_{total}^{H}), and the total duration (T_{CP}) of one cycle path are calculated as shown in Table 2, using the method outlined in [16].

Table 2 Path durations with 30 expected cycles

Operation	Duration (s)
Base station → VP_1	9.55
Total cycle path (T_{CP})	53.36
- Total flight time (T_{total}^{F})	13.22
- VP_1→ VP_2	5.64
- VP_2→ VP_3	1.70
- VP_3→ VP_1	5.88
- Total hovering time (T_{total}^{H})	40.14
- Hovering at VP_1	10.04
- Hovering at VP_2	10.03
- Hovering at VP_3	20.07
VP_1→ Base station	9.55

Due to the higher level of interest associated with the task of pouring concrete, a higher importance level weight (W_{WP}) of 2 is assigned, while a weight of 1 is given to other workspaces. The distributions of the hovering durations for each VP are calculated as shown in Table 2. Virtual verification is performed as shown in Figure 3(c) to assess the efficiency and effectiveness of video collection along the optimized path. Figure 3(d) illustrates the simulated camera views when hovering at three VPs along the optimized path.

Finally, an on-site test was conducted to validate the optimized path, as shown in Figure 3(e). The results demonstrate that the UAV successfully navigated to the designated hovering waypoints and adjusted its FOV to the intended angles, capturing videos of the areas of interest where construction activities were happening according to the schedule.

6 Conclusions and Future Work

This paper highlights the key practical considerations for implementing autonomous UAV-based video collection of outdoor construction activities. It also proposes a workflow for achieving optimized and efficient video collection using autonomous UAVs. A case study on a construction site is conducted for validation. The results of the case study demonstrate that the workflow is effective in generating an operational plan with optimized waypoints, enabling the UAV to capture videos of construction activities from areas where the main tasks are taking place.

Despite its effectiveness, several areas of the proposed workflow require further refinement. The proposed workflow focuses on collecting videos of progress-related construction activities within predefined workspaces according to the as-planned schedule. However, the location of the workspaces may change, but these changes are not reflected in the schedule. In addition, other construction activities may occur outside the predefined workspaces. Future studies will develop methods for dynamically adjusting the UAV path during the operation whenever workspace locations change or new workspaces are identified. In addition, the case study presented in this research is based on a medium-scale construction site. Given the diverse and complex nature of construction sites, further testing is needed across various scenarios to evaluate the workflow's robustness, such as indoor environments.

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