UAS Flight Path Planning: A Comparative Analysis of Diverse Use Cases and Approaches

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Abstract

Uncrewed aircraft systems (UAS), also known as drones, have become increasingly popular in various applications due to their ability to access remote or challenging locations. A crucial aspect of UAS operations is flight path planning, which determines the trajectory the aircraft takes to achieve its mission objectives. However, the diverse use cases of UAS demand different planning approaches tailored to their specific requirements. This paper presents an overview over current research in UAS flight path planning and proposes a categorization of use cases based on their distinct goals and considerations. The terminology differentiates the goals of tasks between navigation-centric and data acquisition and also considers their context, domain, perspective, and sensors. We analyze existing approaches with a focus on UAS flight path planning for data acquisition using cameras, highlighting their strengths and limitations. This structured overview facilitates the understanding of the diverse landscape of UAS flight path planning and paves the way for the development of more targeted and effective solutions for various applications and their use cases. The analysis shows, that the term ”UAS flight path planning” is currently used in a variety of distinct use cases with diverging requirements, so a unified terminology should be established for clear communication.

1. Introduction

The application of uncrewed aircraft systems (UAS) for many different use cases has become ever more important. Their ability to fly to many locations unreachable for humans while carrying different payloads has made uncrewed aerial vehicles (UAVs) an important tool in different industries and science, for example civil engineering (Brilakis and Haas, 2020; Shakhatreh et al., 2019), transportation (Gupta et al., 2021; Jeong et al., 2021; Khan et al., 2021), or earth observation (Alvarez-Vanhard et al., 2021; Adade et al., 2021). These different applications bring with them a multitude of specific challenges and requirements for success. One common aspect is the planning of a path for the UAV, such that it reaches one or multiple points of interest (Gugan and Haque, 2023; Maboudi et al., 2023), a field of active research with many publications. One common observation in those publications is the need to plan the path of an UAV for reliably achieving the goals of the UAS application.

Studying the different uses of UASs, it becomes apparent that the different approaches also work towards different goals, even though they often use the same terms, especially ”UAS Flight Path Planning”. These goals are often not compatible, so the resulting solutions do not transfer between domains, such that an efficient path planning method for the navigation of a delivery drone does not support the monitoring of vegetation using UASs. And even in domains that appear to be similar, the results do not provide value across different problems, as for example the monitoring of bridges, as described by Morgenthal et al. (2019) has very different requirements from the monitoring of the environment (Blanchard and Sapsis, 2022). It often happens, that a new research paper with a promising title and keywords is published, only to show upon further examination that it is working towards a different goal with incompatible concepts.

Tackling this point, this work aims to provide an overview over different use cases for UAS flight path planning, with their different goals and considerations, to in the end propose a new terminology to better clarify and differentiate the applications. It further focuses on a specific application range, UAS flight path planning for data acquisition using cameras, and highlights current trends and approaches, together with commonly applied quality criteria and problem formulations. From this, a task definition is derived, that is applicable to this application range and allows distinguishing between different concrete problems.

The main contributions of this work are the following:

1. Presentation and structuring of the field of UAS flight path planning to differentiate between the various use cases
2. Dissemination of the current state of the art for UAS flight path planning for data acquisition with cameras around complex structures
3. Identification of important quality criteria and problem formulations
4. New formulation of the task of UAS flight path planning for data acquisition and generalization of the formulation to other use cases
5. Introduction of a new terminology and language for the field of UAS flight path planning to allow clearly differentiating between different use cases and ease communication

In the following section, the methodology of this study is presented, with focus on the research questions, the categorization of approaches, and criteria for the analysis of different approaches. In Section 3, an overview over the current state of the art is given, where the publications are evaluated using the identified criteria and selected publications are highlighted. The results of the analysis are shown in Section 4, which are used to answer the research questions and the use case of UAS flight path planning for data acquisition with cameras is formulated. The work concludes with a discussion of the results and future possibilities arising from them.

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2. Methodology

This work has the aim of giving an overview over existing approaches and use cases for UAS flight path planning and is therefore built around a literature review. This review is based on the method described by Kitchenham (2004) and consists of three main phases: In the planning phase in this section, the research questions are formulated, together with the criteria for inclusion and exclusion of contributions, and the data that is to be extracted for the selected contributions. In Section 3, the review is conducted by selecting relevant publications, structuring according to the defined criteria, and highlighting concepts and approaches of special interest. The results of the review are reported in Section 4, where the findings are synthesized and the research questions are answered. This section also contains recommendations that are motivated by the results of the study.

2.1 Selection and Categorization of Contributions

To be able to conduct a meaningful literature review, relevant publications need to be selected based on defined inclusion and exclusion criteria. Even though the boundaries between state of the art (what is done in practice) and state of research (what science is currently working on) in UAS flight path planning are not as strict as in other fields, this work only considered peer reviewed publications, either from conferences or journals, and excluded practice reports and documentation from service providers. Impact factor and similar indicators have not been considered for the selection to keep the field as wide as possible.

The collection of literature took place from 2018 to 2024 and was primarily based on Google Scholar, but also searches in Scopus using the terms *"UAS flight path planning"*, *"UAS path planning"*, and variations of those by replacing *"UAV"* with *"UAS"* and *"drone"*. A current (February 2024) Scopus search for these terms produces 5873 results. After also including the terms *"3D"* or *"three-dimensional"*, 1191 results remain. To select those publications, that are going to be analyzed and compared, from these results, the field of application needs to be constrained to compatible use cases, even though all those entries use the same terminology.

To facilitate this selection process, the field of UAS flight path planning was structured and categorized, as shown in Figure 1. The categorization is built on different aspects, that allow the characterization of contributions. Most of those aspects are independent from each other, so that their variations can be combined depending on the context, even though not all combinations are relevant in practice.

The most fundamental distinction is the **Goal** of the path planning. Here, two different goals are shown, while in practice also additional goals can be relevant, as discussed by Khan et al. (2021). The first goal covered here is navigation, where the UAV needs to reach one or multiple locations, while considering different constraints, such as obstacle avoidance, dynamic environments, or no-fly zones. Several publications in this area that use the term "UAS flight path planning, for example Aggarwal and Kumar (2020) or Padilla et al. (2020). The other goal is data acquisition, which in this work is considered as a rather wide field, where the aim of the UAS application is to collect some data and information about a scene.

Another important aspect, here called **Context**, concerns the use and therefore availability of a model of the scene. This influences if exploration or exploitation of the scene are of higher importance. A model usually is a 3D mesh that approximates the geometry of the scene, which needs to be referenced in a coordinate system compatible with the UAVs positioning system. Some model-free approaches do not require a model to be available before the planning, but propose to conduct a first rough data acquisition to obtain such a model. This is a practical way to work around a missing model, if the following planning is relying on the model geometry alone however, this approach is counted as model-based.

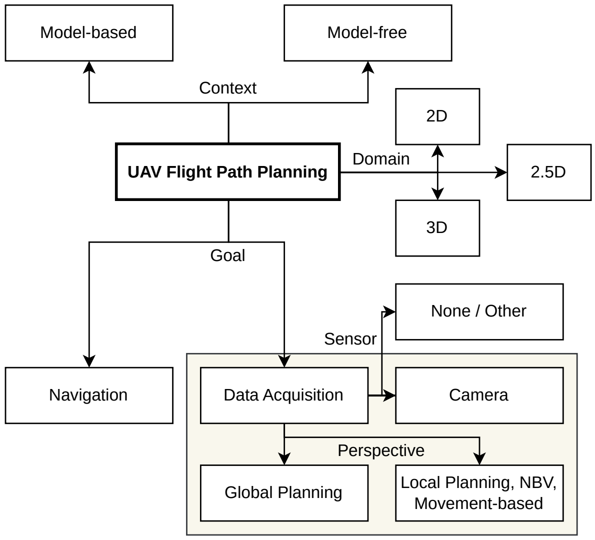

Figure 1. Different aspects of UAS flight path planning, that can be used to categorize approaches. The highlighted box shows the use case of focus for this work.

The **Domain** of a flight path concerns the dimensionality of the application. If a problem is solved in 2D space, the height of the flight and the shape of the terrain underneath it are not considered in the planning. In 2.5D, the height of the scene is considered, such that for each coordinate, also an altitude is known. To be able to fully represent complex structures, such as bridges, the scene and the flight path need to be considered in 3D space, which allows different scene topologies.

In the scope of applications for data acquisition, the used **Sensor** is also of relevance, as it influences the way the UAV needs to be positioned to capture data and what part of the surrounding can be perceived. Common sensors for UASs are laser or Lidar sensors that produce point clouds around the sensor position, and cameras that produce images of the scene. Cameras are commonly mounted on a gimbal for stabilization and face the same direction as the UAV with an additional degree of freedom, the pitch of the camera. Most systems allow the camera to look from $-90°$ (straight down) to $+90°$ (straight up), some however limit the pitch to a smaller range. Generally, UAS are also equipped with a global navigation satellite system (GNSS) receiver for positioning and a compass for orientation. Those are however not treated as sensors in this work.

In the context of UAS flight path planning with the goal of data acquisition, the **Perspective** of the planning procedure is of high interest. This work distinguishes between local and global perspectives. Local planning is defined by considering the movement of the UAV and the next position it should reach. A common concept is next best view (NBV) planning, where the flight path is planned by selecting the next position based on some quality criteria until a stopping condition is reached. Global planning on the other hand looks at the entire scene simultaneously and computes the flight path based on for example achieving full coverage of the scene. A fundamental challenge of both those perspectives is that both need to be considered for a successful application, so all approaches need to combine in some way. In the scope of this work, planning procedures are characterized by the primary perspective, whichever has the most influence on the planning.

To select those publications that are relevant for this work, a specific field of application is defined, and only those approaches are selected, that fall into it. This area is highlighted in Figure 1 and can be described as **UAS Flight Path Planning for Data Acquisition using Cameras**, while scene to be observed is a complex 3D structure, such as building or a bridge, such that the domain is constrained to 3D, while also 2.5D approaches are included, that at least consider vertical surfaces for the planning. Both model-free and model-based methods are considered. These limitations allow the identification of common criteria for the analysis of those approaches, as described in Section 2.3. Together with the 2D domain most applications in the field of earth observation are excluded, where the structure to inspect is fundamentally 2D or 2.5D and the view in nadir direction is generally sufficient.

2.2 Research Questions

To guide the review presented in this work, four research questions are formulated to gain insight into current topics and the use of the term ”UAS flight path planning”:

1. What approaches use the term ”UAS flight path planning” and which problem do they solve?
2. Is there a consensus on a well-defined problem setting? If so, which?
3. Which quality criteria a commonly employed in the planning and evaluation of UAS flight paths?
4. Is there a common terminology in the field of UAS flight path planning? If so, which is it? If not, which terms would be suitable?

While the first and last question concern the general field of the application of UAS, the other two questions target the application of UAS for data acquisition, the area highlighted in Figure 1, as described above.

2.3 Criteria for the Analysis of Approaches to UAS Flight Path Planning

As the literature for this work was collected continuously between 2018 and 2024, the criteria for the analysis were developed while following current research, by observing which aspects are commonly considered and which attributes of a method are suitable for differentiation, as shown in Figure 1. In addition to the **Context** and **Domain** aspects for the categorization, described in Section 2.1, six criteria were identified for the analysis of current approaches for UAS flight path planning for data acquisition with cameras and are shown in the overview over the literature in Table 1.

As the resulting plan is a series of viewpoints, positions and orientations for the UAV and the camera, the first two criteria concern the constraints on the positions and orientations of the viewpoints, which can significantly influence the resulting flight path and its suitability for the task.

The next criterion considers the fundamental approach for the planning procedure, inspired by criteria introduced by Maboudi et al. (2023). This is only meant to give an indication about the procedure and cannot sufficiently describe the approach. Instead, common keywords are used to roughly group the different approaches. Approaches that use *Set Selection* generally start with large set of viewpoint candidates and iteratively select a subset of them based on some criteria. *Iterative Addition* on the other hand means, that viewpoints are added to the flight path until a stopping condition is reached. When *Offset* is used for planning, the viewpoints are placed at a certain distance from the scene, based on some translation procedure. *Sample Refinement* is based on the concept of starting with some set of viewpoints, that is iteratively adjusted in position and orientation. *Movement-based* planning approaches the problem from a local perspective and the movement of the UAV is used to build a complete flight path. Similarly, *Next Best View* (NBV) planning approaches consider the surrounding of the current viewpoint and find the next best viewpoint that is reachable in one step. To simplify the planning procedure, *Decomposition*-based approaches partition the scene into smaller parts, for which simpler approaches or known patterns exist.

The final three criteria describe the quality criteria used for the planning and also evaluation of flight paths. These quality criteria are motivated by the literature, for example Wu et al. (2024), Liu et al. (2022b), or Debus and Rodehorst (2021) and the evaluation concerns, whether they are explicitly considered during planning. One criterion that is generally considered to be important for planning is the coverage of the scene, often also called completeness, abbreviated with the letter C in Table 1, which concerns, whether the entire surface of the structure is contained in the acquired data.

The resolution criterion, abbreviated with the letter δ in Table 1, asks, if the resulting resolution of the images on the surface of the scene, also called ground sampling distance (GSD) is considered in the planning. The resolution is usually defined for each specific application and directly influences the distance between the camera and the surface of the structure. This work puts strong focus on this aspect and also requires the resolution high enough that the surface of the scene can be inspected in detail, which for example in the work by Wu et al. (2024) requires a GSD $< 0.3mm$ and a distance $< 4m$. The effect of this is that scenes cannot be considered to be convex and that lateral views of structures are required, while the concrete shape and geometric features of the structure need to be considered in the planning.

The final criterion, abbreviated by Φ, is the reconstructability of the scene, as a measure how well a photogrammetric reconstruction, usually via structure from motion (SfM) (Ullmann, 1979), is possible from the captured images. While many different formulations exist (Liu et al., 2022b; Zhang et al., 2024; Shang and Shen, 2022b), they generally agree on considering the relative orientation of the viewpoints to each other, which forms the basis for triangulating the position of points on the surface.

It should be noted that this work is not the first overview over the state of the art in UAS flight path planning. Another notable overview has been presented by Maboudi et al. (2023), albeit with a much broader scope, for example also including evaluation strategies and benchmark datasets. A major difference of the here presented work is the strong focus on the quality requirements that are considered during the planning, as a very specific field of application is considered. Maboudi et al. (2023) strictly differentiate between model-free and model-based approaches and apply different criteria for them. For model-free methods, the approach to modelling the environment and planning next steps of the path are highlighted. For model-based methods, the possible space for viewpoints (corresponding to columns 4 and 5 in Table 1), the general idea, and the possibility of online computation are considered, resulting in a more general and broader overview over the field.

3. The Field of UAS Flight Path Planning Research

Using the criteria described in Section 2.1, 33 publications were selected and analyzed, an overview of which is shown in Table 1, is sorted by publication date and does not represent any ranking. This selection is not intended to give a complete overview of all relevant publications, but highlight different approaches and concepts, that are being applied to UAS flight path planning for data acquisition. In the following, those approaches are presented and categorized, to demonstrate the current field of research.

The group of model-free approaches stands out in particular, as they do not require a model of the scene to be available for the planning. While some of the model-based approaches use a preliminary data acquisition to build and model and therefore claim to not need a model, those model-free approaches actually do not rely on knowing the geometry, but build a model during inspection. Accordingly, some of them belong into the group of autonomous or real-time data collection, as they can – except for computational constraints – be conducted live without any real planning. While being outside of the core of this work, some interesting approaches are shown here to highlight their contributions, that could also improve model-based solutions. Zhou et al. (2020) use a map and satellite images to compute rough 2.5D proxy geometry based on the shadows, which they then use for planning. Liu et al. (2022a) manually place geometric primitives likes lines or polygons on a map and compute multiple rings of viewpoints around those. Zeng et al. (2023) define an implicit information gain model that is updated during flight and predicts useful next viewpoints. Feng et al. (2023) use a surface prediction module that integrates the observations during the flight to predict the geometry of the scene and plan the next viewpoints towards unseen faces. For the capturing of dynamic scenes, Jiang and Isler (2023) developed a system, that predicts the change in geometry and captures views from areas that are not well covered.

For the constraints on position and orientation of the viewpoints, many fundamentally different approaches are identified, as they all find different ways to combine the local placement of viewpoints with achieving global coverage of the scene. One common approach is to identify primitives on the surface of the structure and place the viewpoints directly over them along the normal direction, with a viewing direction towards the primitive. For example, Hoppe et al. (2012), Shang et al. (2020), and Li et al. (2023) use the triangles of the geometrical model, while Wu et al. (2024) use polygon clusters on the surface. Shang and Shen (2022b) place viewpoints over surface patches and use an iterative refinement scheme in which insufficiently covered surface patches are split until complete coverage is reached. They finally optimize the position of the viewpoints over the corresponding patches. Shang and Shen (2022a) start from a set with one viewpoint over each triangle and select a subset of those that provide best coverage and reconstructability, which finally is refined by adjusting viewpoint positions and orientations to increase reconstructability.

Other approaches place uniform grids in the scene and place viewpoints on those positions with different ways to determine the viewing direction and possible refinement of the viewpoints. For example, Roberts et al. (2017) place viewpoint candidates on the nodes of a grid with multiple viewing directions, from which first those directions are selected, that provide best coverage, and then in a submodular optimization those positions, that together fully cover the object. Schmid et al. (2012) place viewpoints on grid with viewing directions towards the center of the object and discard redundant viewpoints. Smith et al. (2018) start from a regular grid above the scene and views in nadir direction and adjust positions and orientations iteratively. Hepp et al. (2019) compute a large set of viewpoint candidates on a grid with viewing directions towards close faces of the mesh and solve a submodular optimization, where only candidates in the surrounding of existing viewpoints are available for selection. Koch et al. (2019) and Zhou et al. (2023b) use a grid to place multiple viewpoint candidates on each node with different viewing directions, from which a subset of suitable viewpoints is selected, by taking special consideration for resolution and reconstructability. Gómez-López et al. (2020) place viewpoints on a grid over an area of interest and adjust the height of the viewpoints based on the height profile of the ground and add viewpoints on a grid around an extruded 2D polygon. Based on simplified geometrical models, such as BIM models, Tan et al. (2021) place viewpoints on a grid that is placed parallel to the facades of a building, looking perpendicular to the surface. Zhao et al. (2023) create a large set of viewpoint positions in a grid around the structure and use genetic algorithms to compute a path through a selection of them, that reaches all parts of the scene. In a second step, they determine the orientation for each viewpoint towards not well covered triangle faces. A special case for grid-based methods is presented by Sui et al. (2023), where a 2D grid is used to compute the reconstructability contribution of viewpoint candidates, which are selected during planning as the next best viewpoint to reach a target position.

As finding suitable flight paths for complex geometries is a challenging problem, some authors propose to automatically simplify the geometry of the scene by decomposing it into primitives, where suitable flight paths are known or easily computable. A good example is given by Besada et al. (2018), where cylinders, rectangles, and lines are used to approximate the geometry of the scene. Peng and Isler (2019) place adaptive rectangles around the structure to approximate larger surface areas and place viewpoints on a grid in those rectangles. Zhou et al. (2023a) combine larger parts of the structure into approximately planar primitives and place viewpoints over them. Wang et al. (2022) decompose a simplified BIM model of a structure into surface parts, for which they compute viewpoints on parallel surfaces with special consideration for curvature and corners, to keep resolution and reconstructability high.

One approach that has been demonstrated in multiple versions is based on analyzing the reconstructability of the scene based on an initial flight path and adding viewpoints in those areas that are not well covered. **?** and Yan et al. (2021) start with a regular

Reference	Model	3D	Position	Orientation	Approach	C	δ	Φ
Hoppe et al. (2012)	●	●	Over center of the triangle	$\perp$ to triangle	Set Selection	●	○	◐
Schmid et al. (2012)	●	○	Grid over object	$\perp$ to smoothed surface model	Set Selection	●	◐	◐
Roberts et al. (2017)	●	●	Uniform grid around the scene	Towards most unseen faces	Set Selection	●	◐	○
Besada et al. (2018)	●	●	Sampled around primitives	$\perp$ to primitive, or constant for all	Offset	○	◐	○
Smith et al. (2018)	●	○	Optimized starting from regular grid in one height	Optimized for contribution to reconstruction	Sample Refinement	◐	○	●
Hepp et al. (2019)	●	○	Neighborhood of existing viewpoints	Random towards center	Iterative Addition	◐	○	◐
Sharma et al. (2019)	●	○	On parallel contour around cross section	Optimized for coverage from a slicing offset ring	Offset, Decomposition	◐	◐	○
Koch et al. (2019)	●	●	Grid in free space around structure	Towards the center of visible points	Set Selection	◐	●	●
Peng and Isler (2019)	●	●	Grid on adaptive viewing rectangle	$\perp$ to adaptive viewing rectangle	Offset	○	◐	◐
?	●	○	Initial nadir path plus over uncertain areas	$\perp$ to surface and error ellipsis	Set Selection, Sample Refinement	●	○	○
Shang et al. (2020)	●	●	Over triangular surface in distance	Limited pitch, no roll	Sample Refinement	◐	●	○
Zhou et al. (2020)	○	○	Over sampled points on surface	Normal direction	Set Selection	○	○	●
Gómez-López et al. (2020)	●	○	Grid over ground and on the boundary of a polygon	$\perp$ to surface	Offset	●	◐	○
Yan et al. (2021)	●	○	Nadir path, over uncertain areas	Towards point on surface	Iterative Addition	●	○	●
Tan et al. (2021)	●	○	Grid over each surface	$\perp$ to surface	Offset	◐	●	○
Zhang et al. (2021)	●	○	Randomly placed, steps in between for continuity	In direction of max. information gain	Movement-based	●	○	●
Shang and Shen (2022a)	●	●	Over center of triangle	Towards uncovered area	Set Selection	◐	○	●
Shang and Shen (2022b)	●	●	Hemisphere around triangle	$\perp$ to triangle	Iterative Addition	◐	○	●
Wang et al. (2022)	●	●	Offset grid over surfaces and edges	$\perp$ to edge	Offset	◐	●	●
Liu et al. (2022a)	○	○	Offset grid over primitives	$\perp$ to primitive	Offset	○	◐	◐
Liu et al. (2022b)	●	○	On hemisphere above sample point	Towards point on surface	Iterative Addition	●	○	●
Ivić et al. (2023)	●	●	Free placement in high potential area	Towards closest point on the surface	Movement-based	○	●	◐
Zeng et al. (2023)	○	●	Neighborhood of last viewpoint	Sampled pitch and yaw	Next Best View, Iterative Addition	◐	○	●
Zhang et al. (2023)	●	○	On hemisphere above hole or $\perp$ to error ellipsoid	Towards point on surface	Iterative Addition	●	○	●
Feng et al. (2023)	○	●	Area that covers unseen surface	Towards point on surface	Movement-based, Next Best View	●	○	●
Li et al. (2023)	●	●	Poisson sampling on the surface and offset via normal	Normal of the corresponding surface	Offset	○	●	●
Zhou et al. (2023a)	●	●	Along the normal above the computed primitives	Inverse surface normal of the primitives	Offset, Decomposition	◐	○	●
Zhao et al. (2023)	●	●	Grid in space around object	Towards uncovered faces	Optimization, Set Selection	●	○	○
Jiang and Isler (2023)	○	○	Free	Free	Movement-based, Next Best View	◐	○	●
Sui et al. (2023)	●	○	Grid in free space around structure	Towards point on surface	Next Best View	◐	○	●
Zhou et al. (2023b)	●	○	Voxel grid around structure	Fixed based on cube directions	Set Selection, Iterative Addition	●	○	●
Zhang et al. (2024)	●	○	Hemisphere above hole or $\perp$ to error ellipsoid	Towards point on surface	Iterative Addition	●	○	●
Wu et al. (2024)	●	●	Along the normal above triangles	$\perp$ to triangle	Iterative Addition	●	●	○

Table 1. Overview over publications in the field of UAS flight path planning research, categorized after the described criteria. The column abbreviated column titles mean: C: Coverage, δ: Resolution, Φ: Reconstructability. The $\perp$ symbol stands for perpendicular.

overhead flight and then add viewpoints to refine the reconstruction, close holes, and increase reconstructability. Zhang et al. (2023) create a first set of viewpoints by computing one candidate per triangle and reducing this set to only keep those required for complete coverage. This set of viewpoints is refined by adding viewpoints over incomplete or imprecise regions. In an extension of their work (Zhang et al., 2024), they start from an initial set of images of a previous inspection instead and refine those viewpoints.

While most of the analyzed publications approach the task of UAS flight path planning from the global perspective, some movement-based approaches look from a local perspective. During planning, the next viewpoint is selected based on the last position and an estimation of the quality of possible next viewpoints. Zhang et al. (2021) compute a view information field for this purpose, which encodes the information gain from viewpoint positions in free space. From a starting point, they conduct an iterative tree search to find a flight path that achieves complete coverage of the scene and maximizes the information gain. With the goal deploying multiple UASs optimally, Ivić et al. (2023) compute a distance field around the structure and use it to guide the UAVs around the structure in the correct distance for the required resolution. To find the next viewpoint, they combine a second order movement model with a gradient-based search for a good viewpoint and obstacle avoidance. The resulting flight paths provide smooth flight and high resolution, but may contain holes in the coverage.

Liu et al. (2022b) trained a neural network to predict the improvement in reconstructability for a viewpoint candidate and use this network to iteratively initialize, eliminate, and adjust viewpoints to achieve high reconstructability of the scene.

By intersecting the model of the scene with horizontal planes, Sharma et al. (2019) extract the contours of the scene and can place viewpoints on a parallel line around that contour, while adjusting for obstacles. By combining the viewpoints from all slices with a grid of nadir viewpoints over the scene, a path for the complete structure can be computed, even though sharp geometric features of the structure and large height differences can be a challenge.

One important observation in Table 1 is that only seven approaches explicitly consider the resolution of the captured data, while another seven approaches address it as a less relevant aspect. This shows a possible gap in the current research, as the resolution of the data is important to be able to gain the desired knowledge about a scene. This could be motivated in the fact, that very high resolution and coverage can be conflicting goals that cannot be easily unified, so most approaches prioritize the reconstructability of the scene, which is considered in 23 out of 33 analyzed approaches.

4. Results of the Analysis and Task Definition

The conducted literature review allowed insight gain into the current state of research in the field of UAS flight path planning. The analysis of the approaches showed that the chosen criteria are suitable for differentiating the approaches. The quality criteria coverage, resolution, and reconstructability allow identifying important aspects that are considered for the planning and show promising contributions. One special point to note is that the consideration of reconstructability has become more important in later contributions. Further, those quality requirements showed, that no approach explicitly considers all of them, so single preferred solution could be identified.

Based on this analysis, the three formulated research questions can be answered:

1. Many different approaches use the term ”UAS flight path planning”, as described in Section 2.1. They consider very diverse problem settings, so the term alone is not sufficient to classify an approach. Instead the term ”UAS flight path planning for data acquisition” is more suitable for this specific use case.
2. However, even in this smaller field, the problem that approaches solve is different, especially regarding the target qualities and the constraints on the viewpoints. The requirement of high-resolution surface coverage is only rarely covered by the analyzed approaches and remains an open question. Accordingly, no consensus on the problem formulation exists.
3. The most common quality criteria are coverage, resolution and reconstructability, even though they have not been considered together yet. Other aspects, such as energy consumption, path length, or number of images are sometimes included and generally treated as optimization targets.
4. The analysis of the approaches showed, that some terms, such as coverage and reconstructability are used consistently in literature. For the definition of concrete tasks and the delimitation of different problems, however, exist no established terms. A structuring of the field, based on the terms in Figure 1, in a new taxonomy could improve this situation by characterizing different approaches based on their context, goal, domain, perspective, and sensors.

To unify the terminology in this field and to allow simpler communication of ideas and approaches, we propose the following formulation for this specific task, based on the definitions made by Debus and Rodehorst (2021). The goal is to acquire data about a structure, that has a complex 3D geometry and significant differences in height above ground. The sensor used for the data acquisition is a camera mounted on the UAV, so the entire capturing system has 5 degrees of freedom (roll around the viewing direction is not permitted). The result of the flight path planning is one (or multiple for multiple UASs) ordered series of viewpoints. The requirements for the planning are complete coverage of the surface, sufficiently high resolution for the task, and good reconstructability. All three requirements need to be fulfilled over the entire surface. The concrete requirements for resolution and reconstructability depend on the specific setting and need to be defined before the planning. The number of images and the path length are used as optimization targets to produce efficient flight paths. Additional constraints are the depth of field, safety distance to the surrounding, and a first order motion model for the UAV, such that target positions can be directly given and a smooth flight path is not required.

5. Conclusions and Outlook

In this work, a study over the current research in the field of UAS flight path planning was conducted. The motivation of the study was to differentiate approaches for different use cases that all use the same term ”UAS flight path planning”, a source of confusion. For the selection of suitable approaches for a deeper analysis, a system for the characterization was presented in Section 2.1. The use case considered for the analysis is the UAS flight path planning for data acquisition using cameras, for which additional criteria for the analysis were defined in Section 2.3, specifically coverage, resolution, and reconstructability. In Section 3, a total of 33 publications were selected and analyzed, while significant contributions were highlighted and presented.

The presented approaches in Table 1 are shown in chronological order without any ranking. To provide a different order and be able to compare the suitability of different approaches, a ranking could be introduced, based on an evaluation method such as proposed by Debus and Rodehorst (2021), that considers the use case defined above and the specific requirements of the inspection task. Apart from allowing practitioners to select favourable approaches for their application, this would allow to compare different approaches to UAS flight path planning and identify those ideas that are most promising to advance this field of research.

The analysis of the different approaches showed, that even in this specialized field, the concrete problems are still varying, especially with regard to the considered criteria, so no consensus on a problem formulation could be identified. To remedy this, a specific problem formulation was proposed in Section 4, which together with the characterization of use cases based on Figure 1 can support clearer delimitation of different research fields and their solutions.

In future, those characterizations could be used to build out a taxonomy for the field of UAS flight path planning, which allows the clear and unambiguous definition of applications in the field of UAS flight path planning. This could form the foundation for better collaboration of researchers by bringing clarity to the terminology and allowing easier identification of suitable and transferable solutions. By using a common language to communicate results and ideas, promising approaches and concept could be identified and combined, to work towards reliable application of UAS across industries and disciplines.

References

Adade, R., Aibinu, A. M., Ekumah, B., Asaana, J., 2021. Unmanned Aerial Vehicle (UAV) Applications in Coastal Zone Management—a Review. *Environmental Monitoring and Assessment*, 193(3), 154.

Aggarwal, S., Kumar, N., 2020. Path Planning Techniques for Unmanned Aerial Vehicles: A Review, Solutions, and Challenges. *Computer Communications*, 149, 270–299.

Alvarez-Vanhard, E., Corpetti, T., Houet, T., 2021. UAV & Satellite Synergies for Optical Remote Sensing Applications: A Literature Review. *Science of Remote Sensing*, 3, 100019.

Besada, J., Bergesio, L., Campaña, I., Vaquero-Melchor, D., López-Araquistain, J., Bernardos, A., Casar, J., 2018. Drone Mission Definition and Implementation for Automated Infrastructure Inspection Using Airborne Sensors. *Sensors*, 18(4), 1170.

Blanchard, A., Sapsis, T., 2022. Informative Path Planning for Anomaly Detection in Environment Exploration and Monitoring. *Ocean Engineering*, 243, 110242.

Brilakis, I., Haas, C., 2020. *Infrastructure Computer Vision*. Butterworth-Heinemann, Oxford.

Debus, P., Rodehorst, V., 2021. Evaluation of 3D UAS Flight Path Planning Algorithms. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLIII-B1-2021, 157–164.

Feng, C., Li, H., Gao, F., Zhou, B., Shen, S., 2023. PredRecon: A Prediction-boosted Planning Framework for Fast and High-quality Autonomous Aerial Reconstruction. *2023 IEEE International Conference on Robotics and Automation (ICRA)*, IEEE, London, United Kingdom, 1207–1213.

Gómez-López, J. M., Pérez-García, J. L., Mozas-Calvache, A. T., Delgado-García, J., 2020. Mission Flight Planning of RPAS for Photogrammetric Studies in Complex Scenes. *ISPRS International Journal of Geo-Information*, 9(6), 392.

Gugan, G., Haque, A., 2023. Path Planning for Autonomous Drones: Challenges and Future Directions. *Drones*, 7(3), 169.

Gupta, A., Afrin, T., Scully, E., Yodo, N., 2021. Advances of UAVs toward Future Transportation: The State-of-the-Art, Challenges, and Opportunities. *Future Transportation*, 1(2), 326–350.

Hepp, B., Nießner, M., Hilliges, O., 2019. Plan3D: Viewpoint and Trajectory Optimization for Aerial Multi-View Stereo Reconstruction. *ACM Transactions on Graphics*, 38(1), 1–17.

Hoppe, C., Wendel, A., Zollmann, S., Pirker, K., Irschara, A., Bischof, H., Kluckner, S., 2012. Photogrammetric camera network design for micro aerial vehicles. *Computer Vision Winter Workshop (CVWW)*, 8, 1–3.

Ivić, S., Crnković, B., Grbčić, L., Matleković, L., 2023. Multi-UAV Trajectory Planning for 3D Visual Inspection of Complex Structures. *Automation in Construction*, 147, 104709.

Jeong, H. Y., Song, B. D., Lee, S., 2021. The Flying Warehouse Delivery System: A Quantitative Approach for the Optimal Operation Policy of Airborne Fulfillment Center. *IEEE Transactions on Intelligent Transportation Systems*, 22(12), 7521–7530.

Jiang, Q., Isler, V., 2023. Onboard View Planning of a Flying Camera for High Fidelity 3D Reconstruction of a Moving Actor. *arXiv preprint arXiv:2308.00134*.

Khan, M. T. R., Muhammad Saad, M., Ru, Y., Seo, J., Kim, D., 2021. Aspects of Unmanned Aerial Vehicles Path Planning: Overview and Applications. *International Journal of Communication Systems*, 34(10), e4827.

Kitchenham, B., 2004. Procedures for Performing Systematic Reviews. *Keele, UK, Keele University*, 33(2004), 1–26.

Koch, T., Körner, M., Fraundorfer, F., 2019. Automatic and Semantically-Aware 3D UAV Flight Planning for Image-Based 3D Reconstruction. *Remote Sensing*, 11(13), 1550.

Li, Q., Huang, H., Yu, W., Jiang, S., 2023. Optimized Views Photogrammetry: Precision Analysis and a Large-Scale Case Study in Qingdao. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 1–17.

Liu, X., Ji, Z., Zhou, H., Zhang, Z., Tao, P., Xi, K., Chen, L., Marcato Junior, J., 2022a. An Object-oriented UAV 3D Path Planning Method Applied in Cultural Heritage Documentation. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, V-1-2022, 33–40.

Liu, Y., Lin, L., Hu, Y., Xie, K., Fu, C.-W., Zhang, H., Huang, H., 2022b. Learning Reconstructability for Drone Aerial Path Planning. *ACM Transactions on Graphics (TOG)*, 41(6), 1–17.

Maboudi, M., Homaei, M., Song, S., Malihi, S., Saadatseresht, M., Gerke, M., 2023. A Review on Viewpoints and Path Planning for UAV-Based 3-D Reconstruction. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 16, 5026–5048.

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.

Padilla, G. E. G., Kim, K.-J., Park, S.-H., Yu, K.-H., 2020. Flight Path Planning of Solar-Powered UAV for Sustainable Communication Relay. *IEEE Robotics and Automation Letters*, 5(4), 6772–6779.

Peng, C., Isler, V., 2019. Adaptive View Planning for Aerial 3D Reconstruction. *2019 International Conference on Robotics and Automation (ICRA)*, IEEE, Montreal, QC, Canada, 2981–2987.

Roberts, M., Dey, D., Truong, A., Sinha, S., Shah, S., Kapoor, A., Hanrahan, P., Joshi, N., 2017. Submodular Trajectory Optimization for Aerial 3D Scanning. *arXiv:1705.00703 [cs]*.

Schmid, K., Hirschmüller, H., Dömel, A., Grixa, I., Suppa, M., Hirzinger, G., 2012. View Planning for Multi-View Stereo 3D Reconstruction Using an Autonomous Multicopter. *Journal of Intelligent & Robotic Systems*, 65(1-4), 309–323.

Shakhatreh, H., Sawalmeh, A. H., Al-Fuqaha, A., Dou, Z., Almaita, E., Khalil, I., Othman, N. S., Khreishah, A., Guizani, M., 2019. Unmanned Aerial Vehicles (UAVs): A Survey on Civil Applications and Key Research Challenges. *IEEE Access*, 7, 48572–48634.

Shang, Z., Bradley, J., Shen, Z., 2020. A Co-Optimal Coverage Path Planning Method for Aerial Scanning of Complex Structures. *Expert Systems with Applications*, 158, 113535.

Shang, Z., Shen, Z., 2022a. Flight Planning for Survey-Grade 3D Reconstruction of Truss Bridges. *Remote Sensing*, 14(13), 3200.

Shang, Z., Shen, Z., 2022b. Topology-Based UAV Path Planning for Multi-View Stereo 3D Reconstruction of Complex Structures. *Complex & Intelligent Systems*.

Sharma, O., Arora, N., Sagar, H., 2019. Image Acquisition for High Quality Architectural Reconstruction. *Proceedings of Graphics Interface 2019*, Kingston.

Smith, N., Moehrle, N., Goesele, M., Heidrich, W., 2018. Aerial Path Planning for Urban Scene Reconstruction: A Continuous Optimization Method and Benchmark. *ACM Transactions on Graphics*, 37(6), 183:1–183:15.

Sui, H., Zhang, H., Gou, G., Wang, X., Wang, S., Li, F., Liu, J., 2023. Multi-UAV Cooperative and Continuous Path Planning for High-Resolution 3D Scene Reconstruction. *Drones*, 7(9), 544.

Tan, Y., Li, S., Liu, H., Chen, P., Zhou, Z., 2021. Automatic Inspection Data Collection of Building Surface Based on BIM and UAV. *Automation in Construction*, 131, 103881.

Ullmann, S., 1979. The Interpretation of Structure from Motion. *Proceedings of the Royal Society of London. Series B. Biological Sciences*, 203(1153), 405–426.

Wang, F., Zou, Y., del Rey Castillo, E., Ding, Y., Xu, Z., Zhao, H., Lim, J. B., 2022. Automated UAV Path-Planning for High-Quality Photogrammetric 3D Bridge Reconstruction. *Structure and Infrastructure Engineering*, 1–20.

Wu, W., Funabora, Y., Doki, S., Doki, K., Yoshikawa, S., Mitsuda, T., Xiang, J., 2024. Evaluation and Enhancement of Resolution-Aware Coverage Path Planning Method for Surface Inspection Using Unmanned Aerial Vehicles. *IEEE Access*, 12, 16753–16766.

Yan, F., Xia, E., Li, Z., Zhou, Z., 2021. Sampling-Based Path Planning for High-Quality Aerial 3D Reconstruction of Urban Scenes. *Remote Sensing*, 13.

Zeng, J., Li, Y., Ran, Y., Li, S., Gao, F., Li, L., He, S., Chen, J., Ye, Q., 2023. Efficient View Path Planning for Autonomous Implicit Reconstruction. *2023 IEEE International Conference on Robotics and Automation (ICRA)*, IEEE, London, United Kingdom, 4063–4069.

Zhang, H., Yao, Y., Xie, K., Fu, C.-W., Zhang, H., Huang, H., 2021. Continuous Aerial Path Planning for 3D Urban Scene Reconstruction. *ACM Transactions on Graphics*, 40(6), 1–15.

Zhang, S., Liu, C., Haala, N., 2024. Guided by Model Quality: UAV Path Planning for Complete and Precise 3D Reconstruction of Complex Buildings. *International Journal of Applied Earth Observation and Geoinformation*, 127, 103667.

Zhang, S., Zhang, W., Liu, C., 2023. Model-Based Multi-UAV Path Planning for High-quality 3D Reconstruction of Buildings. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-1/W2-2023, 1923–1928.

Zhao, Y., Lu, B., Alipour, M., 2023. UAS-based Automated Structural Inspection Path Planning via Visual Data Analytics and Optimization. *arXiv preprint arXiv:2312.15109*.

Zhou, H., Ji, Z., You, X., Liu, Y., Chen, L., Zhao, K., Lin, S., Huang, X., 2023a. Geometric Primitive-Guided UAV Path Planning for High-Quality Image-Based Reconstruction. *Remote Sensing*, 15(10), 2632.

Zhou, H., Liu, Y., Ji, Z., 2023b. A UAV Photographic Path Planning Method for High-quality Reconstruction of Cultural Heritage. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-1-W1-2023, 579–586.

Zhou, X., Xie, K., Huang, K., Liu, Y., Zhou, Y., Gong, M., Huang, H., 2020. Offsite Aerial Path Planning for Efficient Urban Scene Reconstruction. *ACM Transactions on Graphics*, 39(6), 1–16.

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