Virtual Prototyping-Based Path Planning of Unmanned Aerial Vehicles for Building Exterior Inspection

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Abstract –

Proper building maintenance is critical to ensuring the well-being of citizens and sustainable development of the urban environment. For high-rise high-density cities, one challenge to building maintenance concerns the inspection of building exteriors, which has been mostly done manually but is of highly risky, labor-intensive, and error-prone. Unmanned aerial vehicles (UAVs) have the potential to support building exterior inspection in a safe and efficient way. However, the effective application of UAVs for exterior inspection is hindered by path planning problems in high-rise high-density urban areas. Previously developed path planning algorithms are constrained by algorithmic complexity and cannot be implemented in a large three-dimensional space. Besides, path planning assisting tools available in the market that supported by Google Earth Pro can hardly assure high accurate results. In this paper, a new virtual prototyping-based path planning system is developed for UAVs for building exterior inspection in high-rise high-density urban areas. Unreal Engine as a widely-used game engine was applied. The system provides a realistic game world to simulate real-world activities, which enables operators to design UAV paths like playing games. The flight paths and viewpoints can be repeatedly tested in a gaming context until requirements are satisfied. The system integrates expert knowledge through "human in the loop" and realistic information on the virtual environment featured with repeatability. The system thereby greatly alleviates the risks that are induced by physical constraints in the real world when adopting UAV, and thus should significantly improve the effectiveness and efficiency of building exterior inspection.

Keywords –

Unmanned aerial vehicles (UAVs); Path planning; Building exterior inspection; Virtual prototyping; Human in the loop

1 Introduction

The importance of proper maintenance of buildings has been widely recognized to ensure that buildings are function effectively and efficiently for well-being of citizens and sustainable development of the urban environment [1]. For high-rise high-density cities like Hong Kong, one of the most challenging issues with maintenance is the inspection of building exteriors. Visual inspection by professionals is the most common method, but is highly risky, labor-intensive, and error-prone. Tools, such as telescopes and cameras, are applied to help inspectors. Still, they are limited in the distance and inefficiency until the commercialization of Unmanned Aerial Vehicles (UAVs).

UAVs refer to an aircraft that is operated with no pilot on board, also termed as drones or Unmanned Aerial Systems (UASs) [2]. UAVs have great potentials in the construction industry [3]. When paired with video recording and digital cameras, UAVs could provide professionals with an aerial perspective to overcome the inaccessible areas without compromising their safety. UAVs enable various types of surveying services for professionals [2]. Despite the well-demonstrated benefits in reduced labor, cost and risk, there are issues hindering the effective application of UAVs. A critical one is path planning, which is closely related to UAV performance and usually done by drone operators. Due to the flight time limitation, operators could make limited adjustments during operation. It is a sophisticated task to plan paths and viewpoints in a highly accurate manner to avoid collision and invalid data collection, which is even more difficult in high-rise high-density urban contexts like Hong Kong. Especially for tasks such as building exterior inspection (e.g. crack and loose object detection). Moreover, poor path planning could result in distorted images captured from inappropriate viewpoints that further induce false positives [7].

Previously developed path planning methods, such as Dijkstra algorithm [8], A* [9], and D* [10], focus on the optimization of path distance by considering physical constraints in mathematics. These methods well tackle the distance and obstacle problems, but seldomly address the data effectiveness with the environment in high abstraction. In addition, path planning for UAVs requires the exploration of three-dimensional (3D) space. Many existing algorithms are constrained with its space complexity such as A*, since desktops cannot offer enough memory to store all generated nodes if it needs to explore a large space. Simulation-based methods are preferable to investigate the mechanisms behand path planning for UAVs cost-effectively. Particularly, virtual prototyping offers a favorable platform to animate the real world by using advanced game engines for optimization and visualization. By integrating expert knowledge and experience through "human in the loop" [11], virtual prototyping can be used to handle complex tasks in uncontrollable environments. Nevertheless, there is still lack of knowledge of how to effectively use virtual prototyping for UAV path planning.

Therefore, this paper aims to develop a new virtual prototyping-based path planning system for UAVs, within the context of building exterior inspection in high-rise high-density urban areas. Unreal Engine as a widely-used game engine was applied. Drone operators can simulate flight tasks such as playing games in the simulation system, e.g. controlling the virtual drone to fly in the game environment with virtual cameras providing real-time images and videos. The flight paths and viewpoints can, therefore, be repeatedly tested in a gaming context until requirements are satisfied.

2 Literature Review

2.1 UAV for Exterior Inspection

UAVs originated from the military in 1916 [12], which has not been popularized until UAVs commercialization companies grow up in recent years. Later on, commercial companies, like DJI, made the UAVs commercialized and accessible to the public by providing low-price UAVs that are easy to operate. Owing to the aerial perspective that enables a broad variety of surveying services, UAV has gained considerable interest in the construction industry. One of the important applications is the exterior inspection of buildings. Caballero et al [3] developed a vision-based method to estimate the real motion of an UAV and applied it to the external building inspection. Emelianov [4] inspected the building facades by aerial laser using an UAV for difficult site conditions. Ellenberg [5] detected masonry cracks with visual images captured by an UAV. These applications promote the productivity of building inspection works and greatly reduce the risk of relevant workers. However, there are still some issues that need to be tackled, such as path planning and data effectiveness. Most commercial UAVs have a minimal capacity on flight time, which is usually less than 30 minutes. Path planning is, therefore, critical to not only avoid obstacles but also reduce unnecessary adjustments when operating UAVs [2]. Otherwise, the UAV operator has to abort the task frequently to change batteries, which no doubly decreases the productivity of inspection works.

2.2 Path Planning Methods for UAV

Considerable research has been conducted on the topic of path planning. Many reported methods for path planning are based on mathematics like Dijkstra's algorithm [8], A* [9], D* [10], rapidly-exploring random tree (RRT) [14], bath informed trees (BIT*) [15]. These algorithms can be used to address obstacles and distance problems, which have been successfully applied in game development and robotics for path planning. However, for tasks in building exterior inspection, an essential consideration is imaging effects that are greatly influenced by viewpoints, view angles, and light [2]. Previous path planning algorithms cannot take such constraints into account.

Therefore, in UAV applications in the construction industry for surveying and inspection, path planning tasks are usually conducted manually, which is highly related to operators' experiences. In addition, some operators use the waypoint method assisted by Google Earth Pro, which however has the accuracy issues [16]. The reported root mean square error (RMSE) of its control point is around 24.1m in developed countries and 44.4m in developing countries [16]. Other path planning tools on the market that are developed based on Google Earth Pro service have similar accuracy limitations. For high-rise high-density cities like Hong Kong, accuracy is a critical aspect when adopting UAVs to avoid accidents and improve data effectiveness. There is an urgent need for a user-friendly and accurate path planning tool that can help operators to effectively and efficiently design UAV paths for missions.

2.3 Virtual Prototyping in the Construction Industry

Virtual prototyping refers to the process of constructing and testing a digital mock-up to present, analyze, and test life-cycle aspects [17]. The development of building information modeling (BIM) promotes the application of virtual prototyping in the construction industry, which has been widely reported to increase productivity in design [18], manufacturing [19], construction [20] and maintenance stages [21]. Recently, virtual reality (VR) and augmented reality (AR) supported by powerful game engines are gaining increasing interest in both practice and research in the construction industry. For example, Du et al. [22] developed a real-time synchronization method between

BIM data and VR environment for collaborative decision. Cao et al. [23] adopted VR to study indoor fire evacuation and found out that people under the file emergency condition spent more time in finding their way to exit the building that those under control condition. Shi et al. [24] applied VR for impact assessment of construction workers' fall risk behavior, which demonstrates the effectiveness of using VR in safety studies. Webster et al. [25] developed an AR system for the construction, inspection, and renovation of architectural structures, which improved the construction of performances. Wang et al. [26] integrated AR with BIM to control the onsite construction progress, which demonstrated how AR and BIM can improve the way the information is accessed. With the development of game engines, virtual prototyping has demonstrated its greater potentials for the construction industry.

3 System Architecture

The overall system architecture by using a game engine for UAV path planning for building exterior inspection is proposed in Figure 1, including building environment model structure, game engine structure, device structure and professional structure. In building environment model structure, professional software provides 3D building and environment models, such as 3ds Max, Revit, Rhino 3D, etc. Game engine is the core of the system architecture that consists of a game world and three plugins: a UAV simulator, a model converter, and a path generator. Device structure consists of a remote controller and an UAV. In the human structure, relevant professionals (operators) could assess paths and viewpoints according to their expert knowledge.

The proposed system functions with three stages. Firstly, building environment models will be imported to the game engine by the model converter plugin, which provide the main contents of the game world. Secondly, remote controller will be linked to the game engine by the UAV simulator plugin. The remote controller enables professionals to control a virtual UAV in the game world to simulate the inspection task. The flight paths and viewpoints are repeatedly tested until all requirements are satisfied. Finally, the path generator plugin will generate a path planning file that can be directly used in a real UAV for automated operation.

4 System Development

To develop the system based on the proposed architecture shown in Figure 1, this research is based on the Unreal Engine as it is open source and one of the most popular game engines. The following sub-sections describe the design and development of three major components in the game engine, namely a UAV simulator, a model converter, and a path generator.

4.1 UAV Simulator

UAV simulators are usually designed for testing, operational training and research because of its cost-effectiveness and safety assurance. There are more than 20 types of UAV simulators reported in history [27]. By considering its openness, functions and stability, this research adopted the Microsoft AirSim UAV simulator built on Unreal Engine, shown in Figure 2 [28]. AirSim provides a broad variety of sensor simulations including camera, infrared camera, distance sensor, barometer and so on, which together with Unreal Engine could develop a realistic game world as shown in Figure 3. These sensors can greatly help the operators to make sophisticated mission planning tasks e.g. UAV path planning for building inspection in a cost-effective, safe and robust manner.

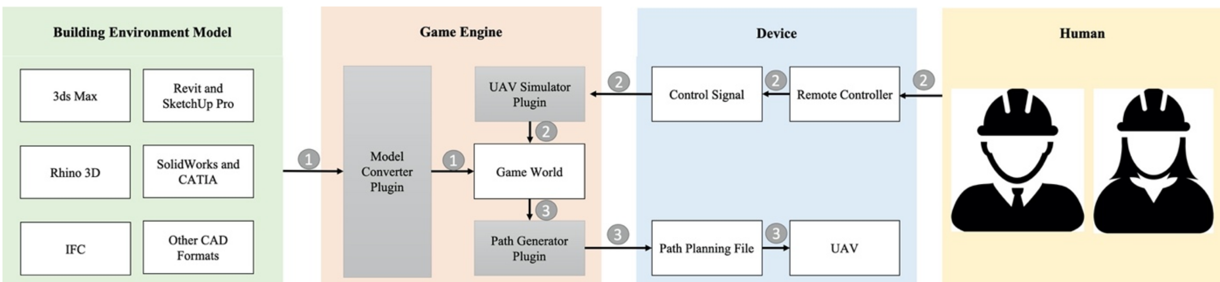

Figure 1. System architecture of the Virtual Prototyping-Based Path Planning for UAV

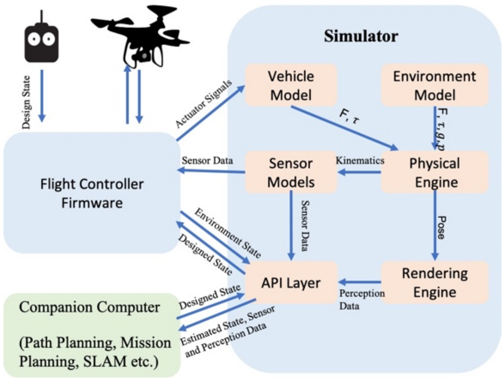

Figure 2. AirSim simulator architecture (reproduced from [28])

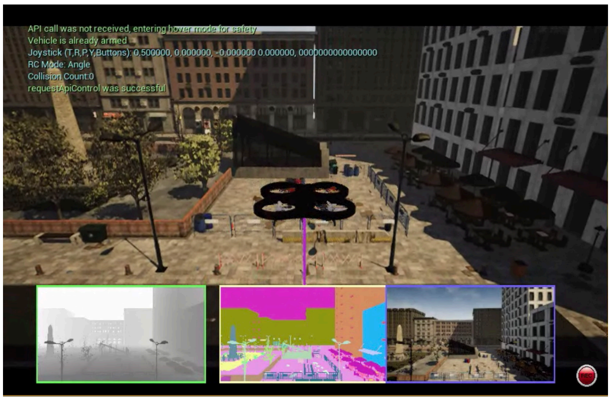

Figure 3. Game world in Unreal Engine

4.2 Model Converter

The model converter enables users to import building and environment models from other professional software. The model converter in the developed system is based on the DataSmith module in Unreal Engine, which supports model importation from a broad variety of professional software (e.g. 3ds Max, Revit and Rhino 3D) [29]. The model converter makes it convenient to build a game world in Unreal Engine based on building and environment models that are commonly available from the design stage of a construction project.

4.3 Path Generator

The path generator plugin records the UAV waypoints, view angles, actions (e.g. take an image or video) and speeds in the game world when professionals are testing paths and viewpoints. After the playing process, the path generator will output a path planning file that can be used in a real UAV, shown in Figure 4. In this research, DJI Matrice 210 V2 RTK (Figure 5) was used, and the path file is generated according to the requirements of DJI products. For example, the North East Down (NED) Coordinate System is applied in the developed path planning system, while geodetic datum is required as input coordinates by DJI products. Thus, the axes conversion [30] is needed during the path file generation, as shown in Figure 4. When the developed system is used for other types of UAVs, the path generator can be easily extended to generate a new path file according to specific requirements by other types of UAVs.

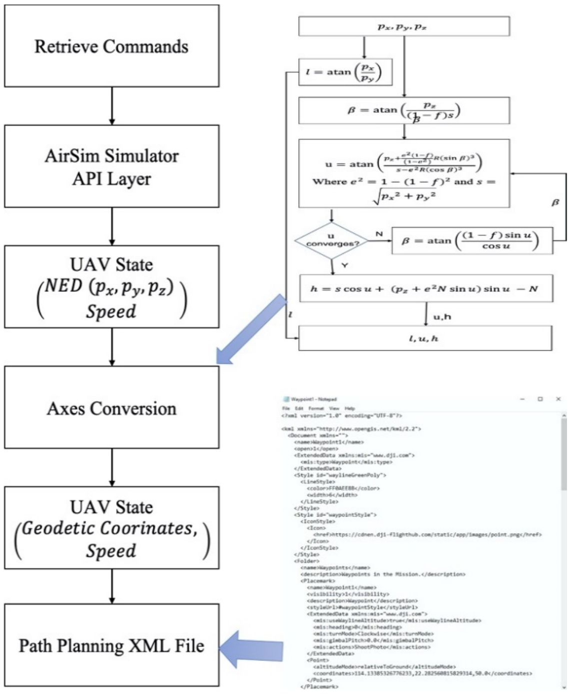

Figure 4. Procedure of path recording and file generation

Figure 5. DJI Matrice 210 V2 RTK used for the study

5 System Demonstration

In this section, demonstration of the developed virtual prototyping-based UAV path planning system was conducted for building exterior inspection, including viewpoint selection and path generation. To illustrate the effectiveness of the developed system, results from virtual prototyping-based method are analyzed and compared with results from using A* method [31] that is the most widely used algorithm for path planning [32].

5.1 Viewpoint Selection

To ensure a virtual camera in the game world can function like a physical camera in the real world, specifications of the virtual camera should be set up like the physical ones, e.g. field of view (FOV), aspect ratio, lens, etc. After that, the virtual camera can be used to test the locations and view angles of viewpoints (Figure 6). When the inspection area is larger than the FOV, more than one viewpoint should be used to cover the whole area, and overlaps could be tested at the same time.

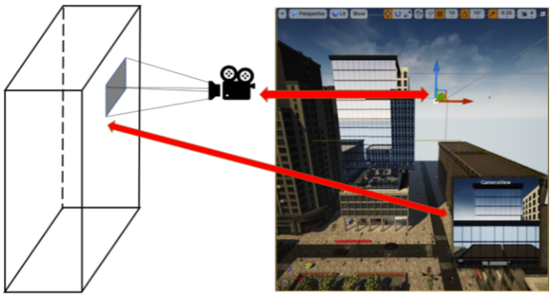

Figure 6. Viewpoint selection

5.2 Path Generation

As the space and the number of viewpoints increases, the challenge of adopting A* method will dramatically increase due to the algorithm complexity [31]. On the contrary, the virtual prototyping-based method is nearly not constrained in such cases. To avoid the problem of out of memory when adopting A* method, the comparative analysis is conducted with a single-viewpoint case. Results are shown in Figure 7, Figure 8 and Table 1.

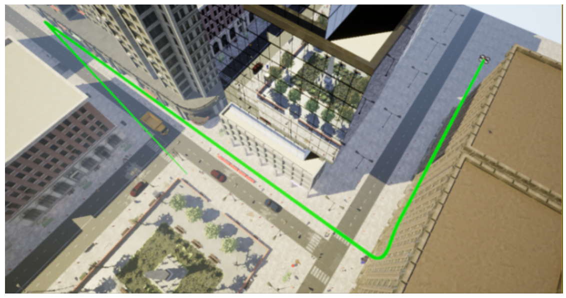

Figure 7. Path generated by the developed system (shown by green line)

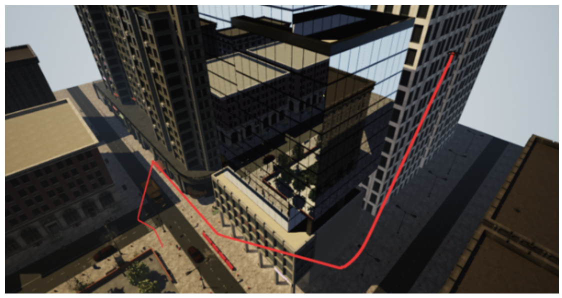

Figure 8. Path generated by A* (shown by red line)

Table 1. Geometry Comparison

Method	A*	Proposed Method
Start Point	(0, 0, 0)	(0, 0, 0)
Middle Points	(-0.9, 0.1, -5.0)	(0, 0, -48.8)
	(1.6, 2.6, -12.5)	(39.6, 0, -48.8)
	(6.6, -2.4, -27.5)	-
	(26.6, -2.4, -27.5)	-
	(41.6, -7.4, 32.5)	-
Viewpoint	(39.6, -22.3, -48.8)	(39.6, -22.3, -48.8)
Distance	88.7	110.7

Notes: local north, east, down (NED) coordinates and international system of units (IS)

In general, the path generated by the proposed visual prototyping-based method (Figure 7) has less twists and turns compared with the path generated by A* method (Figure 8). When implementing A*, the exploration space is discretized into 3D grids. By searching the whole 3D grids, A* method can usually find a shorter path (shown in Table 1) with more twists and turns by linking nodes in the 3D grids, compared with the proposed visual prototyping-based method. If the twists and turns are extremely irregular, UAVs cannot flight as the designed path due to motion constraints [33]. Besides, the path generated by the proposed method (Figure 8) crossed less dangerous areas (e.g. roads) compared with A* method

(Figure 7). The developed system provides a realistic game world for relevant professionals to design a path for UAVs in building exterior inspection like playing games. By implementing "human in the loop", the developed system can easily take more constraints into consideration by integrating expert knowledge and experience.

6 Discussion

Manual visual-based building exterior inspection is usually labor-intensive, time-consuming, error-prone and highly risky. As the low-price commercial UAVs are popularized, professionals start to use UAVs for building exterior inspection works, which brings in benefits including enhanced safety and efficiency. However, in high-rise high-density cities like Hong Kong, the complex flight environments require a more accurate path planning method that can help professionals to design path for their inspection task to avoid accidents (e.g. collision). Previously developed path planning methods like A* [9] well tackle the distance problem but cause too many twists and turns on a path. In addition, these mathematically based path planning methods like A* have a bottleneck on algorithmic complexity when they need to be applied in a large 3D space. The required computing time is too long, or the required memory space is too large [31]. Also, these algorithms seldomly considered the data effectiveness (e.g. image distortion and light effect). Therefore, these path planning algorithms are seldom adopted for inspection tasks in the construction industry.

Virtual prototyping enabled by game engines offers a realistic game word to simulate detailed activities in the real world. The virtual prototyping-based path planning method developed in this paper enables professionals to design UAV paths for their inspection tasks like playing games. The new method not only overcomes the bottleneck of algorithmic complexity of previous algorithms [31], but also takes into consideration more constraints (e.g. dangerous area, images distortion and light effect) by taking the advantage of expert knowledge through "human in the loop". Compared with path planning tools that are supported by Google Earth Pro, the developed system has a higher level of accuracy because the game world is constructed using accurate BIM models.

The developed path planning system involves game engine, UAV and professionals, which can be extended for more general applications in the construction industry. First, game engine can be used for mission planning for robotics. As the development of automation and control technology, adopting robotics has great potentials to improve the productivity in the construction industry [34][35] Robots can be trained, tested and assigned tasks by a game engine. Second, a cyber-physical system for construction management or even smart city management can be built by synchronization between the real and game worlds. Third, human can also be linked to the game world to maximize the power of human/hardware-in-the-loop (HHITL) [36]. For example, a professional can use remote controller to control a robot to conduct a task in a game environment for once, then the robot can learn how to conduct the task in the real world by itself through imitation learning [37].

7 Conclusions

Building exterior inspection using UAVs is widely recognized around the world in recent years, because of a broad variety of benefits including low cost, high safety and efficiency. However, there has been no user-friendly tool that can help professionals with path planning in an accurate and efficient manner. In this paper, a new virtual prototyping-based path planning system is developed for UAVs. It helps professionals to design an accurate path for inspection tasks efficiently. The new method will not only overcome the algorithm complexity problem that exists in many previously developed path planning algorithms, but also provide a higher level of accuracy than the path planning assisting tools available in the market do.

The developed path planning system can be easily extended for other mission planning tasks for robotics in the construction industry. Furthermore, it can also be developed into a cyber-physical system for construction management or even smart city management. These extensions will be explored in future research.

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