A Flight Simulator for Unmanned Aerial Vehicle Flights Over Construction Job Sites

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Hashem Izadi Moud, Mohamad A. Razkenari, Ian Flood, and Charles Kibert

Abstract

In 2015, the construction had the highest rate of fatalities among all industries in the United States. Unsafe operation of construction equipment is one of the main causes of fatal incidents. Operation, management and interactions between construction equipment and construction crews should be thoroughly regulated to minimize the risk of fatal incidents on job sites. While use of most traditional construction equipment is regulated, the construction industry has struggled with regulating new, innovative and smart equipment such as Unmanned Aerial Vehicles (UAVs) that have recently been introduced to construction job sites. In this paper, collision avoidance and spatial safety theories in construction are discussed. The bases of these theories are extended to UAV operation in order to establish the first known theory on safe use and operation of UAVs in construction. Also, basic principles of UAV flights are discussed. By applying the basic principles of UAV flights and construction spatial safety theories, a UAV flight simulator in construction environments has been developed in Unity game engine. The flight simulator is designed for UAV pilots, construction managers and safety managers, and enables users to fly a UAV within a simulated environment extracted from a BIM model. This UAV flight simulator is tested in a case study of a building currently under construction. This simulator can be used to assess UAV pilots' capabilities, test the risks of UAV flights in any construction environment, and UAV safe flight path planning.

Keywords

Flight simulator • Unmanned aerial vehicle • UAV • Flight simulation

73.1 Introduction

Unmanned Aerial Vehicles (UAVs) have been applied to a diverse range of construction related applications for more than a decade. UAVs have been used in structural health monitoring and inspection [1–8], 3D modeling and surveying job sites [9] progress monitoring [10, 11], infrastructures management [12–17], sustainable energy production site management [18], material tracking [19] and construction safety related applications [20]. Although there have been numerous efforts by governmental agencies, such as the Federal Aviation Administrations (FAA) and academia to explore, educate, address and govern UAV flight safety procedures [21], there have not been any rigorous studies specifically within the field of

H. Izadi Moud (✉) · M. A. Razkenari · I. Flood · C. Kibert
University of Florida, Gainesville, FL 32611, USA
e-mail: izadimoud@ufl.edu

M. A. Razkenari
e-mail: mahmadzade@ufl.edu

I. Flood
e-mail: flood@ufl.edu

C. Kibert
e-mail: ckibert@ufl.edu

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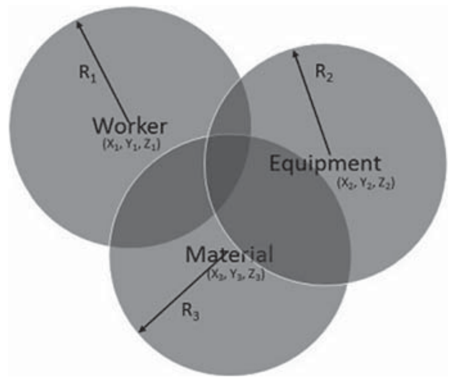

Fig. 73.1 Schematic view of a threatened proximity. Adapted from [25]

construction to investigate UAV flight challenges. The construction industry can generally consider to be hazardous, experiencing relatively high rates of both fatalities and casualties. In 2015, a total of 4836 fatal work incidents were reported in the US. Of these, nearly 20% (937) were attributed to construction, more than any other industry [22]. Using UAVs on construction job sites without full consideration of their safety threats, risks and hazards can put the well-being of construction personnel in jeopardy. Mechanical failure and human errors in operation are the two common risks associated with using UAVs that can lead to crashes, accidents, and mission failures [23]. In order to understand and help avoid UAV-related accidents, safe proximity between UAVs and other equipment, machinery, personnel, buildings and roads on site need to be studied. Also, there is a need to put plans in action that notify the UAV pilot, construction personnel, and safety officer on site from risky procedures such as close proximities between UAV flight paths and construction workers. An important strategy that can significantly help improve UAV flight safety is pilot training in simulated environments. This study investigates risks associated with UAV flights in close proximity to construction equipment and machinery, materials, construction personnel and structures. The objectives of this research are to: (1) present a recently built interactive UAV flight simulator that can be used for tasks such as UAV pilot training, UAV flight path planning and UAV flight assessment, based on the construction spatial safety theory, and (2) test the UAV flight simulator in a real construction job site environment in order to verify the usability of the UAV flight simulator.

73.2 Proximity and Collision Avoidance in Construction Safety

Spatial safety refers to safety related to the space comprising any construction site. The focus on construction safety has not been on spatial safety. Traditional construction safety plans are grounded on static data of job sites, 2D drawings and Occupational Health and Safety Administration (OSHA) regulations and recommendations. Temporal and spatial data have rarely been incorporated in OSHA regulations and recommendations or construction site safety plans. Live spatial and temporal data have not been a focus in construction safety planning. Although OSHA regulations and recommendations form an important part of establishing construction site safety, they do not satisfy the need for a live space and time aware construction safety planning scheme. There have been numerous efforts in academia to fill this gap and introduce dynamic safety site planning schemes that incorporate live and dynamic spatial and temporal data into safety plans [24–26]. This section mainly focuses on spatial theories that are dealing with proximity and how to avoid collision risks associated with UAVs. A few different theoretical frameworks have been proposed and tested in order to increase spatial and temporal awareness among construction equipment and personnel. A dominant collision avoidance theoretical framework in construction is proposed by Teizer et al. [25], which is based on a circular zoning view of construction equipment and personnel (see Fig. 73.1).

Teizer et al. [25] developed a proximity warning mechanism that alerts construction personnel operating in close proximity to construction machinery. This proximity warning mechanism is based on a theoretical framework that views construction materials, equipment and workers as objects surrounded by safe circles. Each object is surrounded by a safe circle. The warning mechanism triggers when at least two of these safe spheres overlap. The bases of the Teizer et al. [25] proximity warning system are: (1) each construction object is entitled to a safe sphere, (2) each object is in the center of its safe sphere and (3) it is safe for all objects to freely move until they enter another object's safe sphere. The proximity warning mechanism triggers and sends a warning when an object's safe sphere is threatened by another object's safe sphere. Figure 73.1 shows a schematic view of the threatened safety spheres in a construction site. The mathematical bases of the framework are presented as follow: (1) objects are safe as long as: $[(X_i, Y_i, Z_i) - (X_{i+1}, Y_{i+1}, Z_{i+1})] \geq (R_i + R_i)$, and (2) objects are not safe when: $[(X_i, Y_i, Z_i) - (X_{i+1}, Y_{i+1}, Z_{i+1})] < (R_i + R_i)$.

73.2.1 Spatial Safety of UAV in Construction Environment

Currently the use of UAVs on construction job sites does not follow any specific guidelines, safety codes, safety recommendations or regulations. The only existent guideline for UAV flights are the general rules and recommendations published by FAA for flying UAVs. Although UAVs have many potential applications for the construction industry, using UAVs without proper caution, including professional training of UAV pilots, could significantly increase the safety hazards on construction job sites. Flying UAVs in close proximity of personnel, equipment and structures increases the risks of injuries and mission failure. This section incorporates the Teizer et al. [25] spherical safe proximity strategy into UAV flights safety. Based on the Teizer et al. [25] proximity theory, equipment, workers and structures have a safe sphere surrounding them. The safe proximity between these objects is only maintained as long as these safe spheres do not cross over. Figure 73.2 shows a general proximity example between two UAVs on a construction job site based on Teizer et al. [25] spherical proximity theory. An example of standoff distance between two UAVs, a construction equipment (crane), a construction personnel and a building are presented.

The location of each element followed by safe sphere radius is as follows: UAV-1: {(X1, Y1, Z1), d-1}; {UAV-2: (X2, Y2, Z2), d-2}; Crane: {(X3, Y3, Z3), R-3}; Crew: {(X4, Y4, Z4), R-4}; Building: {(X5, Y5, Z5), R-5}.

An ideal *UAV proximity system* should issue a warning each time a UAV standoff distance collides with other construction objects safe surroundings, which is shown in the formula below: (1) For UAV-1: (X1, Y1, Z1) – {(Xi, Yi, Zi): i Ɛ (2, 3, 4, 5)} $\leq$ {d-1 + ((Ri: i Ɛ (3, 4, 5)) OR d-2)}, & (2) For UAV-2: (X2, Y2, Z2) – {(Xi, Yi, Zi): i Ɛ (1, 3, 4, 5)} $\leq$ {d-2 + ((Ri: i Ɛ (3, 4, 5)) OR d-1)}.

Based on these basic construction proximity principles, a UAV flight simulator is designed for pilots that warns users when the UAV proximity rules are compromised.

73.3 Principles of Unmanned Aerial Vehicle Flight Simulator

While the construction industry puts UAVs to good use, the investigation of their potential safety and risk should not be neglected. The UAV operation in close proximity to the construction activities and pieces of equipment may increase the collision hazards for site crews and workers. There is a need for applying safety control and monitoring systems for UAV

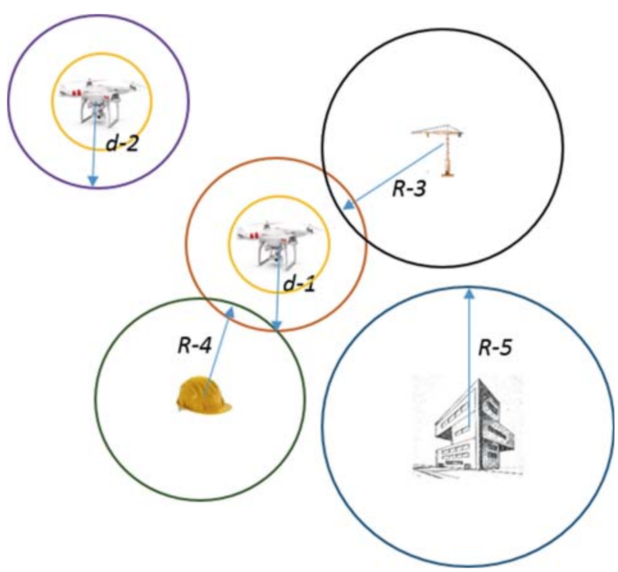

Fig. 73.2 An example of a close proximity situations between some objects in a construction environment

operation on the construction site. The primary consideration to augment the safety in UAV services is to supervise the training of operators with regards to the safety and proximity consideration. This section clarifies the considerations and assumption for developing a simulation platform for particular UAV applications. Next, after a quick review of the existing UAV simulators, the approach adopted in this study for developing the UAV simulation platform is discussed.

73.3.1 Considerations for UAV Simulation

The physical characteristics of UAVs are among the most significant inputs for the simulation process. UAVs are described and classified considering a wide range of characteristics, such as size, weight, flight range, endurance, capabilities, and engine type [27]. They have a rigid body with multiple actuators that produce forces and torques. UAVs come with specific operational parameters such as mass, inertia, coefficients for linear and angular drag, coefficients of friction and restitution which are necessary for computing rigid body dynamics. A quadcopter UAV, which is currently the most common type of UAV used in construction, has four propellers with adjustable rotation speed located at the vertices. By having C_T and C_{pow} as the thrust and the power coefficients, r as air density, D as propeller's diameter and $\omega_{\max}$ as the max angular velocity in revolutions per minute, the forces and torques generated by propellers at vertices are [28]:

$$F_i = C_T \rho \omega_{\max}^2 D^4 u_i \quad and \quad \tau_i = \frac{1}{2\pi} C_{\text{pow}} \rho \omega_{\max}^2 D^5 u_i \tag{73.1}$$

UAVs are used for a wide range of civil and military applications in very challenging outdoor or indoor environments. They may be exposed to multiple physical phenomena including gravity, air pressure, and strong magnetic fields. Taking into account all these phenomena in a simulation process will result in very accurate yet computationally expensive models. Therefore, the existing models are developed for desired accuracy in the selected case or scenario analysis.

73.3.2 Software Simulation Tools

There are a wide range of commercial or open source UAV simulators available each with its own specific configuration and features. The available simulators have a limited scope in terms of the operating environment. Craighead et al. [29] reviewed 14 of these simulators and their significant features. Gazebo [30], which is a major robot simulation tool, is one of the most popular simulation platforms for research work. It has a modular design that allows use of different physics engines, sensor models, and creates 3D worlds. Multiple examples of open source simulators have been developed using the Gazebo platform coupled with Application Programming Interfaces (APIs) to develop simulation applications [31–33]. Although Gazebo [30] has many robust features, it is challenging to create large-scale complex virtual environments that are closer to the real world. Game engines such as Unreal [34] and Unity [35], allow various advancements in rendering and creation of any environment but are slightly limited regarding vehicle creation. A good example is Microsoft AirSim [28], an open-source, cross-platform simulator for UAVs, built on Unreal Engine, with physically and visually realistic simulations. In addition, there are many commercial UAV simulators and training applications available with customized specifications. The commercial simulators are developed for specific applications such as structured flight challenges [36, 37], safety training [37, 38], and different working environments and flight scenarios [36, 38].

73.3.3 Drone Movement

The methodology adopted for the simulator considers a quadcopter with four propellers. The propellers generate thrust forces, F_1, F_2, F_3, F_4, by altering the rotation speeds, to achieve the desired movement or maintain the position of the UAV (Fig. 73.3). In the hovering condition, the forces of propellers must be equal and must add up to the weight of the UAV for the generated moments to cancel out. For vertical movement, the forces will increase or decrease equally and will cause no additional moment or angular speed. The gravity may change, slightly, in different environments and in a complex manner [28]. However, for most ground-based or low altitude UAV applications, the variations are negligible, and many models consider a constant number to model gravity [28]. In addition to gravity, the UAV may be subject to air density, air pressure, or other air movement based on the physical characteristics of the operating environment.

The controlled change in thrust forces will cause moment inequality and lead to angular movement of the UAV. If we consider X_L, Y_L, and Z_L, as the UAV local reference system and X_G, Y_G, Z_G as the Global reference system, and X_G as the

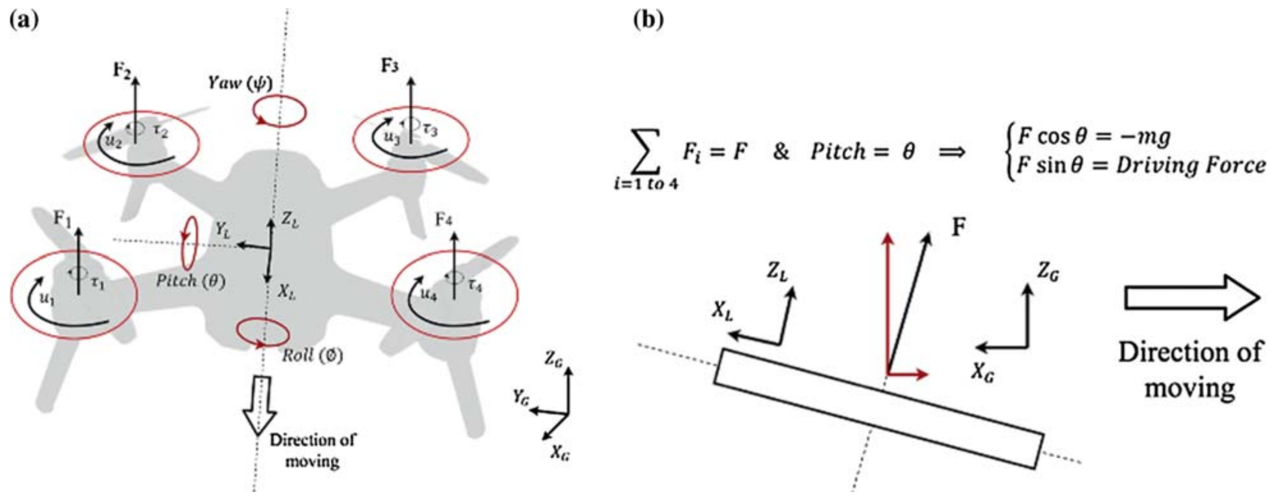

Fig. 73.3 An illustration of forces, movements, reference systems, and rotations in a UAV (left). The simple representation of driving force in X_G direction in the pitch rotation (right). Adapted from [28]

moving direction of the UAV, the angular movement in X_L, Y_L, and Z_L axis are respectively recognized by roll (∅), pitch (θ), and yaw (ψ) (Fig. 73.3). If the control signal is intended to move the UAV in the X_G direction, it will increase the total forces at the propellers until it cancels out the gravitational force in the Y_G direction and, as illustrated in (Fig. 73.3), an additional force in the X_G direction will lead to the lateral movement. Therefore, the UAV driving force is associated with the tilting angle and moving direction.

73.4 Unmanned Aerial Vehicle Flight Simulator

Using UAVs on construction job sites usually includes a pre-flight survey, setup (preparation), flight mission (take-off to landing), and post-flight data analysis. In this study, a visual interactive platform is developed in the Unity game engine to present the state of UAV safety during its operation. The proposed platform includes the process of creating a 3D environment of construction job sites where UAV flights can be simulated. All the existing simulators on the market have a pre-developed environment that is not customizable for a given project features. The platform also has a collision avoidance system with consideration of specific construction site safety features and Teizer's proximity theory [25]. The collision avoidance system is unique to this platform and is customized for construction project activities. The platform is the first proposed tool for training operators in the construction environment and with safety considerations. To create the 3D model of a building in the Unity platform, a BIM 3D model was exported in *.fbx* format and introduced to the game engine. The game development in the engine is powered with the C# scripting language. While the Unity platform allows definition of each subject separately, for this case study, the whole building was set as one object. By integrating 4D site-specific temporal and spatial safety information [39] with the Unity model, the simulator will allow users to monitor the safety level of each UAV operation or scenario considering the existing safety plan. There are two cameras in the model including the operator eye-level view which is used as the main camera for the game view and the UAV camera which is placed on the right side of the game view (Fig. 73.4). The simulation is based on a generic drone that is commonly used on construction job sites with an average speed of 50 km per hour (km/hr.) operating in an outdoor environment. The simulator has a modular architecture which allows the addition of new features, such as specific weather conditions, air density (for hot days or high altitude), air movement (wind, convection up the side of buildings), etc. However, these features are not considered within this case study. The next modeling step was to develop the control strategy for UAV movements. As mentioned earlier, a UAV is expected to have movement in three directions including forward or backward (X_G), right or left (Y_G), and up or down (Z_G). The forwards/backwards and right/left movements will include tilting angles, respectively pitch (θ) and roll (∅). The UAV tilting is associated with its weight and moving speed; however, the experiments show that the tilting angles are approximately between −30° and +30° [35] and the same values are used in the model.

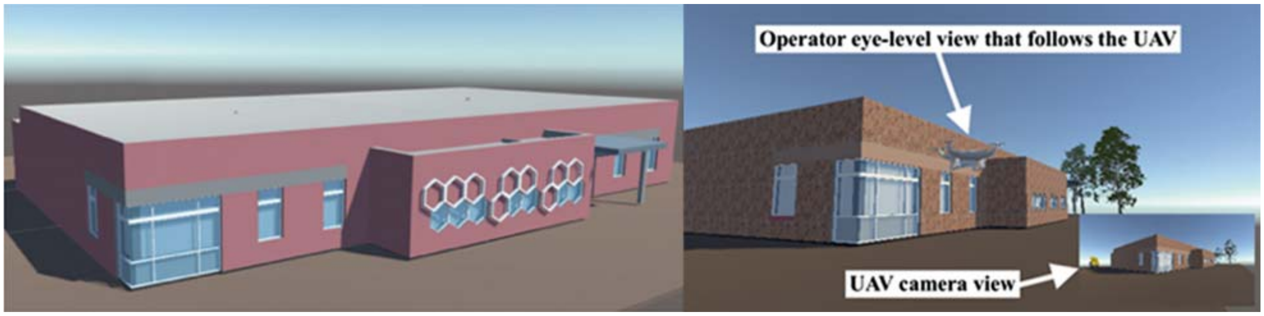

Fig. 73.4 The 3D building model in the Unity platform before rendering edits (left) and simulated UAV in the operator view and with additional UAV camera view (right)

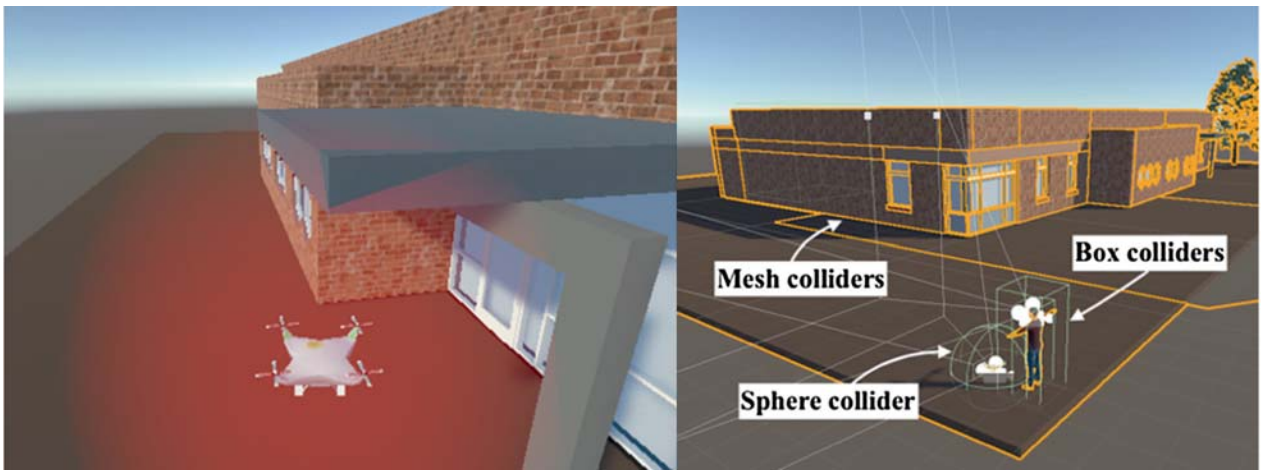

Fig. 73.5 The color-coded proximity warning system that works according to Teizer et al. [25] proximity theory (left); and sphere, mesh, and box colliders in the system (right)

In the simulator, the user can send inputs using a keyboard to control its movement. The UAV will move in the requested direction with the proper tilting angle for each movement. The user may select moving in more than one component of the directional vector at the same time (for example, up and forward). In this step, it was made sure that the simulated UAV prototype can maneuver through the simulated construction job site environment (Fig. 73.4). The next feature added to the simulator was the ability to capture real-time spatial information of the UAV during an operation. The coordination of UAV with respect to the set reference point in UNITY model for each update frame (9 frames per second) were recorded and exported as a text file. These coordinates can be used for further analysis or updating the safety plan on other platforms.

Finally, the users can set a customized proximity distance for any given UAV, construction component, item of equipment, or worker and the simulator provides a color-coded warning system to the UAV controller using the red signal if any of the proximity requirements are violated (Fig. 73.5). The warning system is developed by using pre-defined collision detection methods within the Unity platform. The warning system is working in the scope of Teizer's proximity theory for construction safety [25] and can easily be extended to the color-coded safety zones with specific configurations or other spatial related applications.

73.5 Discussion and Conclusion

This paper presents the first ever known UAV flight simulator, developed in Unity, that is dedicated to construction environments. This UAV flight simulator is based on basic principles of safe proximity theories used in construction safety research for developing collision avoidance systems. The presented UAV flight simulator uses a color-coded scheme to warn the users of near-collision incidents. It is easy to use for construction managers, safety managers, owners and UAV pilots. Some of the applications of this system are: (1) train UAV pilots to fly in complex construction job site environment, (2) assess complexity of construction job sites prior to plan UAV flights on site, and (3) safe UAV flight path planning. This simulator is tested using a BIM model of an actual construction site, which is currently under development. The BIM model of this project is exported to Unity and the platform is tested within this environment, navigating a UAV around the building. While more than a dozen UAV flight simulators are available on the market, this platform is distinguished by being dedicated to construction job sites. It works with the BIM model, is easy-to-use, and specifically tailored for needs of the construction environment. For the future, the authors plan on adding more features to this platform so that it can be applied to more complex construction environments.

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