Monte Carlo based Risk Analysis of Unmanned Aerial Vehicle Flights over Construction Job Sites

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Abstract: While Unmanned Aerial Vehicles (UAVs) have been used on construction job sites for different purposes for over a decade, the risks and hazards of flying UAVs on construction job sites has not been either quantitatively or qualitatively assessed. Quantifying the risks of flying UAVs over general populations is a common practice in the general UAV industry. This study uses an established model that has been used to quantify the risks of flying UAVs over general population, propagates the bases of the model based on the construction industry needs, tailors some of the input of the model based on the construction industry specifications, and uses the Monte-Carlo Simulation method to quantify the risks of flying UAVs over a real construction job site adopted as a case study. This model is based on mishap rate for UAVs, population density of the area that UAVs fly over and the lethal area of UAVs that could be potentially fatal in the event of a crash. While this paper presents the very first effort in quantifying the risks of flying UAVs over construction sites, there is a need in the construction industry to tailor this model based on the needs of the industry to make the model more accurate.

1 INTRODUCTION

Unmanned Aerial Vehicles (UAVs), also known as drones, were first introduced to construction job sites around ten years ago. Over the past 10 years, the use of UAVs for construction applications has grown exponentially (Ham et al., 2016; Liu et al., 2014; Michael Zucchi, n.d.), largely due to ready access to low-cost, reliable and easy to fly UAVs that are equipped with a variety of sensors, including high-resolution cameras. UAVs have been used in construction projects for various purposes, including progress monitoring (Han et al., 2015; Lin et al., 2015), site monitoring (Wen and Kang, 2014), building and structural inspection and health management (Eschmann et al., 2012; Kerle et al., 2014; Kruijff et al., 2012; Michael et al., 2012; Morgenthal and Hallermann, 2014; Pratt et al., 2008; Roca et al., 2013; Wefelscheid et al., 2011), 3D modeling and surveying job sites (Siebert and Teizer, 2014), infrastructure asset management (Ellenberg et al., 2016; Eschmann et al., 2013; Metni and Hamel, 2007; Rathinam et al., 2008; Sankarasrinivasan et al., 2015; Zhang and Elaksher, 2012), urban monitoring (Qin, 2014), material tracking (Hubbard et al., 2015), sustainable energy production site management (Murphy et al., 2011) and construction safety (Irizarry et al., 2012). While UAVs are being used on a daily basis for construction processes and activities, the risks and safety concerns associated with flying UAVs have yet to be investigated.

The direct risk of flying UAVs would be falling UAVs due to mechanical failure during flight, and debris from collisions with an object present within the job site flight zone (Clothier and Walker, 2006; Opfer and PE, 2014). However, flying UAVs could potentially cause indirect hazards, such as:

- threatening workers' personal space (Duncan and Murphy, 2013);
- distracting workers due to the noise and motion of UAVs in flight (Christiansen et al., 2016; Liew and Yairi, 2013; Sinibaldi and Marino, 2013); and
- threatening the privacy of workers through the perceived surveillance by UAV cameras (Clarke, 2014; Finn and Wright, 2012).

While there are numerous risk and safety concerns associated with UAV flights over construction job sites, there has never been a coherent method to quantify the risks of UAV flights over construction job sites. The construction

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industry struggles with high rates of fatalities and injuries. In 2015, a total of 4,836 fatal work incidents were reported in the United States (US). Of these, nearly 20% (937) were attributed to construction, more than any other industry. The top three causes of these fatal work incidents were: (i) falls, slips and trips (364), (ii) transportation incidents (226), and (iii) contact with objects and equipment (159) (BLS, 2017). The high number of items of equipment involved in fatal incidents in construction highlights a need to tighten equipment-related safety regulations. Equipment such as loaders, graders, and bulldozers, have been widely used in construction for many decades and is highly regulated in order to protect personnel against equipment-involved incidents. However, the construction industry struggles with regulating the safety of newly-introduced equipment, such as UAVs. Being the industry with the highest fatality rate in the US creates an even more urgent need for a tightening of safety measures in the use of new technologies on construction sites. This research paper presents a model for quantifying the risks of UAV flights over construction job sites. It further applies the presented model to a real case study, an under-construction building within the University of Florida campus. The rest of this paper is organized as follows. Section 2 describes the formula used to quantify risks associated with UAV flights. Section 3 describes the current regulations of UAV flights in the united states. Section 4 discusses the Monte-Carlo simulation as a risk assessment scheme. Section 5 goes into the detail of the case study used in this research and discusses the assumptions used to run the simulation. The discussion of the results, conclusions, and acknoledgement close the article.

2 QUANTIFYING RISKS ASSOCIATED WITH UAV FLIGHTS

Quantifying risks associated with UAV flights over construction job sites provides decision makers, such as construction project managers and/or superintendents, with reliable metrics for assessing whether or not it is safe to fly the UAV over a given area on a construction job site. Also, it offers the basis for health and safety governmental agencies and insurance companies to decide on the legal aspects of potential cases of fatality and injuries which involve UAVs.

This paper describes a ground fatality expectation model based on the Clothier and Walker (Clothier and Walker, 2006) approach. It is worth noting that this model only quantifies the expected ground fatalities due to a falling UAV(s) and/or falling debris. This model does not provide any perspective towards quantifying risks due to indirect UAV risk hazards, such as threatening workers' personal space, distracting workers due to noise and motion and/or threatening the privacy of workers.

According to Clothier and Walker (Clothier and Walker, 2006) the ground fatality expectation model is formalized as:

$$SO = MR * \varphi * A_L \tag{1}$$

where:

SO refers to the safety objective in terms of the number of fatalities per flight hours;

φ is the population density of the area under the flight path of the UAV;

A_L refers to the lethal area, which is determined by the circular area of the maximum length of UAV diameter plus a (safety) buffer; and

MR refers to the mishap rate and is calculated according to Eq. (2).

$$MR = SFR + MC_{Debris} + Other \tag{2}$$

where:

SFR represents the system failure rate per flight hour;

MC_{Debris} refers to the debris from a possible midair collision per flight hour; and

other refers to the other hazards that might result in fatality risks.

According to Clothier and Walker (Clothier and Walker, 2006), the expected fatality rate in the general aviation industry is usually limited to $1*10^{-06}$ or one fatality in every one million flight hours. But the question is how this general aviation industry fatality rate affects the UAV flights safety objective in the construction industry. Due to a lack of data for calculating UAV flight safety objectives, it is assumed that the fatality rate in UAV flights should be set to the fatality rate of the general aviation industry.

3 CURRENT REGULATIONS OF UAV FLIGHTS IN THE UNITED STATES

The proposed model by Clothier and Walker (Clothier and Walker, 2006) would be useful to quantify the risk of UAV flights only when it is combined with the current rules and regulations regarding UAV flights. In the US, the Federal Aviation Industry (FAA) has the sole power to regulate all aspects of civil aviation. According to the FAA, Unmanned Aerial Systems (UASs) (a broader category for UAVs) flights are divided into two broader categories: (1) fly for hobby purposes, and (2) fly for business purposes. FAA UAS Flight regulations are as follows:

(A) Fly under the Special Rule for Model Aircraft (Section 336)

- Only fly for entertainment or hobby.
- The model aircraft must be registered.
- Follow community-based safety guidelines and fly within the programming of a national community-based organization.
- The maximum weight of the aircraft is 55 lbs., unless certified by a community-based organization.
- Flying range cannot exceed visual line-of-sight.
- Do not fly near other aircraft.
- The airport and air traffic control tower must be notified in advance if a model aircraft is flying within 5 miles of an airport.
- Never fly near emergency response efforts

(B) Fly under the FAA's small UAS Rule (Part 107)

- Fly for entertainment or business use only.
- The drone must be registered.
- The drone must get a remote pilot certificate issued by the FAA.
- The maximum weight of drone is 55 lbs.
- Flight speed cannot exceed 100 mph.
- Flying range cannot exceed visual line-of-sight.
- Do not fly near other aircraft or over people.
- Do not fly in controlled airspace near airports until you get the permission from FAA.
- Fly only during daylight or civil twilight.
- Flying height cannot exceed 400 feet.
- Do not fly from a moving vehicle, unless in a sparsely populated area.

In general, for simplifying the most crucial aspects of these regulations, this paper considers the following assumptions: (1) the construction site used in this paper as the case study is not located within the 5-mile radius of or near any airport, (2) it is assumed that all regulations regarding the piloting of the UAV are being followed, (3) UAV flights are happening within the line-of-sight of the pilot, (4) UAV specifications follow FAA regulations, and more importantly (5) the space over people's heads is a *no-fly* zone.

4 MONTE-CARLO SIMULATION AS A RISK ASSESSMENT SCHEME

This paper uses the Monte-Carlo simulation technique for sampling and analysis of the problem. Monte-Carlo has been widely applied to problems within the construction domain due to the high levels of uncertainty in the execution of construction projects and the large investments that are therefore at risk (Akintoye and MacLeod, 1997).

The safety issue in the construction industry and the uncertainties involved make a case for using Monte Carlo simulation as a means of gaining more insight into construction health and safety management. Monte Carlo simulation has been used to model potential occupational safety and health risk in construction by incorporating hazards related to each activity while considering the stochastic nature of the problem (Sousa et al., 2015). Also, it has been used to analyze the dynamic relationship between the factors leading to an accident and the compensation paid for those accidents (Li et al., 2017). Shohet et al. (Shohet et al., 2018) used this simulation method to find the relationship between the total cost of safety and the degree of investment in preventive safety in order to find the amount of optimal investment. Real-time location-based simulation is another application area where Monte Carlo simulation is used to simulate the safety hazards on construction sites. Li et al. (Li et al., 2016) used historical data to predict the safety hazard level on an individual level through time and based on location.

The sensitivity of small UAVs to wind, their high maneuverability and potential for mechanical failures, along with their potential for operating errors make them a safety threat in general but a more significant one on construction job sites due to uncertain operation conditions. A recent analysis by Plioutsias et al., (Plioutsias et al., 2018) shows a significant gap between the extent to which current commercial UAVs meet safety requirements. Monte Carlo simulation is a suitable means for simulating the conflict between one or multiple UAVs operating in construction sites and the surrounding environment. The method is helpful in taking into account not only the uncertainties regarding the movements of objects but also situational issues such as wind (Alejo et al., 2016). There is extensive literature on the application of Monte Carlo simulation in collision avoidance of UAVs, both between themselves and possibly with other objects (Cook and Brooks, 2015; Douthwaite et al., 2017; Mcfadyen et al., 2016).

5 ANALYSIS

In this section, risks of UAV flights over a real construction job site has been quantified using the Clothier and Walker (Clothier and Walker, 2006) model. Figure 1 represents a schematic design of a construction project that has been used as a case study in this paper. Before analyzing risks of UAV flights over any construction site, it is important to find the available fly-zones by excluding the no-fly zones, such as pedestrian pathways, workstations and any other place that is populated with construction personnel. The following points describe the construction site outline presented in Figure 1 (left).

- The construction site is labeled as *"New Construction Site"*.
- This construction site is surrounded by an existing building, two workstations for on-site construction workers, borders of the site and a few pathways where construction workers usually travel between sites and workstations.
- The layout of two future buildings are also shown in the layout.

In order to simplify this map, the two future buildings are deleted in the layout on the right side of Figure.1. Also, applying the FAA rules and regulations regarding no-fly zone over humans leads to the development of four standalone zones that UAVs are allowed to operate without violating this regulation. Figure. 1 shows how this simple pre-flight mapping is drawn considering basic FAA rules and regulations for UAV operations.

Four separate zones are identified as safe fly-zones for UAV operations with the following areas:

1. Area 1: 4535.84 sq.ft. (421.39 sq.m.)
2. Area 2: 21338.38 sq.ft. (1982.40 sq.m.)
3. Area 3: 54218.06 sq.ft. (5037.02 sq.m.)
4. Area 4: 3461.66 sq.ft. (321.60 sq.m.)

While there could be different outlines of the safe-fly zones, this paper considered the presented zones for the following reasons:

- Area 1: is restricted between building (on the south and west sides), workers' pathways (on the east side) and also one border of the construction site (on the north side).
- Area 2: is restricted between workers' pathway (on the south and west sides), borders of the construction site (on the north, northwest and east sides).
- Area 3: is restricted between workers' pathway (on the north side), the practicality of flight (on the west side) and also the border of the construction site (on the south side).
- Area 4: while Area 4 and Area 3 could potentially be merged, it was decided to have a standalone area, as Area 4, due to the impracticality of flight in the narrow area, which is now named as Area 4.

Recalling Equation 1, Mishap Rate (MR), the Lethal Area (A_L) and also the density of population (φ) in the area are required. For $A_{L,}$ a reasonable range of lethal area of common UAVs is considered. This range corresponds to the area of a UAV that could be lethal in a potential crash. It is usually estimated to be the longest side or dimension of a UAV. It varies based on the radius, or diameter, of the UAV. Most UAVs that fly over construction job sites are commercially available and their diameter is estimated to vary from 0.5 m for mini UAVs to 1.5 m for more advanced UAVs. This range will be used in the Monte-Carlo simulation as an evenly distributed range between 0.5 and 1.5 m.

The density (φ) is the tricky part. The density corresponds to the number of people that are present on the job site (here we consider them to be only construction personnel without any outsider visitor) divided by the area. In this paper, a possible distribution of construction personnel, presented below, is divided by the area of Area 1 through Area 4, in each simulation. The authors do not have any data on the actual number of construction personnel working on job site of this project. Thus, it is just assumed that the existing number of construction personnel present on each of the defined areas is between 3 to 11, in a normal distribution (Average = 7, Standard Deviation (SD) = 1.33). The density then is calculated for Area 1, Area 2, Area 3 and Area 4.

Finding or estimating the MR of UAVs is not an easy task. Unlike the general aviation industry, where abundant information about the MR is available, there is almost no data available regarding the exact MR of UAVs. In this analysis, therefore, the UAV lifetime is assumed to be normally distributed, with a range between 100.00 and 9,900.00, a mean of 5,000.00, and standard deviation of 1,633.33. In other words, the MR would be one crash in this assumed lifetime of a UAV.

A series of Monte-Carlo Simulations for each have been run using the Palisade @Risk 7.5 package. The SO is calculated for each area 1 million times. The results are discussed in the next section.

6 RESULTS, DISCUSSION & CONCLUSION

A series of Monte-Carlo simulations have been run to estimate the SO of each area. In order to give an overview of the inputs of the simulation, all inputs are summarized in the following:

- Lethal Area of UAV: An even distribution with the minimum diameter of 0.5 m and maximum of 1.5 m.
- Population Density (φ): Estimated number of construction personnel between 3 to 11 with a normal distribution.
- UAV MR is assumed to be normally distributed, with a range between 100.00 and 9,900.00, a mean of 5,000.00, and standard deviation of 1,633.33. It needs to be emphasized that there is no data on the MR. This data for MR is just a wide, and very *conservative*, assumption. It is assumed that operation lifetime of UAVs that are being used in the construction industry is between 100.00 and 9,900.00 hours of operation, which is distributed normally. It means that the MR would be one incident in this above-mentioned lifetime.

For each area, a simulation has been run using Palisade @Risk 7.5 with 1,000,000 iterations. The results are as follow.

Results of UAV Flights Simulation over Area 1:

The Population Density (φ) simulation resulted in a normal distribution with mean of 0.016612 and a standard deviation of 0.003156.

The results of the Monte Carlo simulation for SO of area 1 is presented in Figure 2.

Results of UAV Flights Simulation over Area 2:

The Population Density (φ) simulation resulted in a normal distribution with mean of 0.0035311 and the standard deviation of 0.0006709. The results of Monte Carlo simulation for SO of area 2 is presented in Figure 3.

Results of UAV Flights Simulation over Area 3:

The Population Density (φ) simulation resulted in a normal distribution with mean of 0.001,389,7 and the standard deviation of 0.000,264,0. The results of the Monte Carlo simulation for SO of area 3 is presented in Figure 4.

Results of UAV Flights Simulation over Area 4:

The Population Density (φ) simulation resulted in a normal distribution with mean of 0.021766 and the standard deviation of 0.004,136. The results of the Monte Carlo simulation for SO of area 4 is presented in Figure 5.

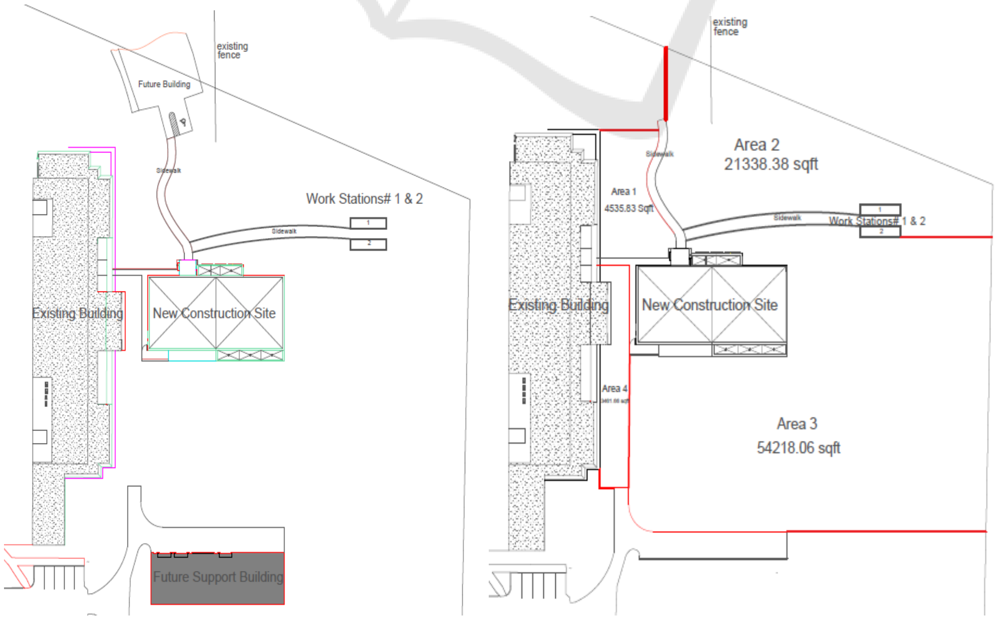

Figure 1: The layout of the site (left), and the designated UAV flight areas during construction (right).

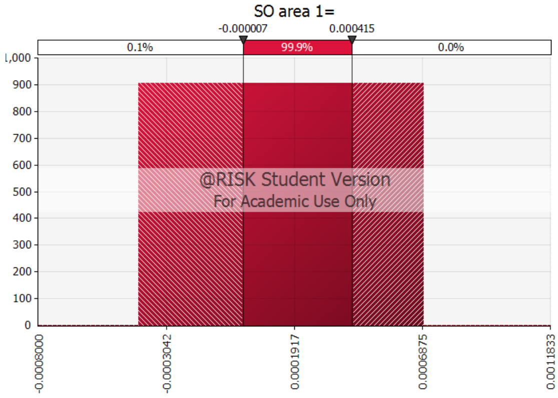

Figure 2: Monte Carlo result of SO simulation area 1.

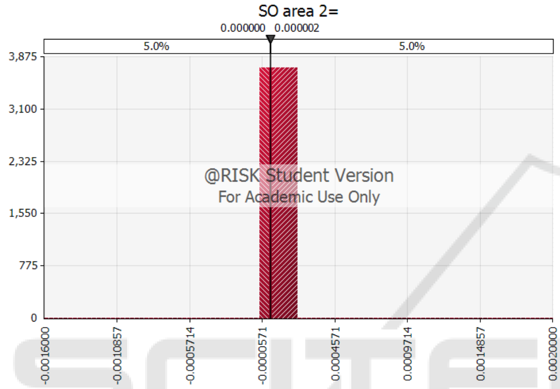

Figure 3: Monte Carlo result of SO simulation area 2.

For each area Monte Carlo simulation results are presented. The SO results correspond to the number of fatalities in flight hours. SO is usually presented in number of fatalities per million flight hours.

The SO Results are summarized as following:

- Area 1:
    - Mean: 3.306E-006
    - Mode: 1.011E-006
    - Median: 2.602E-006
    - Standard deviation:
- Area 2:
    - Mean: 7.067E-007
    - Mode: 1.839E-007
    - Median: 5.534E-007
    - Standard deviation: 1.545E-005
- Area 3:
    - Mean: 2.785E-007
    - Mode: 7.544E-008
    - Median: 2.178E-007
    - Standard deviation: 5.914E-006
- Area 4:
    - Mean: 2.785E-007
    - Mode: 7.544E-008
    - Median: 2.178E-007
    - Standard deviation: 5.914E-006

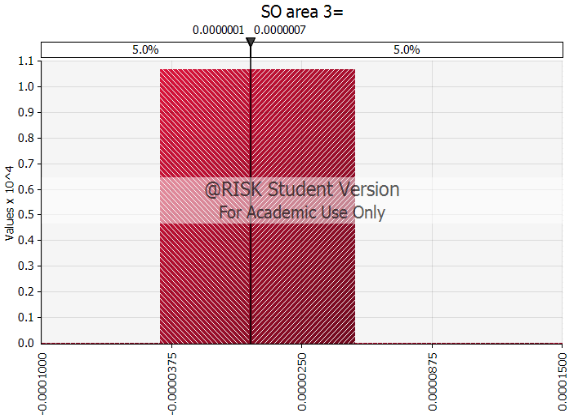

Figure 4: Monte Carlo result of SO simulation area 3.

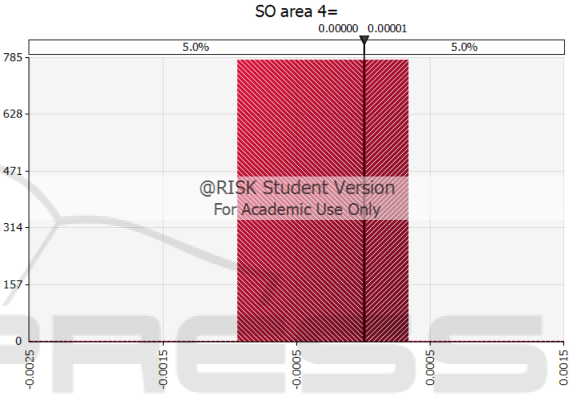

Figure 5: Monte Carlo result of SO simulation area 4.

Based on Clothier and Walker (2006), 1x10^{-06} is considered as a threshold. Comparing the results of SO simulation for each area it can be concluded that Area 1 is not safe while Areas 2, 3, and 4 are safe. This analysis would help the site managers to understand the risks related to flying UAVs over their site and plan proactively to avoid any UAV related incident in their construction site. In this case, the site supervisors would know that flying UAVs over area 1 needs more caution or should be avoided if possible. The research presented in this paper provides the grounding for a quantitative approach towards assessing the risk of flying UAVs over construction sites. The study is limited to a case study but shows how by using a Monte-Carlo simulation, high risk areas could be identified so further mitigation strategies can be adopted. Another limitation of this study is the lack of empirical data regarding some of the underlying assumptions which is rooted in the lack of public data about the mishap rate of UAVs. This study could be used as a foundation for developing more accurate evaluations of UAV flights over construction sites. The next steps in this research would be increasing the accuracy of the risk evaluation by using empirical data, simulating the risk in a spatial manner, and finally developing a real time risk analysis of UAVs flight based on the real-time situation of construction sites.

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