Simulation analysis of the search effectiveness on information-based firefighting

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Abstract: Nowadays, fire accident is still a thorny problem due to the current firefighting still heavily relies on the experience instead of information. Saving lives from fireground is the primary task in firefighting, in which the speed of effective search largely relies on the sufficient and instant information. When insufficient information situation follows firefighter tightly, the firefighter's life can be jeopardised. Equipped firefighter with the advancing information technology, such as IR, laser range-finder, camera, augmented reality and an unmanned aerial vehicle for acquiring more fireground information may be useful for firefighting task. This study focuses on using Monte Carlo simulation model to quantify the feasible alternatives and finds out the significant effect by t-test. The result showed the time in search of victim is significantly reduced as using new way of firefighting. The contribution of this paper is to disclose the value of the proposed information-based technology in support of firefighting.

Keywords: firefighting; simulation; obstacle; search; internet of things; IoT.

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1 Introduction

Based on the fire statistics of International Association of Fire and Rescue Services (CTIF) (Brushlinsky et al., 2015) USA is ranked number one on the average number of fires per year in the world, which is 600,000–1,500,000. The effectiveness and casualty of firefighting are difficult to be improved because of the complicate factors which are mainly uncertainty of fireground. In light of the booming of internet of things (IoT), thanks to the advanced technologies and integrated concepts, the miniature platform and sensors can be seamless integrated such as mini-unmanned aerial vehicle (UAV), infrared (IR) sensor, camera, etc. With that, firefighting has a greater chance to improve its effectiveness and to reduce the risk by using IoT in the search, detection, communication, situation awareness and coordination for support firefighting. The objective of this study is to model and simulate the fire on a factory with the support of IoT for comparing the effectiveness of current firefighting with the one with IoT support.

2 Literature review

The scope of this study contains firefighting operation and performance, the required information to improve firefighting command control, as well as the strategy and tactics. The collected papers are able to fulfil the scope we envisioned for exploring deeper and expand more of the fact of technology used in firefighting.

The damage caused by fire is probably one of the worst disasters in the world. According to NFPA's statistics (Hall, 2014), 1,236,994 fires were reported in 2014 in the USA that resulted in 3,275 civilian fire deaths, 15,775 civilian fire injuries and 11.5 billion USD in property damage. The statistics of CTIF revealed the fact of the USA having been the most frequent fire calls in the world.

Fire can make unpredictable consequence in terms of complexity of fire scene. The complex of fireground situation is beyond control that also causes injury and death to firefighters. Many causes are blamed for the casualties of firefighter including ineffective radio communications, asphyxiation (mainly smoke inhalation), lost inside the structure and running out of air, structural collapses, getting trapped and unexpected flashovers (Fahy et al., 2016; Varone, 2012; Thiel and Stambaugh, 2013). One of the major reasons to keep fireground situation in highly uncertain and to lead firefighter into dangerous situation is the insufficient data and information of fireground factors (Parker et al., 2014; Bearman et al., 2013). The survey made by Li et al. (2014) points out the most frequently required assistance was for information collection. The lack of real time data on thermal conditions, location of firefighters/victims/fires, navigation, communication, distribution of smoke, toxic gas species and building data (Weinschenk et al., 2014; De San Bernabe Clemente et al., 2012; Schultz and Bhatt, 2011).

The decision making of the current state of firefighting on the fireground is information limited – there is a lack of complete, real-time data on the fire, the building's occupants and the firefighters themselves. Very few sensors exist that provide quantitative, real-time information on the changing conditions on the fireground, the changing location of firefighters and the location and status of the building's occupants (Grant et al., 2015). There were 12 categories of means objectives were identified by NIST, six out of it were spotted with ineffectiveness on current firefighting performance including detection, SA, response time, communications, fire isolation and evacuation time (Averill et al., 2009; Pilemalm, 2011). In fact, fire losses in the USA remain too high and firefighting is much too hazardous. The current state of firefighting and fire protection remains far from optimal despite efforts to exploit advances in technology, equipment, training and communications (Hamins et al., 2012).

The studies by Hamins et al. (2014) suggest the requested information that come from community, building occupants, the building itself and from firefighters. Integration of these information can benefit the analyses and return predictions to incident commander (IC) for command and control. The critical data in firefighting include building's layout, contents and number of occupants, building's thermal environment, location of each firefighter, victims, fire and smoke (Roman and Rodwell, 2014; Hamins et al., 2014). In terms of critical information required for improving the situation awareness, several studies' evaluation indicates that some available new off-the-shelf technologies are ready to be the support for the effective firefighting. The common operational picture (COP) can display the information about location of all fighters, victims, fire, smoke and collapse on fireground to all firefighters and IC. The augmented reality (AR) goggle can display all fused critical information such as building layout and path indicator, information from COP, remain air of self-contained breathing apparatus (SCBA), temperature, etc. (Wani et al., 2013). The UAV is now available to play a vital role in firefighting, such as to carry an IR sensor and camera on top of the fire scene for creating surface temperature map, to find victims and avoid firefighter in the risk and also providing the communication link (Aden et al., 2014; Monares et al., 2014; Stanton et al., 2015). Inside the building, the GPS would no longer be available that makes UAV useless in search and rescue (SAR) mission. Under this situation, the small size UAV, capable of performing the indoor stable flight in GPS-denied environment, offers a new solution in firefighting. A laser range-finder sensor on micro air vehicle (MAV) can autonomously explore and map unstructured and unknown environment known as simultaneous localisation and mapping (SLAM), which benefits the localisation, navigation and path planning (Bachrach et al., 2011; Grzonka et al., 2012; Shen et al., 2011). With the search and detection sensors equipped on MAV, the comprehensive data from fireground feeding to IC for forming COP would become possible. The mini-UAV is able to carry thermal imaging system and camera which has 28° horizontal field of view (FOV) (Bendig et al., 2012).

The operation of firefighting, firefighters are capable of walking or crawling in fireground for about 20 minutes with the concern of SCBA capacity of air. The speed of walking and crawling under the condition when firefighter is with personal protective equipment (PPE) is 1.78 m/s and 0.3048 m/s. The crawling is necessary due to the obscure vision in smoke developed space and confronting the heat (von Heimburg and Medbø, 2013; Farmer, 2015).

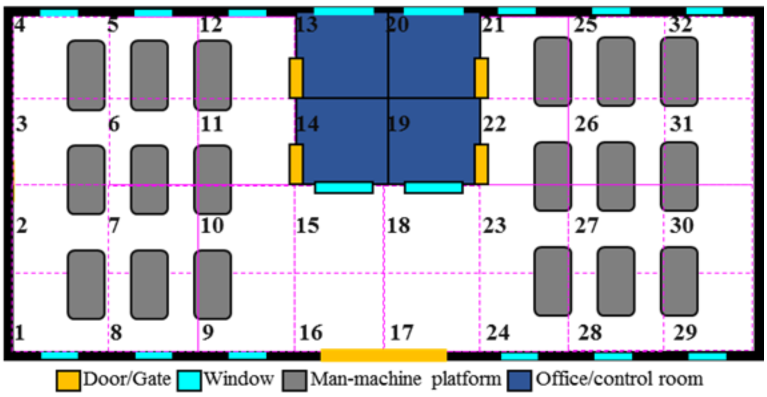
3 Model development

Model development includes establishment of scenario, developing firefighting's operational logic, management of uncertain conditions and movement models of firefighter and mini-UAV in fireground.

3.1 Establishment of scenario

In study, factory is a designated fireground containing several offices and large open space for locating machines and materials. The fire builds up from somewhere of the open space with thick smoke around. The trapped workers are still inside the factory waiting for rescue when fire engines arrive. All firefighters, are with full equipment, are under command by IC. The size of factory is assumed as 80 by 40 m^2, with height 5 m, in which four offices are inside factory as Figure 1. The factory is divided by the dash line for being several square with number as a basic unit of area. And the major task for firefighters is to go through every inch of the building for the search of the unclear number of victim.

Figure 1 Factory layout (see online version for colours)



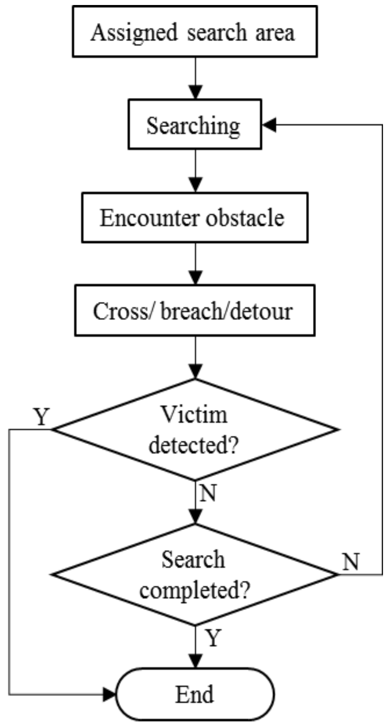
Note: Dash line grid: basic SAR unit.

3.2 Operational logic

There are two cases are setup in simulation. Case 1 is the firefighting in conventional way. Case 2 is to use IOT to assist firefighting. The operational logic of firefighting for these two cases can be different.

In Case 1, the SAR task for victim is executed by firefighters. Firefighters usually operate as two-man team. With full firefighting equipment, around 75 lbs., the movement cannot be as fast as the pedestrian. Once they are inside of the smoky building their SAR action would be even slower due to the extra factors, such as the limited eyesight, SCBA, the possible obstacles made by fire and need to stop and listen for the nearby victim, other than the heavy load. Before they find the victim, they need to visit every inch of the cells by walking or crawling. The other factor should be concerned is the possible disorientation of firefighters in the hardly see the nose situation. Decision on direction, follow on actions and the coordination would be by their instinct and mutual understanding. Without global positioning system support inside building, the situation of fireground for IC is blur because there is no precise location of each firefighter that IC can only command and control his/her firefighters by mostly estimates through radio communication. The search logic of firefighter operation is as Figure 2.

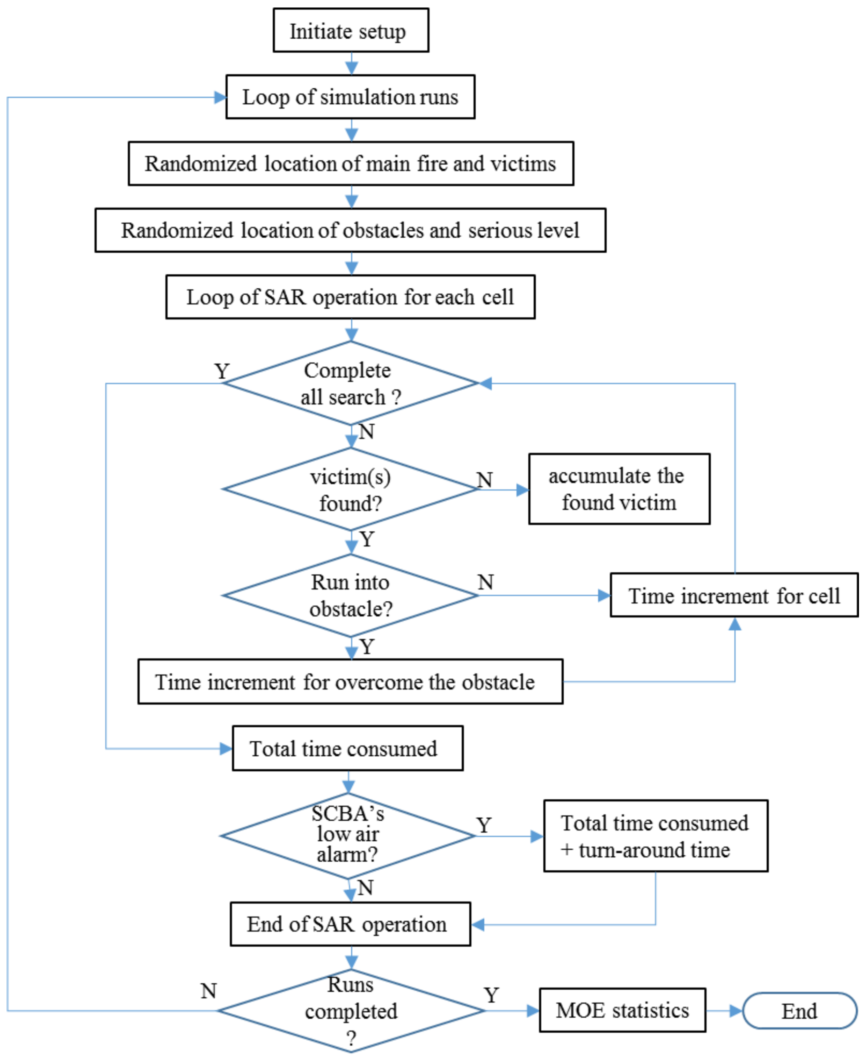
Figure 2 Search operational logic



For simulation, based on operational logic, some specific behaviours such as the location of the fire, victim, obstacle, the moving speed of firefighter and the rate of air consumption of SCBA, need to be modelled. In Figure 3, the location of fire, victim and obstacle have uncertain characteristics that can be represented as uniform random variables. And they will be processed before entering the simulation runs. Parallel search pattern is used. Obstacle is classified as the level of smoke, collapse and blocked access. Search speed for firefighter is changed according to the given level of smoke, serious level of collapse and the blocked access. In fireground, the building is divided into grids. In this study, under very limited fireground information, two teams of firefighter are responsible for the evenly divided factory by IC and the search is one grid after the other.

Case 2 is to use IOT, including UAVs that carried IR sensor, camera with flying capability in GPS-denied environment and AR equipment on firefighter, as support equipment. The operation logic is different from Case 1. The initial situation is obtained from UAV that it continuously sends back the information of fireground, such as main fire, temperature, thickness of smoke, visibility, obstacles and the location of victim, to form COP on screen for assisting IC in one's decision making and for each firefighter to acknowledge the real time situation in fireground.

Figure 3 Simulation logic of SAR in fireground (see online version for colours)



3.3 *The management of uncertain conditions*

Uncertain conditions include the location of main fire, victims and obstacles need to have a representative pattern in simulation for setting up the situation in scenario.

The representative of the location of main fire can be in a way of randomly selecting a cell by uniformly distributed random variable from the n cell building arranged by IC, which is $U(1, n)$.

Location of victims, in theory, can be at different cell with unknown number. Therefore, uniform random variable is used for describe the randomly distributed locations of victim. However, the objective of firefighters is to scrutinise every cell for their SAR, i.e., they have to go through every cell of the building no matter how many victims have been rescued until the last cell is checked.

The obstacle is defined as thick smoke, structure collapse and floor slippery in terms of high possibility to make firefighter slip, trip or fall. The thick smoke is highly dynamic in spreading that may possibly fill several cells in the same time. The number of cell being filled with thick smoke can be very different and highly impossible to predict due to the cause of design, material, weather condition, etc. of building. In this study, triangular distributed variates are used to represent number of cell filled with thick smoke.

To generate triangular distributed variates, it requires to use a random variate U which is drawn from uniform distribution in the interval (0, 1) and three constants value a, b and c standing for lower limit, upper limit and mode, respectively. Then, the variate

$$\begin{cases} X = a + \sqrt{U(a-b)(c-a)} & \text{for } 0 < U < F(c) \\ X = b - \sqrt{(1-U)(b-a)(b-c)} & \text{for } F(c) \le U < 1 \end{cases} \quad \text{where } a \le c \le b \tag{1}$$

While in the SAR task, firefighters could probably encounter two conditions that are either the firefighters would confront with or would not confront obstacles in the cell. Since the condition among cells can be very different, i.e., when without obstacles the search can become smooth with fast walking pace, but when in obstacle scene then it is necessary to classify the various level of difficulty for passing through and the moving speed would no doubt be affected accordingly. For the speed of firefighters, when in obstacle situation, the moving speed of firefighters, all are with PPE, could be slowed or stopped no matter while in walking, crawling or crossing. Hence, there are two behaviours needed representation in simulation, the firefighters' moving speed in different fireground conditions. The moving speed in fireground is divided into two types: walking when no obstacles existed and crawling when under situation such as thick smoke, greasy floor or collapse. The normal distributed variate is a way to mimic these two types of moving speed, in which the mean speed of walking and crawling is u_w and u_c and deviation is σ_w and σ_c.

3.4 Firefighter's movement model in fireground

The cell is defined as a square, Figure 4, with each side L and the sweep width w which would take average of firefighter's ape index. Assume firefighter's search pattern is setup as square search starting from outer search along the wall, then move into the inner search. The total range the firefighter passed in a cell can be obtained from the formula as derivation.

Let n be the integer number from representing number of square search in a cell. The first outer path is $4(L - w)$. The second, the third and the fourth are $4(L - 3w)$, $4(L - 5w)$ and $4(L - 7w)$. When have them all sum up, it turns out to be

$$4\left[(L-w)+(L-3w)+(L-5w)+(L-7w)\right] \tag{2}$$

If n is big enough, equation (2) can be as

$$4\left[nL-(1+3+5+7+\cdots+\max\_odd)w\right] \tag{3}$$

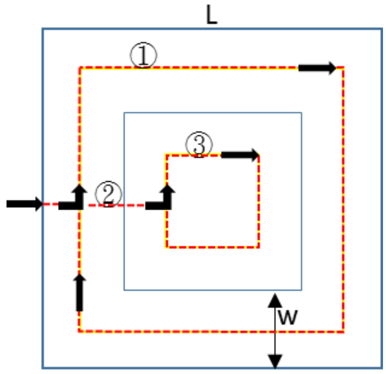
where max_*odd* stands for the maximum odd number, which equals to $n + (n - 1)$.

The range from entering point to the last path is round trip that is $2w(n - 0.5)$.

The formula for the total range of firefighter going through is

$$4\left\{nL - w\left(\frac{\max\_odd - 1}{2} + 1\right)^2\right\} + 2w(n - 0.5) \tag{4}$$

Figure 4 Search pattern in a cell of fireground (see online version for colours)



3.5 *UAV movement model in fireground*

The FOV in horizontal can be regarded as projected sweep width w against height of UAV. Given the ceiling of the cell is 5 m, the assumed maximum height of UAV is *h*, which is less than the ceiling for safety reason, then *w* equals to. Assume the search pattern is same as conventional firefighters'. The formula for the total range of UAV passing through in one cell is

$$4\left\{nL - 2h \cdot \tan\frac{\theta}{2}\left(\frac{\max\_odd - 1}{2} + 1\right)^2\right\} + 4h \cdot \tan\frac{\theta}{2}(n - 0.5) \tag{5}$$

4 Analysis

Objective of analysis is to find out the expected time for complete the searching task with given fireground by both of conventional firefighter (Case 1) and IoT equipped firefighter (Case 2). Measure of effectiveness (MOE) is the expected time of the completion of search task. Both cases have the same concept in firefighting, which is the factory used in this study is cut into two sides, each side has 16 cells. One side has the main fire building and the other side may suffer the thick smoke or other obstacles caused by the possible initial explosion. IC's decision is send out two teams for the suppression of main fire and the other team starts searching task for the victims.

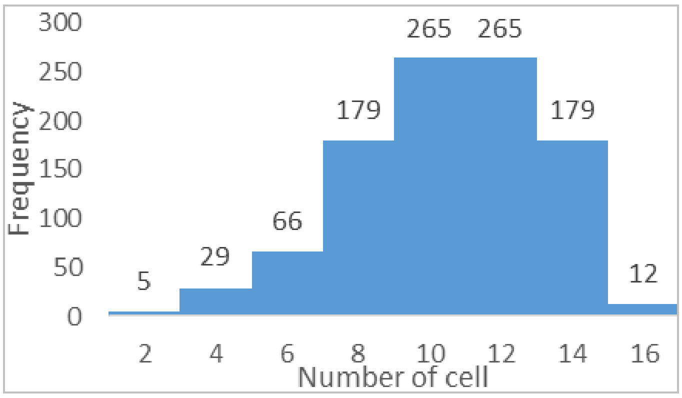
Assumptions used in study are as followings:

- Factory has no enclosed office (cell), which allows UAV to make an indoor-fly freely.
- The fire spreading speed can be slow down by water fog or water spray.
- SAR doctrine: first found first rescue (same as the concept of FCFS in queue theory).

- Equipment of IoT firefighter:
  a. UAVx2, one is for externally use for providing local network for communication link and the other is mini-UAV for internally use for searching inside the building. The sensor on board of mini-UAV, indoor flight capable, includes camera, laser rangefinder and thermal imaging system. FOV for camera and thermal system is set with maximum to 28°.
  b. AR device for being able to make action among firefighters co-ordinately.
  c. COP is available for IC.
  d. SCBA lasts for 30 min that makes 20 min effective stay inside fireground.

In Case 1, the speed of firefighter is one of the major concerns because it is matter with the expect time of firefighter and victim staying in dangerous zone. The expected time of it is the less the better. The number of potential obstacle cell has to be decided in the beginning of simulation. From triangular random variates function, the given low limit, mode and upper limit are (1, 11, 16), then the number of cell with obstacle can be generated. Figure 5 is 1,000 runs of triangular random variates. Each simulation run would take one random generated obstacle cell number as basis for analysing the performance of Case 1 and Case 2.

Figure 5 Triangular distributed number of obstacle cell (see online version for colours)



Note: Mode = 11.

In Case 1, when a cell has no obstacle, firefighter can walk in for the search. Walking speed for each firefighter is different due to the difference of age, physical condition and experiences. Normal random variate is used for describe the different walking status. The walking speed for full equipped firefighter takes 1.78 m/s as reference, has mean walking speed as 70% of reference in realistic situation and deviation is 20% for the description of specific conditions such as very smooth or need an alert to the potential collapse, etc. As for the cell with obstacle, crawling and slower walking are common moving for firefighter in order to overcome the potential risk. The crawling speed takes 0.3048 m/s as a reference, the mean is also 70% of the given reference. One way to setup the mean moving speed in obstacle cell is to take the average speed of walking and crawling. Owing to one of the roles of standard deviation is to serve as a measure of uncertainty, the highly uncertain situation in the near blind and risky obstacle cell which could have higher deviation from mean value. Based on that, the deviation is set with higher ratio of mean speed, i.e., 40%. After 1,000 simulation runs, the histograms are as Figure 6 and Figure 7.

Figure 6 Normal distributed firefighter walking speed (see online version for colours)

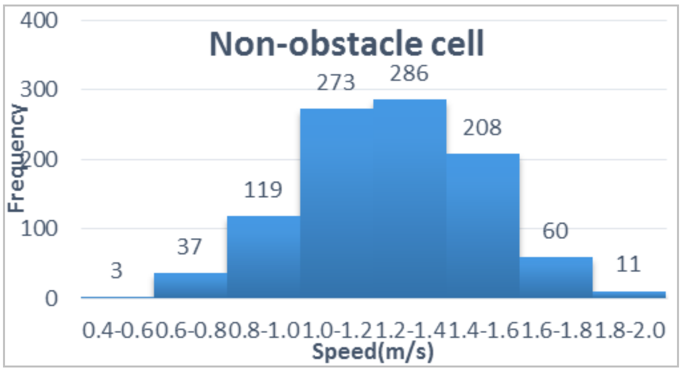
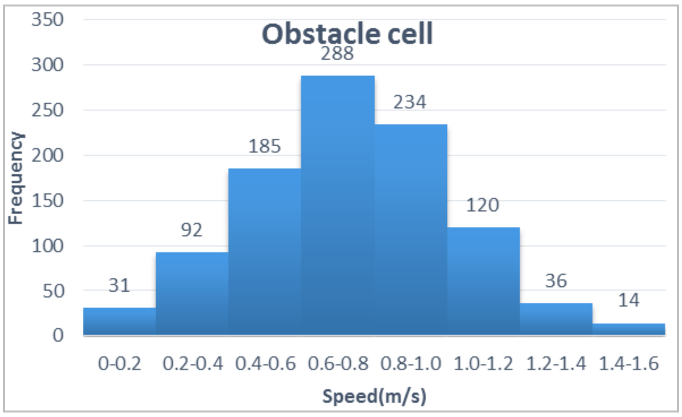


Figure 7 Normal distributed firefighter crawling speed (see online version for colours)



Based on the square search pattern in a cell, the total range depends on sweep width. Firefighter's ape index is to be referred, but the maximum sweep width will be deducted for the sake of crawling posture. Assume the average height of firefighter is 1.75 m, the 80% of ape index is taken as sweep width, i.e., 1.4 m. The range for firefighter has to pass is 57.25 m.

With the same scenario background as conventional firefighting, IoT supported firefighter is with the indoor-fly capable UAV to perform the search. The flying speed of UAV is restricted by the building ceiling and camera of FOV on UAV. When flying height is 4 m and FOV is 28°, the sweep width would be 1.99 m that makes the search range as 54.07 m. The mean and deviation of UAV speed is given as (1.6, 0.4) m/s and (4.8, 1.2) m/s for the cell with and without obstacle respectively.

After 1,000 simulation runs, the statistics shows MOE for conventional firefighting taking 31.8 minutes to complete the search in the assigned space of building, in which the time taken for obstacle/non-obstacle cell is 23.9/7.9 minutes. Using UAV to conduct the complete search is to take 9.8 minutes. After two-tailed t-test, the p-value is 5.5×10^{-76}, which is far less than 0.05 meaning the extremely significant difference exists when the information-based technology is used to support the search in the firefighting scenario.

5 Conclusions

Objective of this study is to evaluate the effectiveness of using UAV to support firefighting is search the possible trapped victim in fireground. Monte Carlo simulation is used for mimicking the highly uncertain searching behaviour caused by the uncontrollable development of fireground. The toxic thick smoke, greasy floor and collapse are major obstacles in fireground that they would certainly one of the drag forces for the searching movement. The movement speed of firefighters in searching is slow due to heavy PPE, messed environment and disoriented space that make more time to process the ambient data. The analysis of this study shows, IoT supported firefighting can greatly reduce the search time for 67.2% off from conventional firefighting. With t-test, p-value is far less than 0.05 which indicates the extremely significant difference actually exists between the IoT supported firefighting and conventional way.

The given scenario in this study in one of many that is hardly represents all of fireground situation. Under the comparison of the how much effectiveness the IoT supported firefighting can achieve from the conventional one, this result just present a significant change in using mini-UAV to do the fireground search. In fact, it would be a problem if the fireground have no access for mini-UAV to fly in such as office building with its doors and windows tightly closed or the obstacle caused by serious collapses and explosions, etc. that would other case for we to do a further study.

Since IoT has become one of the very important factors in affecting the modern world, the way to improve the effectiveness of firefighting by the aid of IoT has been an unavoidable and urgent issue for the sake of saving lives, property and keeping the safety of firefighter. This study focus only on the search in fireground that is even just a part of actions in firefighting, but still make a great contribution to firefighter by revealing the valuable result of new way of firefighting with the support of information equipment. Our future work will be a full evaluation to the IoT supported firefighting in terms of the time needed for firefighter exposing themselves in the fireground, evacuating victim and the requirement of manpower in fireground.

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