J Supercomput
DOI 10.1007/s11227-017-2098-3

Effectiveness evaluation of Internet of Things-aided firefighting by simulation

Kuei Min Wang[1] · **Lin Hui**[2]

Abstract With the emerging Internet of Things technology, the world is facing rapid changes in all areas; firefighting is no exception. Conventional firefighting is a dangerous occupation which involves saving lives and property from fires. The skills of firefighting have not changed greatly over the years; hence, using the IoT to aid firefighters is a way to improve their performance. Due to the lack of research on implementing the IoT in the firefighting domain, the objective of this study was to use the quantitative method to gain insights into the usefulness of using the IoT as an aid to firefighting. A Monte Carlo simulation was developed for processing the detailed firefighting interactions in situations of uncertainty. After the verification of the simulation model, the results showed that the search time ratios of unmanned aerial vehicle (UAV) to conventional firefighting for various levels of severity of fire were 30.09, 26.69, and 22.24%. The search and rescue time ratios of UAV to conventional firefighting were 48.27, 35.95, and 31.87%. The most important of these statistics is that at least 50% of the time spent by firefighters on the scene of the fire can be reduced by using the Internet of Things. All of the above data were analyzed using *t* test, which showed significant improvement when the Internet of Things was implemented in firefighting. The contribution of this study is to present quantitative results for proving the value of integrating the Internet of Things into firefighting.

✉ Kuei Min Wang
willymarkov@gmail.com; willymarkov0413@gmail.com

Lin Hui
amar0627@gmail.com

1 Department of Information Management, Shih Chien University, Kaohsiung 84550, Taiwan

2 Department of Innovative Information and Technology, Tamkang University, Yilan County 26247, Taiwan

Published online: 24 June 2017

Keywords Firefighting · IoT · UAV · Simulation · Obstacle

1 Introduction

Firefighting is a highly uncertain, complicated, and dangerous process, which has claimed countless lives throughout history. With the leaping advances in information technology, there has been a boom in the application of the Internet of Things (IoT) in many fields for providing certain data or information for the support of decision makers. Many studies have contributed views on employing sensors for firefighting so as to collect more data in a short time to give the incident commander (IC) a clearer big picture of the scene of the fire. However, how effective the IoT can be in the support of firefighting has seldom been addressed. Since the effectiveness of IoT-aided firefighting has not yet been studied in any depth, the decision to invest in IoT equipment and integration could lack solid supporting empirical data. The objective of this paper was therefore to model the search and rescue (SAR) behavior in both conventional and IoT-aided firefighting for a specific fire scenario to acquire quantitative results. A Monte Carlo simulation was developed to evaluate the effectiveness of the two approaches. The core factors, including main fire, heavy smoke, collapse, and greasy floor, were considered to develop the scenario of the fireground. A verification process was also carried out to ensure the reliability of the simulation results.

2 Related work

The scope of this study includes firefighting operation and performance, and the required information to support command control (C^2) in firefighting. The reviewed papers were able to fulfill the scope we envisioned for exploring more deeply and to expand more on the facts of technology use in firefighting.

Fires probably constitute some of the worst disasters in the world. According to the statistics of the National Fire Protection Association (NFPA) [1], 1,236,994 fires were reported in 2014 in the US, resulting in 3275 civilian fire deaths, 15,775 civilian fire injuries, and 11.5 billion USD in property damage. The statistics of the Centre Technique des Industries de la Fonderie (CTIF), including the average number of fires per year from 2010 to 2014, revealed that the US has the most frequent fire calls in the world, 13 countries are in the range of 100,000–600,000, 21 countries are in the range of 20,000–100,000, 30 countries from 5000 to 20,000, and 150 less than 5000. In 2014, the average numbers of fire/deaths/injuries of 30 countries were 85,212.1/767.7/2,794.4. Therefore, the way to minimize the casualties caused by fires is an issue of worldwide importance.

Fire can have unpredictable consequences due to the complexity of the fireground, which is difficult to control and can cause injury and death to firefighters. There are many causes of firefighter casualties including ineffective radio communications, asphyxiation (mainly smoke inhalation), getting lost inside the structure and running out of air, structural collapses, getting trapped, and unexpected flashovers [2–4]. One of the major reasons why the fireground situation is highly uncertain and why firefighters find themselves in dangerous situations is the lack of data and information of the fireground factors [5,6]. A survey by Li et al. [7] pointed out that the most frequently required assistance was for information collection. The lack of real-time data on thermal conditions, the location of firefighters /victims /fires, navigation, communication, distribution of smoke, toxic gas species, and building data were all cited [8–10].

The purpose of the Fire Service for the past 250 years has been to save lives, protect property, and reduce harmful impacts on the environment [11]. Interior tactics to extinguish fires are: detect the location of the fire, isolation of the fire area, Confinement of the fire, extinguishment of the fire, rescue of those affected by the fire and smoke, and search of the fire area and adjoining spaces, referred to by the acronym DICERS [12]. However, whether these tactics are sufficient for carrying out the firefighting task is questionable. To verify the current performance of firefighting, the decision-making process of the Incident Commander (IC) is the key. The IC needs to fully control the fireground situation and all of the firefighters' actions. To do so, the on-scene data are very important information for establishing situation awareness (SA). SA in firefighting is defined as the level of understanding and attentiveness the IC has regarding the reality of a set of conditions (fire conditions and fireground operations). Conditions that may impact SA include: a lack of information (size up and progress reporting), a lack of knowledge (training and information), and a lack of cognition (not understanding what is being heard or observed). The consequences induced by these conditions may be misinterpreting conditions and surroundings, not recognizing factors and cues, gathering incomplete information, being too narrowly focused, and being impaired [13].

The decision making regarding the current state of firefighting on the fireground is information limited—that is, 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 of the fireground, the changing location of the firefighters, and the location and status of the building's occupants [14]. Twelve categories of means objectives have been identified by the National Institute of Standards and Technology (NIST), six of which highlighted the ineffectiveness of the current firefighting performance, namely detection, SA, response time, communications, fire isolation, and evacuation time [15,16]. In fact, fire losses in the US remain high, and firefighting is extremely hazardous. The current state of firefighting and fire protection remains far from optimal despite efforts to exploit advances in technology, equipment, training, and communications [17].

The studies by Anthony Hamins et al. and Jesse Roman suggest that the requested information comes from the community, the building occupants, the building itself, and from firefighters. Integration of the information can benefit the analyses and return predictions by models for the IC's decision making. The critical data in firefighting include the building's layout, contents, and number of occupants, the building's thermal environment, the location of each firefighter, victims, fire, and smoke [18,19]. In terms of critical information required for improving the situation awareness, the evaluations of several studies indicate that some available new off-the-shelf technologies are ready to act as supports for effective firefighting. The common operational picture (COP) can display the information about the location of all fighters, victims, fire, smoke, and collapse in the fireground to all firefighters and the IC. Augmented reality (AR) goggles can display all fused critical information such as building layout and path indicators, information from the COP, remaining air in the self-contained breathing apparatus (SCBA), temperature [20]. Unmanned aerial vehicles (UAV) are now available to play a vital role in firefighting. They can carry infrared (IR) sensors and cameras to create surface temperature maps, to find victims, and to save firefighters from risk, while also providing communication links [21–23]. Inside the building, GPS would no longer be available, making the UAV useless in the SAR task. In a fire situation, mini-UAVs, such as micro air vehicles (MAV), are capable of performing the indoor stable flight in GPS-denied environments, offering an aid to firefighting. A laser rangefinder sensor installed on an MAV can autonomously explore and map unstructured and unknown environments, a function known as simultaneous localization and mapping (SLAM), which benefits localization, navigation, and path planning [24–26]. With search and detection sensors installed on MAVs, comprehensive data from the fireground feeding to the IC to form the COP become possible. The thermal imaging system and camera with a 28° horizontal field of view (FOV) can be carried by an MAV for the purpose of search and detection [27].

The movement speed of firefighters is critical for reducing the time spent on the fireground. In firefighting operations, firefighters can stay in the fireground for about 20 min due to the limitation of the self-contained breathing apparatus (SCBA) air capacity. The firefighter’s speed of walking and crawling with personal protective equipment (PPT) is 1.78 and 0.3048 m/s. Crawling is necessary due to the obscure vision in smoke-filled spaces and the heat [28,29]. In [30], Penders et al. set the firefighter crawling speed as 12 m per minute (i.e., 0.2 m/s). The amount of oxygen contained in the breathing apparatus suffices for about 30 min.

The search needs a pattern for firefighters to comply to. The search patterns used are in accordance with the International Aeronautical and Maritime Search and Rescue (IAMSAR) Manual [31] for different purposes, such as Trackline Patterns, Parallel Patterns, Creeping Line Patterns, Square Patterns, Sector Patterns, Contour Patterns, Flare Patterns, Homing Patterns, and Drift Compensation during a search. Square single units in search patterns are used with a high degree of confidence that the search object is close to the estimated datum position, which is quite similar to the firefighter’s search pattern in the fireground.

3 Operational logic and modeling

3.1 Scenario

In this study, a factory containing several offices and a large open space for machines and materials was the setup fireground. The fire builds up from somewhere inside the open space, with thick smoke filling the space. The trapped workers are still inside the factory waiting for rescue when the fire engines arrive. All firefighters are fully equipped and are under the command of the IC. The size of the factory is set as 80 by 40 m, with a height of 5 m, including four offices, as shown in Fig. 1. The factory is divided by the dashed lines into several numbered square cells as the basic unit of

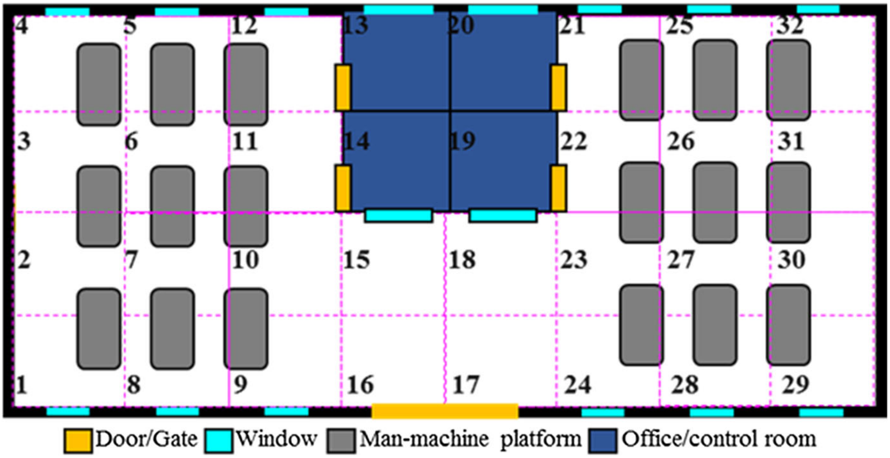

Fig. 1 Factory layout (*dashed line grid* basic SAR unit)

the fireground. The major task for the firefighters is to go through every inch of the building to search for an unknown number of victims. The factory has two separate but identical production areas with a main gate in the center which is blocked due to an explosion. The main fire is in one of the areas. All victims are forced to move to the other area by heavy smoke and heat; the IC therefore determines to make this area the top priority in the SAR task on the resource allocation list. The concept of firefighting is simply to save victims and property as quickly as possible and to ensure the safety of the firefighters during the operation. Based on this concept, the uncertainty of the fireground is exacerbated by adding the condition of obstacles caused by fire or smoke and the probable victims in unknown cells. The firefighting SAR operation logic diagram is shown in Fig. 2.

In conventional firefighting, all SAR tasks would be performed by the firefighters. UAV-aided firefighting would use indoor mini-UAVs to perform the search task before the firefighters enter the fireground. Once a victim is found, the search team would turn their search task into a rescue task to evacuate the victim from the fireground as quickly as possible. The other team would come in from the supply center to continue the search until it is completed.

The obstacle cell would slow down the search pace due to the possible thick smoke, collapse, or greasy floor caused by the fire. With full firefighting equipment, around 75 lbs., the speed under obstacle conditions can be very slow due to the limited eyesight, required breach or crawl. The firefighters also need to stop and listen for nearby victims. Therefore, they need to visit every inch of the rooms by walking or crawling. The other concern is the possible disorientation of firefighters in the low visibility situation which would seriously stall the search progress.

In the simulation, based on operational logic, some specific behaviors and conditions such as the location of the fire, victims, obstacles, and the moving speed of the firefighters and the mini-UAVs all need to be modeled. The problem-solving algorithm is shown in Fig. 3.

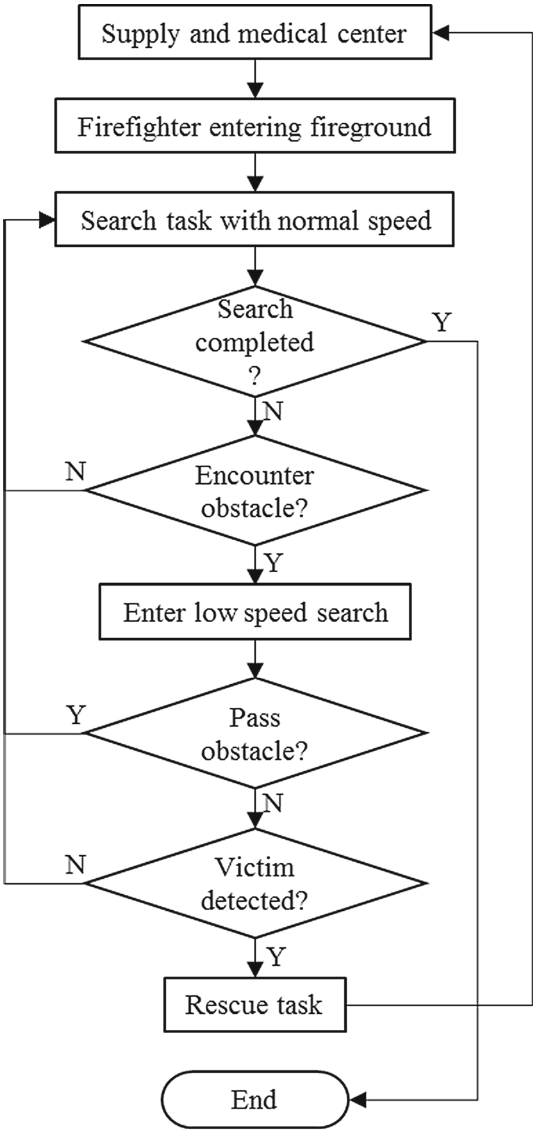

Fig. 2 SAR operational logic diagram

4 The uncertain variables

The uncertain characteristics of the location of the main fire, victims, and the obstacle cells can be represented as uniform random variates. For example, the location of the main fire can be randomly selected in terms of a cell by uniformly distributed random variables from the n cell building arranged by the IC, which is $U(1, n)$. The location of victims, in theory, can be in different cells of unknown numbers. Therefore, the uniform random variable is used to describe the randomly distributed locations of

BEGIN
Initialize parameters of size of fireground area, number of cell, SCBA time, mean and deviation of firefighter (ff) and mini-UAV speed in non-obstacle and obstacle cell, mode of obstacle cell, sweep width of search, number of spread-victim over cells, mean and deviation of evacuation speed with victim

n= 1000 (Simulation runs)
    For i =1 to n
        Decide serious level of the fireground by Triangular distribution (a,c,b) for the number of obstacle cell,
        Decide ff and UAV speed in non-obstacle and obstacle cell by $N(\mu_{no\_ff}, \sigma_{no\_ff})$ and $((\mu_{o\_ff}, \sigma_{o\_ff})$; $N(\mu_{no\_uav}, \sigma_{no\_uav})$ and $N((\mu_{o\_uav}, \sigma_{o\_uav})$
        For j=1 to total_cell
            If RND() < obstacle_cell ratio then
                Calculate required time of searching this obstacle cell by ff and UAV=t_{o_ff} and t_{o_uav}, Accumulation of t_{o_ff} and t_{o_uav},
            Else
                Calculate required time of searching this non-obstacle cell by ff and UAV=t_{no_ff} and t_{no_uav}, Accumulation of t_{no_ff}, t_{no_uav},
            End If
    Next j
    For k=1 to victim_spread_cell
            If RND () < obstacle_cell ratio then
                Calculate required time of evacuating victim thru this cell=t_{o_eva},
                Calculate time needed for turnaround ff thru this cell= t_{o_tr}
                Accumulation of t_{o_eva} and t_{o_tr},
            Else
                Calculate required time of evacuating victim thru this non-obstacle cell =t_{no_uav},
                Calculate time needed for turnaround ff thru this cell= t_{no_tr},
                Accumulation of t_{no_eva} and t_{no_tr},
            End If
    Next k

    Statistics of simulation as the followings:
    Exp(conventionl search time)
    Exp(UAV search time)
    Exp(rescue time)
    Exp(turnaround time)
    END

Fig. 3 Simulation algorithm

the victims. The square search pattern in each cell is used to guarantee that no areas are missed. The obstacles are defined as thick smoke, structure collapse, and slippery floor, creating a high possibility of the firefighters slipping, tripping, or falling. The thick smoke is highly dynamic in its spreading and may fill several cells at the same time. The number of cells filled with thick smoke can be very different and impossible to predict due to the building design, materials, weather conditions, etc. In this study, triangular distributed variates were used to represent the number of cells filled with thick smoke or with obstacles. To generate the triangular distributed variates, a random variate U is drawn from uniform distribution in the interval (0,1), and three constants with values a, b, and c standing for the lower limit, upper limit, and mode, respectively, are used. Then the variate

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

One of the rules in the search is that the firefighters must step in all of the cells, that is, they have to go through every cell of the building without stopping, no matter how many victims have been rescued, until the last cell has been searched. During the SAR task, the firefighters could encounter the two possible conditions that an unpredictable obstacle is hit or is not hit in a cell. Due to the high uncertainty of the fire scene, the conditions of cells can differ greatly. When the SAR encounters no obstacles, the pace can be faster. Otherwise, the various levels of obstacles would certainly hinder the speed of movement. Different obstacles decide the firefighter's movement behavior, for example, walking, crawling, or climbing. In this study, two types of moving speed are defined: walking when no obstacles exist and crawling when an obstacle such as thick smoke, a greasy floor, or a collapse is encountered. 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 the deviation is σ_w and σ_c.

In logic, the victim has a high priority of being evacuated from the cell, whoever finds the victim becomes the rescue team. The following search is taken over by a new team, called the turnaround team, which will take some time. In this situation, the uniform random variate is used to generate the number of victims and the cells over which the victims are spread.

4.1 Firefighter's movement model in the fireground

The cell is defined as a square, as in Fig. 4, with length $L$of each side. The sweep width w would take the average of the firefighter's Ape index. The search pattern in the cell is set up as a square search starting from the search along the wall to the inner search until the search is completed. The total range the firefighter must go through in a cell can be derived as follows:

Let n be the integer number from $\left[\frac{L}{2w}\right]$ representing the number of squares of 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 they are all summed up, we have

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

If n is big enough, (2) can be

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

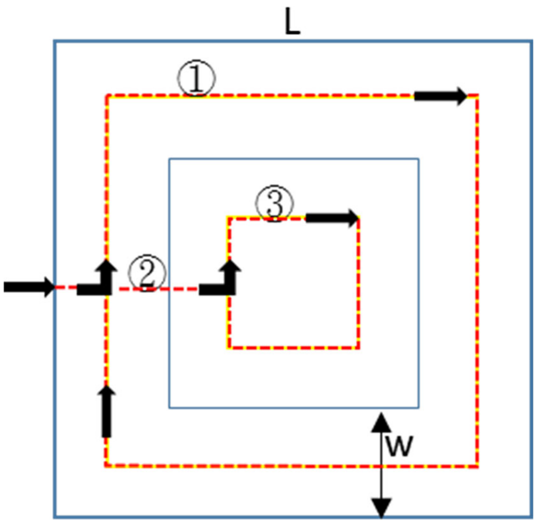

Fig. 4 Search pattern in a fireground cell

where max_odd stands for the maximum odd number, which equals $n + (n - 1)$

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

The formula for the total range of the firefighter going through each cell is

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

4.2 UAV movement model in the fireground

The field of view in horizontal, θ, can be regarded as the projected sweep width w depending on the height of the UAV. Given 5 m of the cell ceiling with h as the maximum height of the UAV, it can fly in the cell, then $w = 2h \cdot \tan\frac{\theta}{2}$. The search pattern is the same as the pattern used by conventional firefighters. The formula for the total range of firefighters and UAVs searching in one cell is

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

4.3 Verification

Since verification focuses on the internal process, a way to verify the developed simulation model is to check if the time to complete the search is about the same for both in the simulation and in mathematics. In the model, the exhaustive search concept is applied to firefighters in order to be sure that every inch of the floor is searched. The

Table 1 Two groups of data

Simulation	Math
17.434	17.660
11.647	12.030
15.115	18.079
14.189	12.413
19.145	18.079

concept of the search theory used in maritime searching can be used to verify the result of the developed simulation model in this study. As the search probability is known, the time for the search can be calculated. The factors considered by probability of detection (Pd) include the sweep width (w), the searcher's speed (s), the total time spent on the search (t), and the assigned area (A). These factors form the coverage factor (C) so that Pd can then be expressed by

$$\mathrm{Pd} = 1 - \exp^{-C} \tag{6}$$

where, $C = \frac{S \times t \times w}{A}$.

Since the search is defined as an exhaustive search, it implies that the searched area would be equal to the area of A. In this situation, $C = 1.0$, i.e., $S \times t \times w = A$. To verify the simulation model, we simply check if there is a significant difference in the total time of searching throughout the designated fireground for both approaches. If there is no significant difference, then we can prove that the model is verified. In this process, five sets of samples are drawn from the simulation as the treatment group, and the other five sets of data are taken as the control group which are calculated by math, as shown in Table 1.

Before performing the t test to calculate the significance, we need to distinguish if equal variance exists between them. We can use the F test to do this. In Table 2, the F statistics value (1.168) is less than the value of F critical (6.388), which means that the sample variances are considered to be equal.

The t test is specified as two-sample with equal variance. The p value is 0.941, which is greater than 0.05, meaning that there is no significant difference between these two groups, and verifying the internal process consistency of the simulation model.

5 Analysis

Since verification focuses on internal processes, one way to verify the developed simulation model is to check if the time to complete the search is about the same for both approaches in simulation and in mathematics. In the model, the exhaustive search concept is applied to firefighters in order to be sure that every inch of the floor is searched. The concept of the search theory used in maritime searching can be used to verify the result of the developed simulation model in this study. As the search probability is known, the time for the search can be calculated. The factors considered

Table 2 *F* test two-sample for variance

	Math	Simulation
Mean	15.652	15.506
Variance	9.856	8.435
Observations	5	5
Df	4	4
F	1.168	
$P\ (F <= f)$ one-tail	0.442	
F critical one-tail	6.388	

by probability of detection (Pd) include the sweep width (w), the searcher's speed (s), the total time spent on the search (t), and the assigned area (A). These factors form the coverage factor (C) that Pd can then be expressed by.

The assumptions used in the analysis are as follows.

- The factory has no enclosed office (cell), which allows the UAV to fly freely indoors.
- SAR doctrine: the victim management doctrine is *first found first rescued*.
- The uncertain number of obstacle cells is decided by the triangular distributed variate, i.e., Triangular (a, c, b), where $a = 0$, c is dependent on the level of severity of the fireground, $b = 16$.
- Equipment of the IoT firefighter:
  - UAVx2, one for external use providing a local network for the communication link and the other is a mini-UAV for internal use for searching inside the building. The sensors on board the mini-UAV include a camera, a thermal imaging system, and a laser rangefinder. The field of view of the camera and thermal system is set to a maximum of 25°.
  - SCBA lasts for 30 min that makes 20 min the effective stay inside the fireground.

The objective of the analysis is to understand the effectiveness of both the conventional and IoT-aided firefighting, which can provide us with information about the differences in the total time needed for SAR and to verify the significance of the IoT-aided firefighting.

The mode of triangular distributed number of obstacle cells is set as (0, 8, 16) for the description of the level of severity of the fireground. The ratio of obstacle cells is 30.9, 46.4, and 63%, respectively. The search time for both the conventional and UAV-aided firefighting is as shown in Fig. 5. The t test result shows that the p value is 0.0098, less than 0.05, which means that the UAV in the search for victims has a significant improvement when compared with the conventional way. The search time ratio of the UAV to the conventional approach is 30.09, 26.69, and 22.24, which indicates that the UAV can save more time in the search than the conventional approach when the obstacle situation is increasingly serious.

The total time for the SAR task includes the rescue task for evacuating the victims from the fireground and the time needed for the turnaround team to get to the latest searched location, as shown in Fig. 6. The t test result shows that the p value is 0.0133,

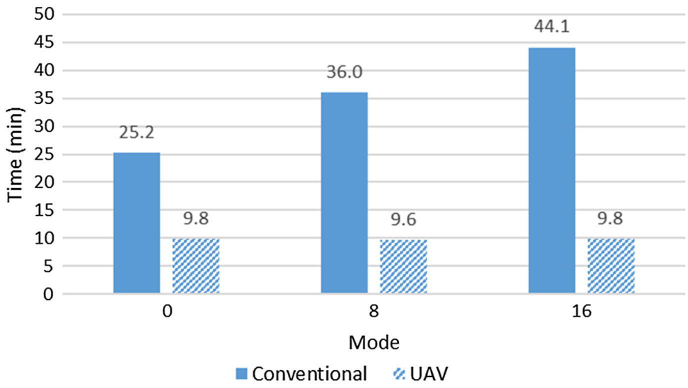

Fig. 5 Time for search

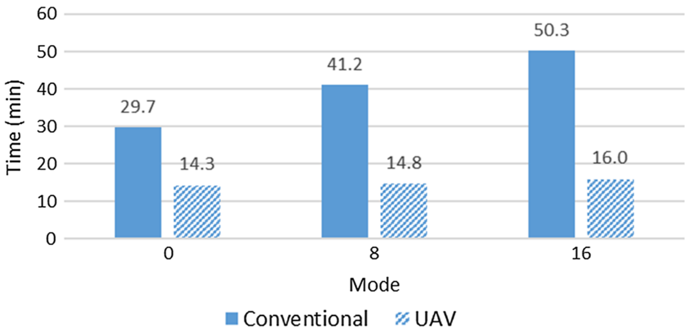

Fig. 6 Time for SAR

which is also less than 0.05, showing a significant improvement when the UAV-aided search is used in firefighting. The SAR time ratio of the UAV to the conventional approach is 48.27, 35.95, and 31.87%.

In the worst situation, when all cells have different obstacles, the total time for SAR for both is 50.33 and 16.04 min. If there are two firefighters per sortie and the maximum time in the fireground is 20 min, the conventional firefighting requires at most three sorties compared with the IoT-aided firefighting which needs only one. This means that the fire department can not only minimize the risk for the firefighters but can also send fewer firefighters into the fireground. These two values, 50.33 and 16.04 in, have new implications, of which reducing the exposure time in the fireground for both firefighters and victims is the first, and the second is reducing the manpower resources required for firefighting.

5.1 Summary of analysis

In the search task, the UAV can not only provide a network which allows the IC to take full control of the fireground, but also reduces the time the firefighters need to stay in the fireground. The percentage of time that can be reduced from conventional firefighting for the three levels of severity, from low to high, is 60.99, 73.31, and 77.76%. These statistics illustrate a trend that the time firefighters spend in the fireground and the level of severity are in inverse proportion when the IoT is implemented. It is the same for the SAR task; that is, the time that can be reduced from conventional firefighting for the three levels of severity is 51.73, 64.05, and 68.13%.

Throughout the SAR task, the IoT-aided firefighting can cut at least half of the time the firefighters spend in the dangerous operation situation.

6 Conclusions

Monte Carlo simulation and *t* tests were used in this paper to analyze the effectiveness of firefighting. Verification of the process was also performed to ensure that the simulation model was consistent and error free. From the simulation, the operation of IoT coordinating with conventional firefighting is quantified and presents the significant improvement made by the IoT. The most important finding is that at least 50% of the time the firefighters stay in the fireground can be reduced for any level of severity by just using two UAVs with the necessary sensors and devices on board. Another insight is that using the IoT as a support can be very helpful for the IC in terms of making more accurate decisions regarding the allocation or reallocation of precious resources. This study provides quantitative results illustrating the huge contribution the IoT can make and also sheds light on a new way of IoT-coordinated firefighting. We suggest that fire authorities should start reaching out to the IoT concept and equipping firefighters with UAVs with detection sensors on board and AR goggles for the sake of improving firefighting effectiveness and minimizing the risk faced by the firefighters.

However, while the scenario used in this paper is in favor of using IoT, in some fireground situations, the maneuverability of the UAV could be restricted due to the limited accessibility or space caused by the attributes of the building and fire. This could create difficulties in the deployment of sensors in the fireground.

Our future work will include a greater variety of scenarios with plausible combinations of the number of UAVs and firefighters in coordinated operation to fully understand the advantages and the restrictions of using the IoT in the real world. The planning topics will consider the effectiveness of employing multiple UAVs instead of a single one inside the fireground, the interactions between the UAVs and firefighters when some of the spaces inside the fireground are tightly closed, thus limiting the UAV's maneuverability and accessibility, the problem of victims being under rubble caused by collapse that could not be sensed by the UAV's sensors, and the effectiveness of the IC's command control in firefighting.

References

1. Hall JR (2014) The total cost of fire in the United States. National Fire Protection Association, Quincy
2. Fahy RF, LeBlanc PR, Molis JL (2016) Firefighter Fatalities in the United States-2015. National Fire Protection Association, Quincy
3. Varone C (2012) Firefighter safety and radio communication. Fire Manag Today 156(3):14
4. Thiel A, Stambaugh H (2013) Improving firefighter communications, U.S. Fire Administration Technical Report 099. 1999. http://www.usfa.fema.gov

5. Parker R, Bayne K, Clifford V (2014) Minimum fitness recommendations for rural fire personnel. New Zealand Fire Service Commission, Wellington
6. Bearman C, Owen C, Brooks B, Grunwald J (2013) Problems of maintaining elective teamwork during out of scale In: Proceedings of the Bushfire CRC and AFAC 2013 Conference Research Forum
7. Li N, Yang Z, Ghahramani A, Becerik-Gerber B, Soibelman L (2014) Situational awareness for supporting building fire emergency response: information needs, information sources, and implementation requirements. Fire Saf J 63:17–28
8. Weinschenk CG, Overholt KJ, Madrzykowski D (2014) Simulation of an attic fire in a wood frame residential structure—Chicago, IL. National Institute of Standards and Technology, Gaithersburg
9. Alberto DS, Bernabe C, Mart'ınez-de DJR, Baturone AO (2012) A WSN-based tool for urban and industrial fire-fighting. Sensors 12:15009–15035
10. Schultz C, Bhatt M (2011) Toward accessing spatial structure from building information models. In: UDMS 2011: 28th Urban data management symposium, Delft, The Netherlands, Urban Data Management Society; OTB Research Institute for the Built Environment; Delft University of Technology, 28–30 Sep 2011
11. Silvernail J (2016) Applying the principles of modern fire attack to the objectives of the fire service. 6 12 2014. http://modernfirebehavior.com/applying-the-principles-of-modern-fire-attack-to-the-objectives-of-the-fire-service/. Accessed 29 July 2016
12. McCormack R (2016) Engine company operations: DICERS-VO for extinguishment. 30 7 2014. http://www.fireengineering.com/articles/2014/07/dicers-vo-protecting-the-egress.html. Accessed 29 July 2016
13. Angulo R, Clark BA, Auch S (2012) Rules of engagement for structural firefighting—increasing firefighter survival. International Association of Fire Chiefs, Fairfax
14. Grant C, Hamins A, Bryner N, Jones A, Koepke G (2015) Research roadmap for smart fire fighting. National Fire Protection Association, Quincy
15. Averill JD, Peacock RD, Keeney RL (2009) Rethinking egress: a vision for the future. National Institute of Standards and Technology, Gaithersburg
16. Pilemalm S (2011) Emergency response systems: concepts, features, evaluation and design. Center for Advanced Research in Emergency Response, Linköping
17. Hamins A, Averill JD, Gann RG, Bryner NP, Davis RD, Butry DT, Maranghides A, Yang JC, Madrzykowski D, Bundy MF, Manzello SL, Gilman JW, Amon FK, Mell WE (2012) Strategic roadmap for fire risk reduction in buildings and communities. National Institute of Standards and Technology, Gaithersburg
18. Roman J, Rodwell S (November/December 2014) Data Driven. NFPA J 40–50
19. Hamins A, Bryner N, Jones A, Koepke G, Grant C, Raghunathan A (2014) Smart firefighting workshop summary report. NIST Special Publication, Arlington
20. Wani AR, Shabir S, Naaz R (2013) Augmented reality for fire & emergency services. In: Proceedings of International Conference on Recent Trends in Communication and Computer Networks, Hyderabad, India
21. Aden ST, Bialas JP, Champion Z, Levin E, McCarty JL (2014) Low cost infrared and near-infrared sensors for UAVs. In: Proceedings of the ISPRS technical commission I symposium on international archives of the photogrammetry, remote sensing and spatial information sciences, vol XL-1. Denver, CO, USA, pp 1–7, 17–20 Nov 2014
22. Monares Á, Ochoa SF, Santos R, Orozco J, Meseguer R (2014) Modeling IoT-based solutions using human-centric wireless sensor networks. Sensors 14:15687–15713
23. Stanton NA, Plant KL, Roberts AP, Harvey C, Thomas TG (2015) Extending helicopter operations to meet future integrated transportation needs. Appl Ergon 47:364–373
24. Bachrach A, He R, Prentice S, Roy N (2011) RANGE—Robust autonomous navigation in GPS-denied environments. J Field Robot 28(5):644–666
25. Grzonka S, Grisetti G, Burgard W (2012) A fully autonomous indoor quadrotor. IEEE Trans Robot 99:1–11
26. Shen S, Michael N, Kumar V (2011) Autonomous multi-floor indoor navigation with a computationally constrained MAV. In: IEEE International Conference on Robotics and Automation, Shanghai, China
27. Bendig J, Bolten A, Bareth G (2012) Introducing a low-cost mini-UAV For thermal- and multispectral-imaging In: International archives of the photogrammetry, remote sensing and spatial information sciences, vol XXXIX (B1). Melbourne, Australia, pp 345–349

28. von Heimburg E, Ingulf Medbø J (2013) Energy cost of the Trondheim firefighter test for experienced firefighters. Int J Occup Saf Ergon (JOSE) 19(2):211–225
29. Farmer CM (2015) Visualization of auditory masking for firefighter alarm detection. The University of Texas, Austin
30. Penders J et al (2011) A robot swarm assisting a human fire-fighter. Adv Robot 25(1):93–117
31. Organization I.M. (2005) IAMSAR manual. International Maritime Organization, London