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Battery Management Systems for Firefighting Robots Using Simulation Modeling

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BATTERY MANAGEMENT SYSTEMS FOR FIREFIGHTING ROBOTS USING SIMULATION MODELING

by

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
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I dedicate this dissertation to my family for nursing me with affections and love and their dedicated partnership for success in my life.

My angelic wife, Yookyung:
Her devoted care for me and our children made it possible for me to complete this achievement.

My seraphic children, Jiho and Jiah:
Thanks to you who always give me happiness, your father has cheerfully been able to finalize this accomplishment.

My honored parents from both families, Sungeun, Yukyeon, Jongsun and Sungja:
In addition to self-efforts, every challenging work needs guidance of elders, especially those who are very close to the heart. This honor was made possible by my parents' guidance, love, encouragement and prays of day and night.

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I would also like to thank Dr. Matson for his support, insight, and assistance that for bringing me to Purdue and led to the completion of my research. In my life, it has been a great fortune for me to meet him and get help from him. From now on, I would like to find a way to give him a big chance as he did.

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LIST OF ABBREVIATIONS

AL – Appliance Loss

ATD – Automatic T-valve Device

ATS – Automatic T-valve System

AWMS – Automatic Water Management System

BMS – Battery Management Systems

DRC – DARPA Robotics Challenge

EL – Elevation Loss

FL – Friction Loss

FRDC – Firefighting Robot Drive Cycles

MRESS – Multi-Robot Energy Saving System

NDFR – Novel Designed Firefighting Robot

OSHA – Occupational Safety and Health Administration

PHSI – Purdue Homeland Security Institute

TPL – Total Pressure Loss

GLOSSARY

Agent-based modeling – If a designed system is able to make decisions by itself, it is called agents. Whenever agents encounter various situations, they are able to solve the problems.

Modeling – In order to solve the problem in the real world, the situations are reproduced in a virtual space.

Simulation – "the process of model "execution" that takes the model through (discrete and continuous) state changes over time" (Borshchev & Filippov, 2004, p. 1).

ABSTRACT

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The battery management systems for firefighting robots are intended to enable firefighting robots to increase operating time and to effectively extinguish a fire while managing the amount of water in a fire hose and cooperating sub-robots. To increase the operating time by managing the traction power of the firefighting robot, a novel automatic T-valve device and sub-robots were designed and added to fire hoses. The main goal of the battery management systems for firefighting robots is to lower the weight of the fire hose and to increase traction power by working with sub-robots. Whenever a firefighting robot wants to move to other spaces, the battery management systems will remove the water from fire hoses and draw the empty fire hoses by using sub-robots; thus, they are able to help the main firefighting robot to carry lighter hoses and to operate for a longer time. As a result, the battery management systems for firefighting robots enable the firefighting robot to successfully extinguish a fire for a longer time and to efficiently reach the desired destinations. The demonstration will be modeled by a computer simulation program, called AnyLogic®, which can model a fire and fire areas and apply the battery management systems to robots in each fire site.

CHAPTER 1. INTRODUCTION

This chapter is designed to provide the research problem statement and the corresponding research questions, scope, and significance. In addition, the assumptions, limitations, and delimitations are addressed.

1.1 Problem Statement

Every year, numerous amounts of deaths and property damages occur at fire scenes. In the U.S. the largest proportion of deaths consists of on-duty firefighter. According to the data collected by U.S Fire Administration, 82.9 firefighters died every year on average in the past 10 years and about 13 billion dollars in property damage occur per year (Karter, 2013; Haynes, 2015). To decrease the number of deaths and the amount of property loss, researchers addressed various types of solutions. One of the effective methods is to quickly move a strong heat-resistant firefighting robot on the fire scene. Although firefighters without robots should invest enough time in setting up the extinguishing planning details for their safety, the robot is able to go quickly into the fire scene and to extinguish the fire without investing time setting up complex planning details. As a result, the robot not only substitutes for the firefighters, but also can decrease the risk of life-threatening situations and property damages. Thus, firefighters no longer need to risk their lives working in hazardous sites, and the property damages can be minimized through shortened extinguishing time. Despite of these exceptional advantages of the robot, there are challenges that should be resolved for efficient operation. The main problem is the short operating time which wastes a lot of energy because of the pulling of a fully charged fire hose.

The topic of this study is to overcome the battery limitation of the firefighting robot by applying novel battery management systems (BMS) such as an automatic water management system (AWMS) and a multi-robot energy saving system (MRESS). The ultimate aim is for the robot to be able to extinguish all of the fire without shortage of the battery.

The purpose of this research is to apply a couple of BMS to the robots, and to demonstrate that the robot can extinguish the fire in dangerous situations effectively by using an AnyLogic® simulation tool.

1.2 Research Questions

The research questions are:

1. What kinds of technologies and inventions could be useful to improve firefighting robot effectiveness for movement and extinguishing a fire?
2. How can the firefighting robot be tested and validated in dangerous situations?

1.3 Scope

This research uses that an agent based modeling, which is used in combination with a discrete event modeling. By using AnyLogic®, everything such as the robots, a fire, and fire areas can be modeled. The standard firefighting robot in this study is modeled after FIRO M, a firefighting robot from South Korea. An advanced firefighting robot, the sub-robots, and the automatic T-valve device are modeled after patents that were created by the Purdue Homeland Security Institute (PHSI). In addition, the fires and various areas for the fire extinguishing simulations are developed from AnyLogic® libraries. The scope of the research is to examine the specific operating hours and covered areas by using various combinations of the firefighting robot, sub-robots and water management devices. With these results, the firefighting robot driving cycle, which was developed based on electric vehicle drive cycle such as European driving cycle, or New york drive cycle (Larminie, 2003; Larson, 2015), can be defined and further evaluated for fuel efficiency and the various combinations of robots and devices.

1.4 Significance

Firefighters have been trained by firefighting requirements in Occupational Safety and Health Administration (OSHA) standards and training guidelines (OSHA, 1985). According to the OSHA standards, when firefighters enter the fire scene, they should organize a team to set up the extinguishing planning details such as hazard monitoring, buddy system, and etc. The firefighting robot, however, is able to go quickly into the fire scene and to extinguish the fire without investing time setting up complex planning details. Therefore, the robot not only substitutes for the firefighters, but also can decrease the risk of life-threatening situations and property damages. In order to take advantage of the robot, many countries have invested in making applicable firefighting robots. Although various prototypes of firefighting robots have been created, most countries could not be able to use them to extinguish a fire at a real fire scene. The Daegu Fire Department in South Korea has worked the robots to extinguish fires and has reported the feedbacks since September 2009 (Kim & Kim, 2010). According to the report, one of the main problems to operate the robots is the battery capacity limitation. Once this limit is solved, many more lives and damages can be saved using the firefighting robot.

The purpose of this study is to provide the solutions to immediately use the firefighting robot at real burning area and to show the simulation results that result using the robots. These solutions can expedite the firefighting robot usage, and it will be able to rapidly reduce death and property damage rates.

1.5 Assumptions

The following assumptions were made in the research:

- The firefighting robot modeling in simulation experiments is based on a firefighting robot (FIRO-M) of Dongil Field Robot Co., Ltd. (2010).
    - The robot has a 24V/40Ah battery.
    - The dimensions of this robot are 1100mm (L) x 710mm (W) x 900mm (H).
    - The weight is 210 kilograms (463 pounds).
    - The robot is able to move at four kilometers per hour speed.
- The automatic T-valve device (ATD) modeling is based on a patent of Purdue Homeland Security Institute (PHSI).
    - An ATD is operated by getting signals to the firefighting robot from a wireless controller.
- The fire hose modeling is based on 65A fire hose-60 meters which is one of standard samples.

- Two types of fire in AnyLogic® libraries can be modeled in simulation experiments.
  - The fire development phases are based on the fundamentals of fire development (Babrauskas, 1980; DiNenno, 2008).
  - The fire can spread to the same size in eight directions.
  - The fire spread through the walls is based on the fire resistance of walls (Takeda, 2003).
  - The probabilities of fire growth and barrier failure are based on the research for the fire growth probabilities (Gaskin & Yung, 1993; Webb & Dutcher, 2000).
- The evaluation methods of the firefighting robot and an advanced NDFR robot with sub-robots and a fire hose are based on European driving cycle, or New York drive cycle (Larminie, 2003; Larson, 2015).

1.6 Limitations

The following are limitations in the research:

- The fire spread experiments are simulated in limited environments that are based on lists of the fire growth probabilities.
- A fire hose in simulation experiments is able to be twisted only by obstacles. It is not affected by any other factors such as gravity, inertia, and etc.

- The actual firefighting robot, FIRO-M, was deployed in only Hoopeston fire, Illinois because the robot company asked for the robot to be returned before this research was concluded.

1.7 Delimitations

The following are delimitations for the research:

- Only single story building is able to be modeled in simulation experiments.
- Because the leading firefighting robot is controlled by a person in an actual fire area, it moves to destinations in an optimal navigation.
- To compare the performances of the robots, the same amount of fire was generated in the same area.
- The firefighting robot starts in the same position in each simulation experiment.
- The amount of fire is able to be counted because the fire size was adjusted by the pixels.

1.8 Chapter Summary

This chapter has introduced an outline to the study of battery management system for firefighting robots, including problem statement, research questions, scope, significance, assumptions, limitations, and delimitations. The next chapter outlines the battery management system for firefighting robots, fire spread modeling, and the performance evaluations by collaborating robots and devices.

CHAPTER 2. LITERATURE REVIEW

This chapter presents literature reviews of battery management systems (BMS) for a main firefighting robot and an additional sub-robot, including a fire modeling, an automatic water management system (AWMS), a multi-robot energy saving system (MRESS), and firefighting robot drive cycles (FRDC). First, the AWMS and MRESS are modeled to manage battery efficiency. And then a fire is modeled to validate fire extinguishing efficiency by robots. As a result, FRDC are tested and evaluated by simulating the AWMS, MRESS and fire modeling. The discussion concludes with a validation of how the new systems can control water and robots to increase the robot energy efficiency.

2.1 Fire Loss in the United States

Substantial amounts of deaths and property loss occur at fire areas every year (Karter, 2013; Haynes, 2015). Approximately 1.3 million fires occurred in the United States in 2012 and 2014. About sixteen thousand civilian fire injuries, three thousand civilian fire fatalities and estimated 12 billion dollars in direct property loss were reported in 2012 and 2014. In order to show the damage details of the past decade, Figure 2.1 and Figure 2.2 show the extent of direct property damages and number of deaths of on-duty firefighters in the United States to demonstrate the damage details of the past decade.

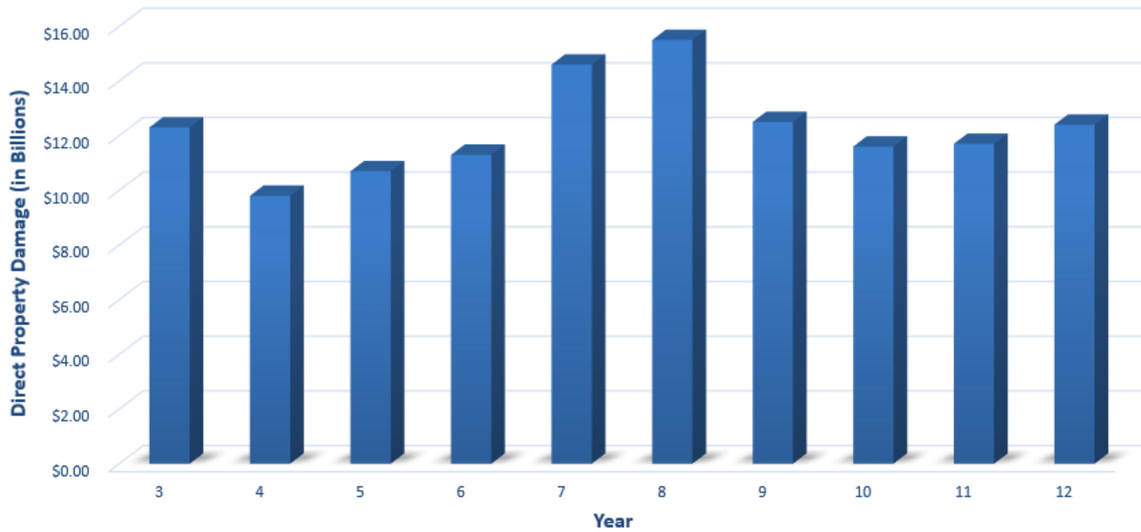


Figure 2.1 Property Damages in the United States (Karter, 2013)

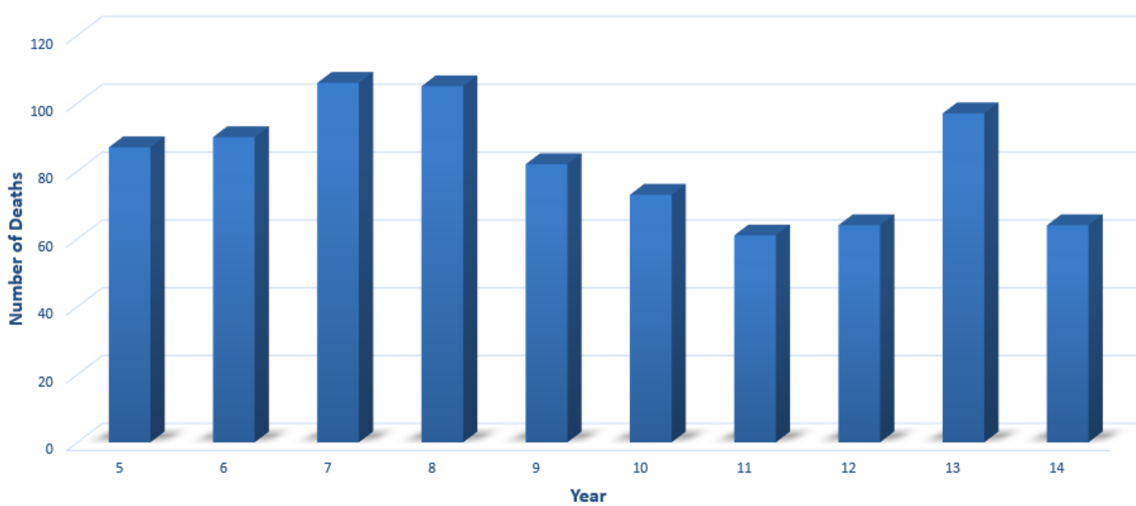


Figure 2.2 Firefighter Deaths On-Duty in the United States (Haynes, 2015)

As shown in Figure 2.1 and Figure 2.2, the fires of the decade resulted in average 12.24 billion dollars in direct property loss and 81.54 firefighter fire fatalities every year (Karter, 2013; Haynes, 2015).

2.2 Firefighting Robots

The OSHA standards require a number of firefighters to make an entry into the fire scene (OSHA, 1985). Whenever firefighters try to enter the fire scene, they should organize a team to set up the extinguishing planning details, such as hazard monitoring, buddy system, and etc. The firefighting robot, however, is able to go quickly into the fire scene and extinguish the fire without the need of investing time to set up complex planning details. Therefore, the robot not only substitutes for the firefighters, but also can decrease the risk of life-threatening situations and property damages. In order to take advantage of the robot, many countries have invested in making applicable firefighting robots.

In DARPA Robotics Challenge (DRC), the world class rescue robots including but not limited to DRC-HUBO (Zhang, 2014), Atlas (Feng, 2015), and THOR-OP (Kim, 2015) have competed for carrying out complex tasks such as vehicle driving, connecting fire hoses, climbing a ladder, and etc. (Pratt, 2013). Although the renowned robots try to solve the tasks, some of them barely overcome the tasks in the limited space. As a result, no robot in this challenge can be used in an actual hazard scene.

On the other hand, stable firefighting robots that operate like a tank have worked with firefighters. In the last thirteen years, the competition for tank types of firefighting robots has been held by the IEEE (Dubel et al., 2003). Therefore, the firefighting robots have been fully developed and are working in some fire departments. Thermite 3.0 in the U.S. (Howe, 2016), TAF35 in Europe (MAGIRUS, 2016), and FIRO M in South Korea (Dongil, 2010) are well-made firefighting robots that have the same characteristics such as moving with caterpillar wheels, monitoring by equipped camera, and managing by wireless controller. In this study, the FIRO M will be modeled.

The standard firefighting robot, FIRO M, used in this study was created by Dongil Field Robot Co.,Ltd. (2010). The firefighting robot (FIRO M) was designed to suppress, monitor, and extinguish fires in dangerous sites such as warehouses, industrial complex areas , oil storage, and chemical plants etc. The robot is equipped with an applied compressed air form and is designed to be loaded into the fire engine. The dimensions of this robot are 1100mm (L) x 710mm (W) x 900mm (H). The weight is 210 kilograms (463 pounds) and the speed is 4km/h. In addition, the operating time is 1.5 hours with a 24V/40Ah battery when the robot pulls the 65A fire hose-60 meters and 40A fire hose-90 meters. The control systems for this robot work by a gas detection device, a thermal image camera, and a wireless control which can control the firefighting robot as far as 100 meters. Figure 2.3 shows the details of the firefighting robot (FIRO M).

Figure 2.3 Firefighting Robot (FIRO M)

The development plan for firefighting robots was researched by Kim et al. (2010). The Daegu Fire Department in South Korea has worked the robots to extinguish fires and has reported the feedbacks since September 2009. Based on the feedbacks of the firefighters in the Daegu Fire Department, the development plan for firefighting robots was established. The satisfaction rate of the firefighting robot function is in Table 2.1 (Kim et al., 2010).

Table 2.1 Satisfaction Rate of the Firefighting Robot Function (Kim et al., 2010)

Function	**Very dissatisfied**	**Dissatisfied**	**Neither satisfied nor dissatisfied**	**Satisfied**	**Very satisfied**
Battery	20.2	48.3	30.0	1.5	0.0
Mobility	38.4	40.3	19.8	1.1	0.4
Wireless Control	18.3	55.5	20.9	4.9	0.4
Heat-resistant	37.3	57.0	5.7	0.0	0.0
Water resistant	34.2	54.8	10.3	0.7	0.0
Camera	13.3	30.4	50.2	6.1	0.0

The satisfaction results have shown that all of the robot functions should be upgraded to work in real firefighting area. This study presents how advanced technologies can be used to improve the battery consuming and mobility of the robot in several experiments.

2.3 Automatic Water Management System

The Automatic Water Management System (AWMS) is intended to expand the operating time of the firefighting robot so that the robot can effectively extinguish a fire while managing the amount of water in the fire hose. To do this, a novel automatic T-valve device (ATD) and a novel designed firefighting robot (NDFR) were created. The ATD was added on a fire hose, and the design of the existing firefighting robot was updated to increase the working hours by enhancing the traction power of the firefighting robot. The main goal of AWMS is to lower the weight of the fire hose. Whenever the firefighting robot needs to relocate itself to other spaces, the AWMS will remove the water from the fire hose and NDFR; thus, it helps the robot to carry a lighter hose and operate for a longer time. In result, the AWMS helps the firefighting robot and its fire hose to efficiently reach the desired destinations and successfully extinguish a fire for a longer duration by decreasing the use of energy.

2.3.1 Frictional Forces and Traction Efficiencies

The calculation methods for frictional forces and traction efficiencies between a fire hose and floors were addressed by Kragelsky et al. (2013). In order to verify the improvement of traction efficiencies, frictional forces are calculated based on an empty fire hose and a fire hose that is full of water. A frictional coefficient for rubber was used in calculation of frictional force since most sheaths of fire hoses are made of rubber polymers. The formulas are able to calculate while the firefighting robot with a fire hose moves on various floors, how the frictional forces and traction efficiencies of the robot were changed according to density and volume of water (Kell, 1967), frictional coefficient (Marghitu, 2001), etc. The frictional coefficient is in table 2.2.

$$F = \mu mg \quad (1)$$

$$W = fs \quad (2)$$

F = Frictional force (N)

μ = Frictional Coefficient

m = Mass (kg)

g = gravity (m/s^2)

W = work (J)

s = distance (m)

Table 2.2 Frictional Coefficient (Marghitu, 2001)

Rubber and Materials Combination	**Static Frictional Coefficient(μ_s)**	**Kinetic Frictional Coefficient(μ_k)**
Rubber	1.16	0.928
Dry Asphalt	0.85	0.67
Wet Asphalt		0.53
Dry Concrete	0.9 (~1.0)	0.68 (~0.8)
Wet Concrete		0.58
ICE	0.18	0.15

2.3.2 Discharging Water

The amount of water that is discharged in a fire hose can be used to evaluate the energy efficiency of firefighting robot. The discharging formula was introduced by Kulin et al. (1975). The formula is able to calculate the amount of discharged water as well as the amount of saved battery power. Due to the gap between height and ground of firefighting robot, the water in the first several feet of a fire hose will be easily discharged.

However, while the gap between upstream and downstream is decreasing, the amount of discharging water is also decreased.

$$Q = 0.61\ A\ \{2(g*\cos\theta)(h_u-h_d)\}^{1/2} \quad (1)$$

0.61 = discharge coefficient

A = area of the hole (m^2)

g = gravity (m/s^2)

H_u = upstream water height (m)

H_d = downstream water height (m)

2.3.3 Total Pressure Loss in the Fire Hose

The pressure loss reduction in fire hoses was studied by Min et al. (2013). Total Pressure Loss (TPL) can be calculated by the sum of friction loss (FL), appliance loss (AL), and elevation loss (EL). Friction loss is conflict with wall to overcome resistance while water passes through fire hoses and appliances such as ATD. Because the fire hose is located on a position that is higher or lower than the water source, an elevation gain or loss has to be considered.

$$TPL = FL + AL +/- EL \quad (1)$$

2.3.3.1 Friction Loss

Friction loss is what it takes for the wall to overcome resistance while water passes through fire hoses and appliances such as ATD. Although friction loss is independent of the pressure in the hose, it is necessary to know the following factors for calculating the friction loss:

- The volume or quantity of water flowing (gpm)
- The hole size of the fire hose
- The fire hose length

Friction loss is independent of pressure when the water flowing remains constant in the same size hose. In other words, if 200 gpm is flowing through a 2.5” hose at 50 psi, the friction loss will remain the same although the pressure is increased to 100 psi. The friction loss coefficient is in table 2.3.

$$FL = C \times (Q/100)2 \times L/100 \quad (2)$$

FL = Friction loss (psi)

C = Friction loss Coefficient

Q = Flow rate in GPM

L = Hose length

Table 2.3 Friction Loss Coefficient in Fire Hoses (Min et al., 2013)

Diameter (inch)	**Coefficient**	**Diameter (inch)**	**Coefficient**	**Diameter (inch)**	**Coefficient**
0.75	1100	1.75	15.5	3.5	0.34
1	150	2	8	4	0.2
1.25	80	2.5	2	4.5	0.1
1.5	24	3	0.667	5	0.08

2.3.3.2 Appliance Loss

Because the friction loss in small appliances is negligible, it will not be calculated. In general, the friction loss of 25 psi is added for the deck gun mounted the engine and the friction loss of 15 psi is used for a ground monitor.

2.3.3.3 Elevation Gain or Loss

When the fire hose is located on a position that is higher or lower than the water source, an elevation gain or loss has to be considered. 0.434 psi should be calculated per 1 foot difference of the fire hose. Up to 10-12 feet high, this gain or loss is estimated.

$$EL = 0.434 \times H \quad (3)$$

EL = Elevation loss or gain (psi)

H = height

2.4 Multi Robot Energy Saving System

The multi-robot energy saving system (MRESS) enables a main firefighting robot with sub-robots and a fire hose to move lots of goals while extinguishing fires. a sub-robot was designed based on the automatic T-valve system (ATS) and installed between regular fire hoses to enhance working hours and firefighting range of the main firefighting robot. A sub-robot mainly works to expel water from a fire hose for energy saving, and adding an additional fire hose to increase the working range. MRESS manages a sub-robot including a fire hose by integrating a tracking method (Siagian et al., 2013), an edge limit-cycle navigation method, and an endrunning navigation for efficient cooperation. The combination of limit-cycle navigation and hose tracking method brings incredible merits that are fast data processing and smooth path planning. Furthermore, the endrunning navigation method may lower the collision chances that could tangle the fire hoses.

2.4.1 Limit Cycle Navigation System

The mobile robot can move quickly to their goals by using limit-cycle navigation system that based on a 2nd-order nonlinear function. A novel limit-cycle navigation system is proposed by Kim et al. (2003). This system is very good for a dynamic robot system such as a soccer robot system. The proposed navigation method allows robots to move easily towards their final goals by changing the circle sizes and obstacle direction.

The 2nd-order nonlinear system for limit-cycle navigation is shown below,

$$\dot{x_1} = x_2 + x_1(1 - x_1^2 - x_2^2) \tag{1}$$

$$\dot{x_2} = -x_1 + x_2(1 - x_1^2 - x_2^2) \tag{2}$$

In addition, the Lyapunov function is as follows,

$$V(x) = x_1^2 + x_2^2 \tag{3}$$

By combining these formulas, the trajectory of the system can be obtained,

$$\begin{aligned} \dot{V}(x) &= 2x_1\dot{x}_1 + 2x_2\dot{x}_2 \\ &= 2x_1x_2 + 2x_1^2(1 - x_1^2 - x_2^2) - 2x_1x_2 + 2x_2^2(1 - x_1^2 - x_2^2) \\ &= 2V(x)(1 - V(x)) \end{aligned} \tag{4}$$

According to this system formula,

$$\begin{aligned} &\dot{V}(x) > 0 \text{ for } V(x) < 1 \\ &\dot{V}(x) < 0 \text{ for } V(x) > 1 \end{aligned} \tag{5}$$

From the Poincare-Bendixson, V(x) is able to close to 1. As a result, the unit circle could be the limit cycle. Figure 2.4 shows the details of the limit-cycle for clockwise and counter-clockwise.

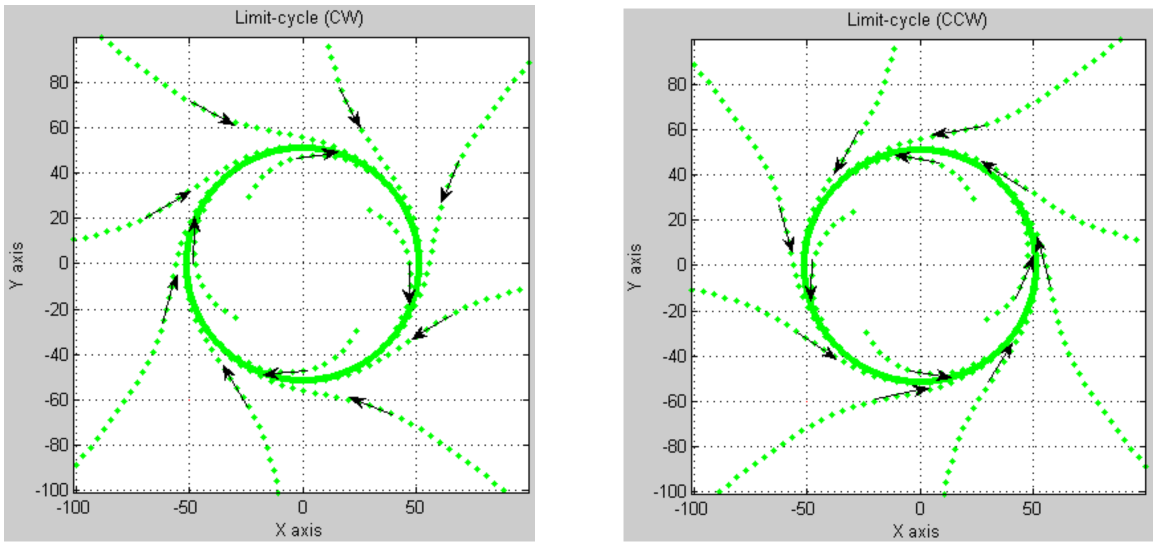


Figure 2.4 Limit-cycles of Clockwise and Counter-clockwise (Kim et al., 2003)

In addition, the general form of formula (1), (2) is able to be made by exchanging 1 with r. This means it can change the circle size for the limit-cycle. Therefore, the limit-cycle can cover all kinds of obstacles, as shown in figure 2.5.

$$\dot{x_1} = x_2 + x_1(r^2 - x_1^2 - x_2^2) \quad (6)$$

$$\dot{x_2} = -x_1 + x_2(r^2 - x_1^2 - x_2^2) \quad (7)$$

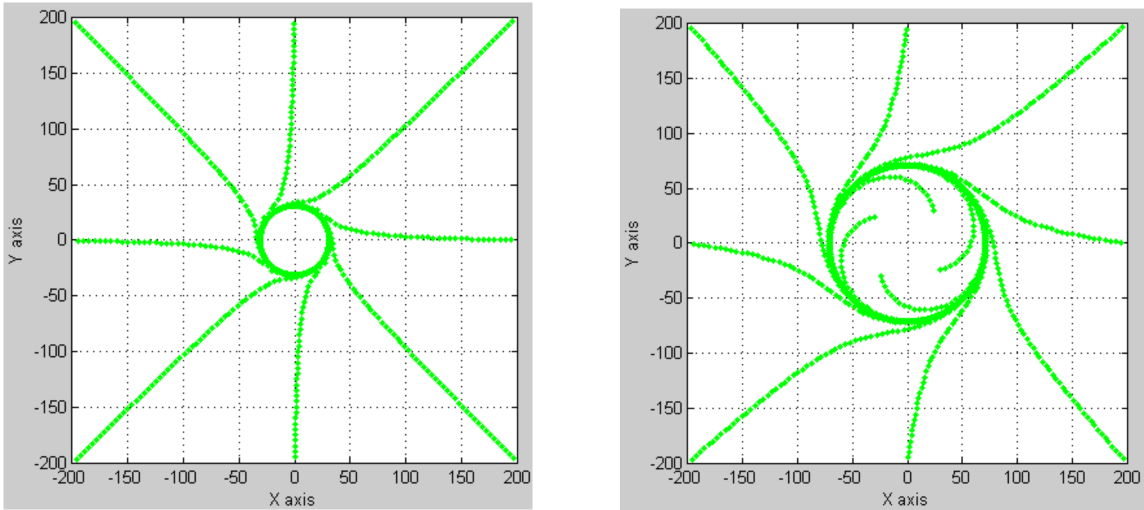
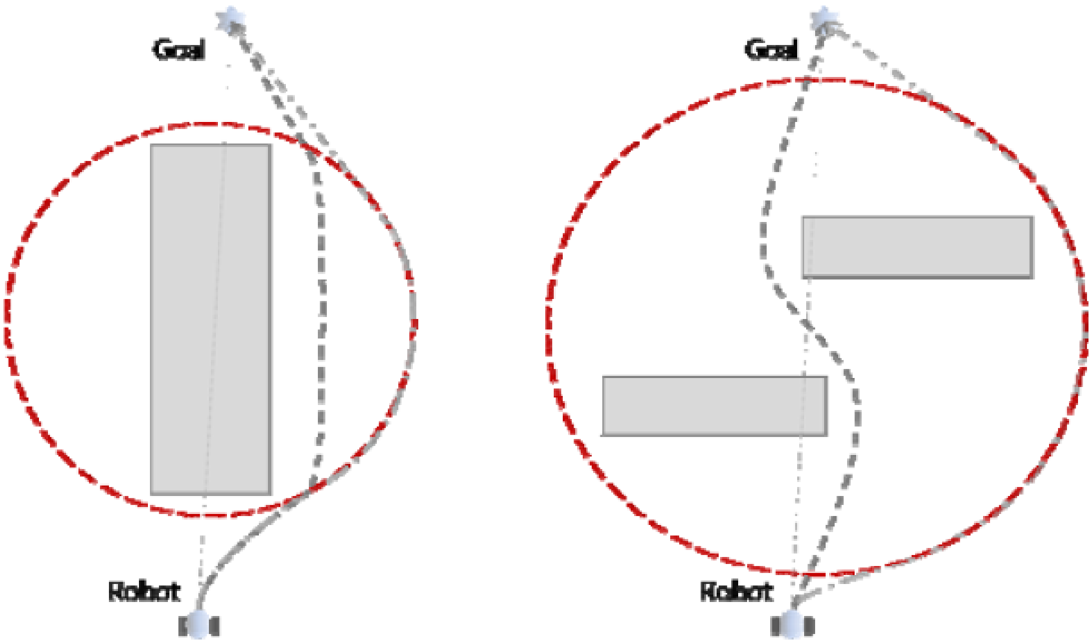
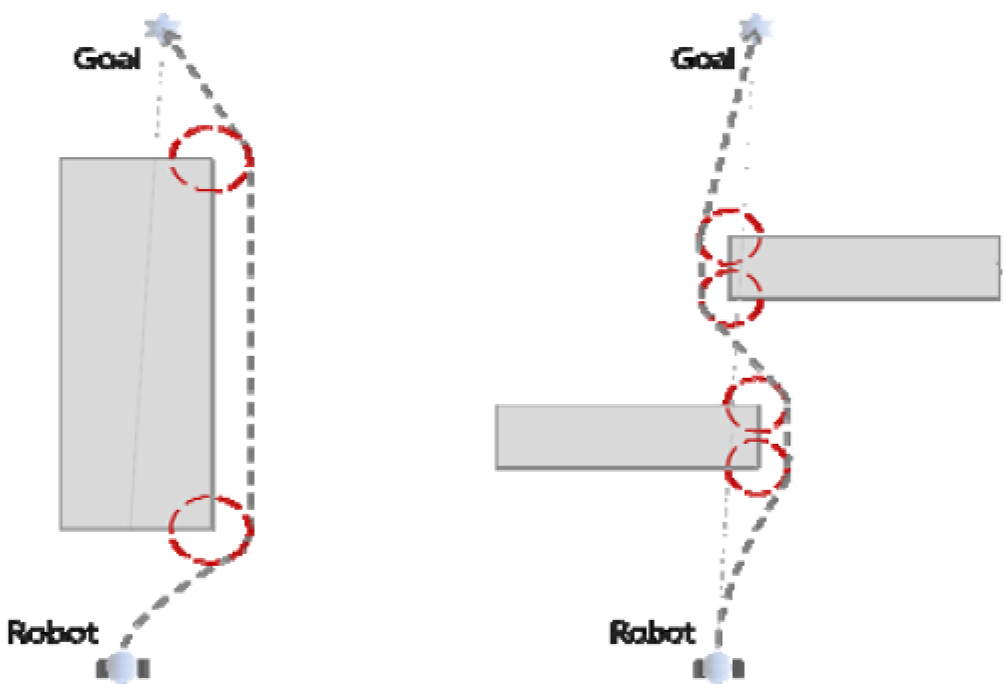


Figure 2.5 Limit-cycles of Radius 30 and 70 (Kim et al., 2003)

An advanced limit cycle navigation method designed for obstacles avoidance was presented by Lim et al. (2010). A novel algorithm was applied for advanced path planning so that the robot is able to get to a desired goal while bypassing all kinds of static obstacles. For the effective obstacle avoidance, an edge limit cycle applies to the edge of obstacles, so that the moving path is able to be shorter than existing moving path that applied an original limit cycle based on the center of obstacles. This advanced method was researched by combining a limit-cycle navigation system and an edge detecting system. Whenever the robot detects an edge of obstacles, the edge limit-cycle makes a circle to the edge for generating new path. The excellence of this edge based method is shown in Figure 2.6.



(a) Paths made by using the Original Limit-cycle



(b) Paths made by using the Edge Limit-cycle

Figure 2.6 Comparison between the original limit-cycle and edge detecting limit-cycle

(Lim et al., 2010)

2.4.2 Endrunning Navigation System

The Endrunning Navigation system is able to make a firefighting robot including a sub-robot and fire hose move easily to move the destination without blocking of obstacles. The new navigation method is based on tacit navigation method (Kim et al., 2010) that is made by mixing a limit-cycle navigation method (Kim et al., 2003) and the standard rules of airplane traffic (Jang et al., 2005). The robots with fire hose will move according to a novel navigation system applying the changed standard rules of airplane traffic.

- The standard rules for airplane traffic

Airplanes are supposed turn to the right and away from each other to give way and avoid a collision if both approach each other from opposite sides. Also, if airplanes have conflicting paths that are next to each other, the left airplane is supposed to yield by turning right. The robots with fire hose will either stop or use the limit-cycle to avoid a collision by moving accordingly to a new navigation method that uses the changed standard rules of airplane traffic.

- The endrunning navigation method

If the firefighting robot with sub-robots approaches to the first obstacle, the first robot starts to give way by turning to the close direction to avoid a collision, and if the way is turning to the right, the robots keep turning right to avoid obstacles while they reach to the end of the alley. In addition, when the robots encounter in conflicting paths next to each other, the left robot turns right to yield.

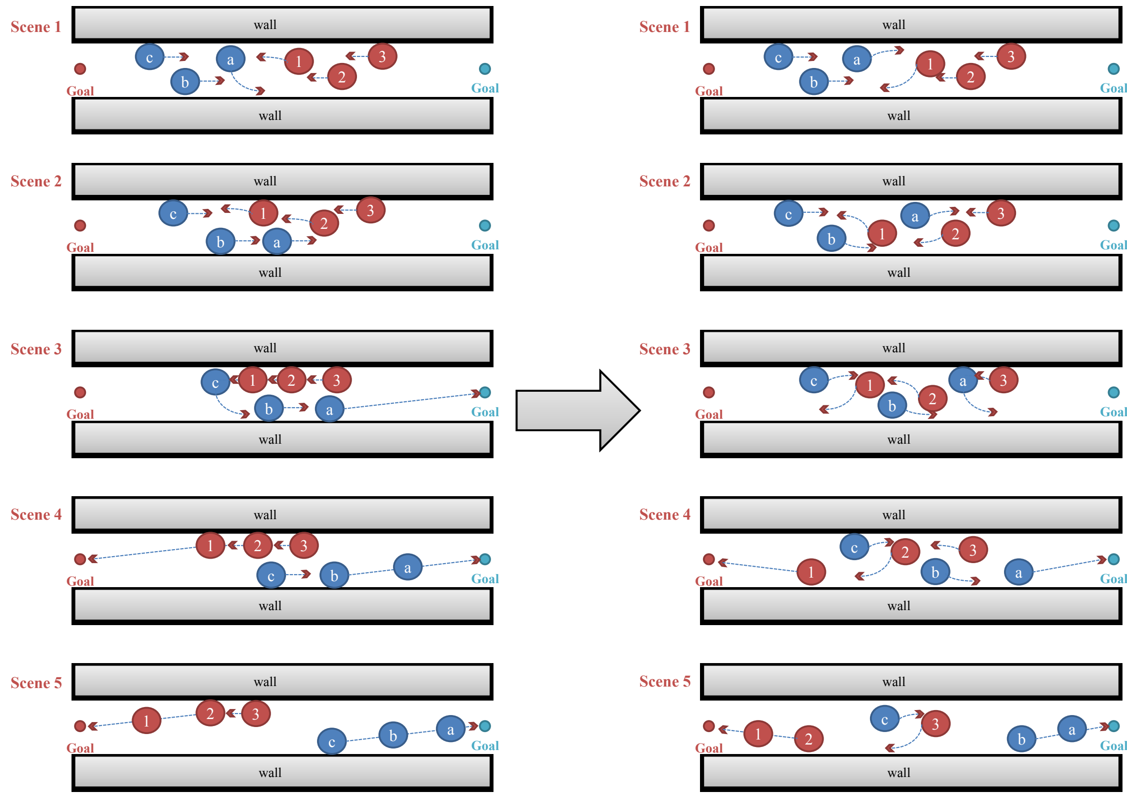


Figure 2.7 Tacit Navigation Method (Kim et al., 2010)

2.5 Fire Modeling

A statistical modeling of fire spread allows firefighters to make an optimal plan for fire suppression, and to quickly extinguish fires in buildings. In this research, a statistical fire spread modeling displays the fire spread processes in buildings. The fire spread is able to be predicted by using statistical methods including decision tree and bayesian network. In addition, the modeling methods are applied with various conditions: the fire ignition location, barrier failure probability, fire growth parameter, and backdraft. With the modeling, firefighters are able to expect the probability for how big amounts of fires are growing and where the fires are located. As a result, the firefighters are able to know the fire growth and spread in a layout exactly and economically.

A convincing fire spread modeling by Bayesian network was studied by Cheng et al. (2011). In order to use Bayesian network, the layout is divided based on compartments, and the fire is ignited in a specific location. And then combining the probability distribution between compartment and compartment, the fire spread probability is able to be calculated. This fire modeling is very useful for not only fire suppression but also building cost analysis.

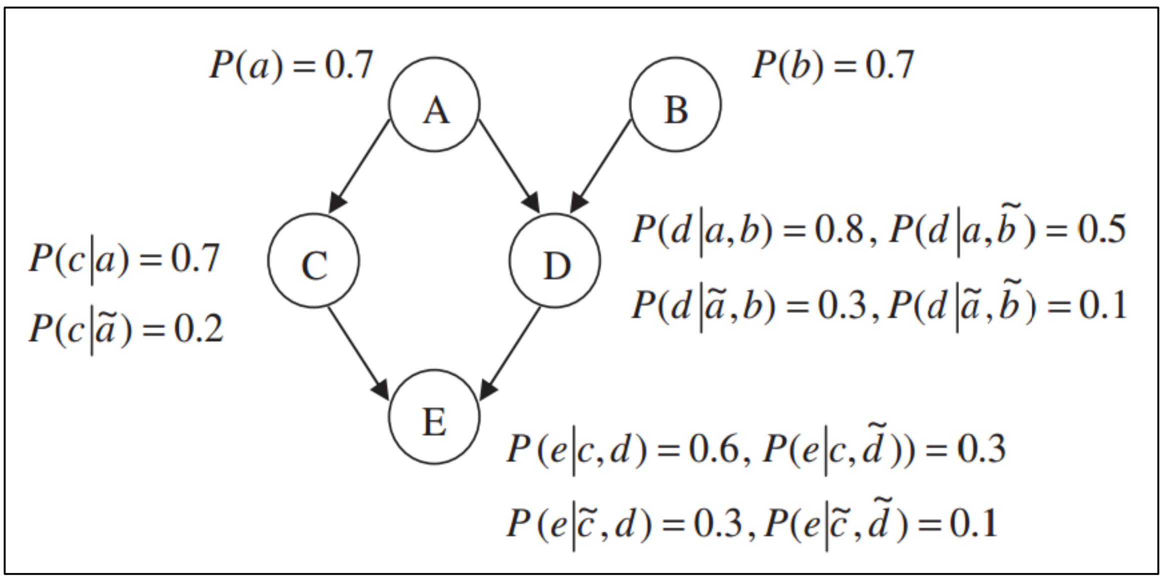


Figure 2.8 Example of Bayesian Network (Cheng et al., 2011)

A fire modeling by decision tree is also reliable to predict the fire spread (Parsons, 2004; Cortez et al., 2007). When the fire ignition location, fire growth parameter, and barrier failure probability are known, the fire spread modeling designed by the decision tree is able to predict the fire spread. Because a decision tree is a flowchart-like tree structure, more and more conditions are able to train the decision tree for the better prediction.

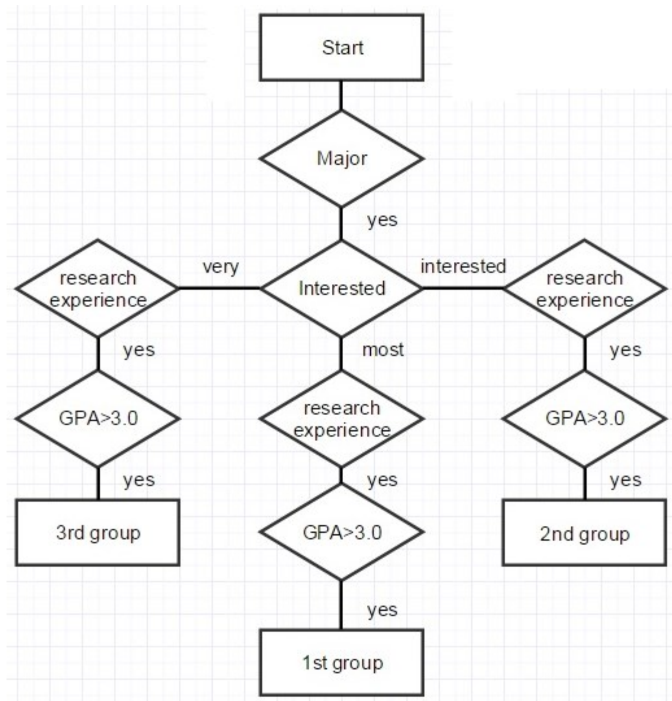


Figure 2.9 Example of Decision Tree

The fire development has been researched by Babrauskas (1980) and DiNenno (2008). Reviewing the fundamental fire development is crucial for building a reliable fire spread model. The fire undergoes four phases: dormant, growth, development and decay. In order to validate the phases, lots of formulas had been studied, and a couple of results such as fire growth parameter and fire development graph were produced in Figure 2.10 and Table 2.4.

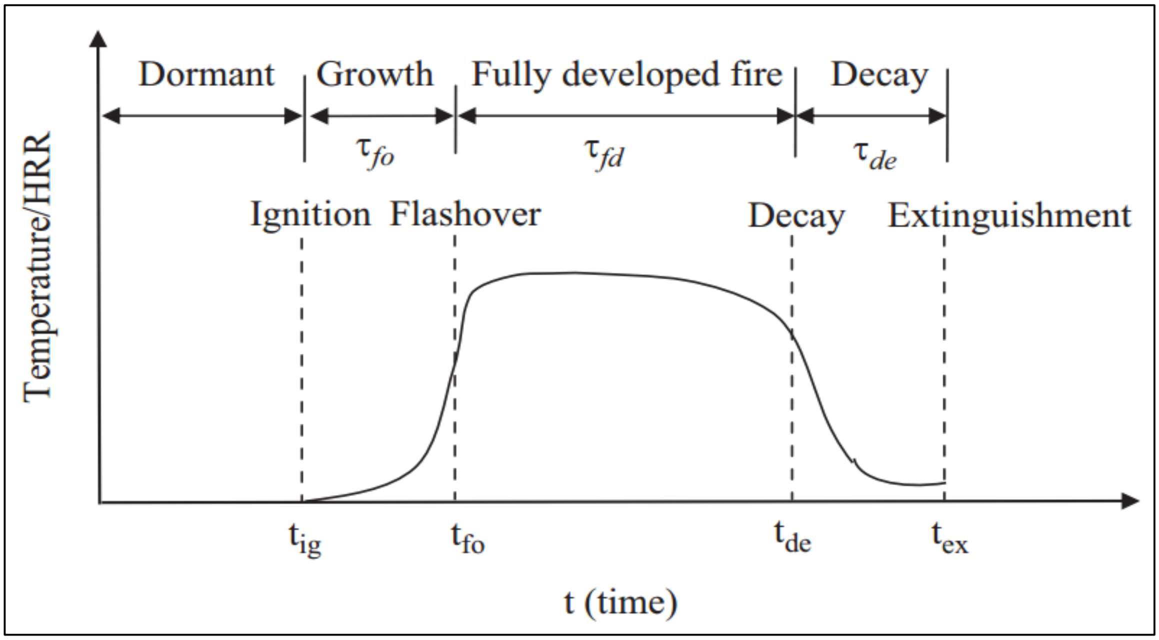


Figure 2.10 The Phases of Enclosure Fire Development (Karlsson et al., 1999)

Table 2.4 Fire Development Parameter (DiNenno, 2008)

Fire development rate	**Fire development parameter (kW/S^2)**	**Developement Time (s) (when Q=1MW)**
Slow	0.0029	600
Medium	0.012	300
Fast	0.047	150
Ultra-fast	0.188	75

The fire wall resistances were researched by Takeda (2003). The author is also the researcher who has developed computer models that predicts the fire resistance of wood floors and walls. The computer model is able to calculate heat transfer and displays the result of wall insulation. The results are very useful to train the decision tree of fire development in table 2.5.

Table 2.5 Fire Resistance of Walls (Takeda, 2003)

Test	**Scale**	**Description of wall assembly**	**Finish rating (min)**	**Time to charring (min)**
1	Small	Four layers of 12.7 mm Type C gypsum board on each side of wood studs	19.18	24.43
2	Small	One layer of 15.9 mm Type X gypsum board on each side of wood studs	22.07	27.87
3	Small	Two layers of 15.9 mm Type X gypsum board on each side of wood studs	57.47	71.20
4	Full	Four layers of 12.7 mm Type C gypsum board on each side of wood studs (loaded)	17.75	23.10
5	Full	Four layers of 15.9 mm Type X gypsum board on each side of wood studs (loaded)	20.68	26.57

The probabilities for barrier failure and fire growth are researched by Gaskin and Yung (1993), Webb and Dutcher (2000). This research illustrate the probability between compartment and compartment.

Case 1: Fire spread on the floor without intervention

Case 1 shows that the fire spread without intervention. The probabilities for barrier failure are shown as below,

(1) The barrier failure probabilities between compartment and compartment

- room to room that separated by corridor: 0.84
- room to room that separated by wall: 0.81
- room to stairwell, elevator shaft or duct that separated by wall: 0.57
- room to stairwell, elevator shaft or duct that separated by corridor: 0.28
- stairwell, elevator shaft or duct to room that separated by wall: 0.60

(2) The fire growth probabilities in a compartment without a suppression system and intervention

- space to space in a room: 0.242
- space to space in a stairwell, elevator shaft or duct: 0.05

Case 2: Building with sprinkler system

Case 2 shows that the building has a sprinkler system

- space to space in a room: 0.051
- space to space in a stairwell, elevator shaft or duct: 0.005

2.6 Firefighting Robot Drive Cycles

Most vehicles usually repeat some patterns or routes while they are driving on various roads. Based on this information, vehicle companies set up the fuel efficiencies for the vehicles. The drive cycle is one of the best methods to evaluate the automobile efficiency (Martyr et al., 2011). Various drive cycles such as the Highway Fuel Test drive cycle and the New York drive cycle are developed, and they make a standard for vehicles efficiencies. A firefighting robot, however, has no standard drive cycles to set up the fuel efficiencies because it works in uncommon areas. Based on various firefighting robot experiment results, a novel drive cycle is able to be set up for a firefighting robot.

A drive cycle is able to determine the traction power and average speeds (Larminie, 2003). Two of the popular driving cycles such as the European Urban Driving Cycle ECE-15 (Figure 2.11) and NYCC (Figure 2.12) are useful samples. The European Urban Driving Cycle ECE-15 displays acceleration, coasting, and deceleration although it is impossible to drive with three steps in the real road. However, this cycle is considered as a normal driving. Another popular drive cycle is NYCC that was developed by the Los Angeles and New York. They represent average real driving cycles in New York and Los Angeles. For comparison, each driving results for the NYCC and the ECE 15 are shown in Table 2.6.

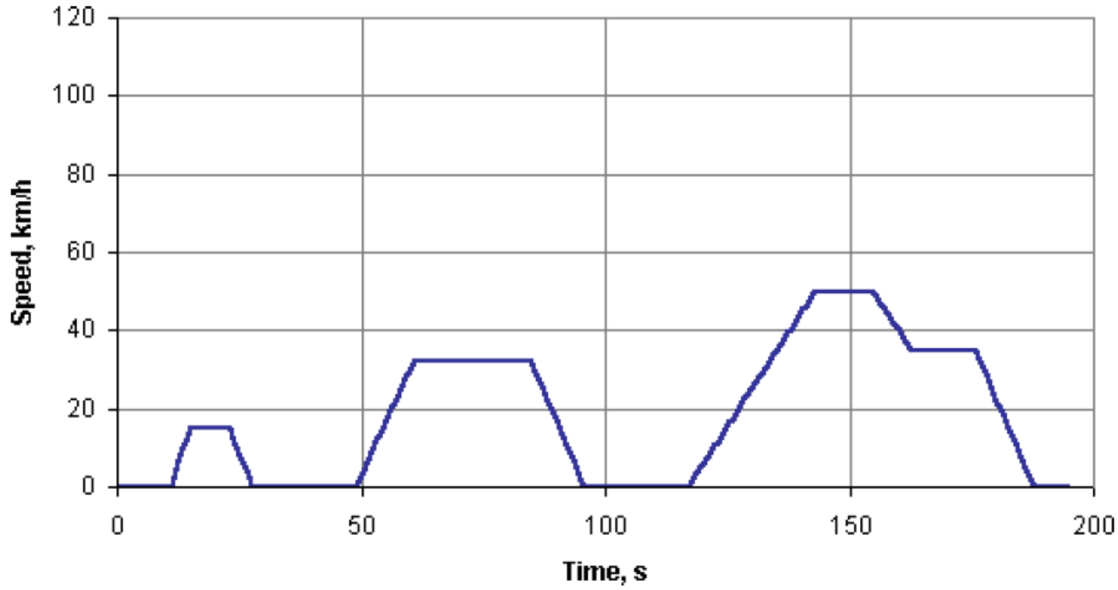


Figure 2.11 European Urban Driving Cycle ECE-15 (Larminie, 2003)

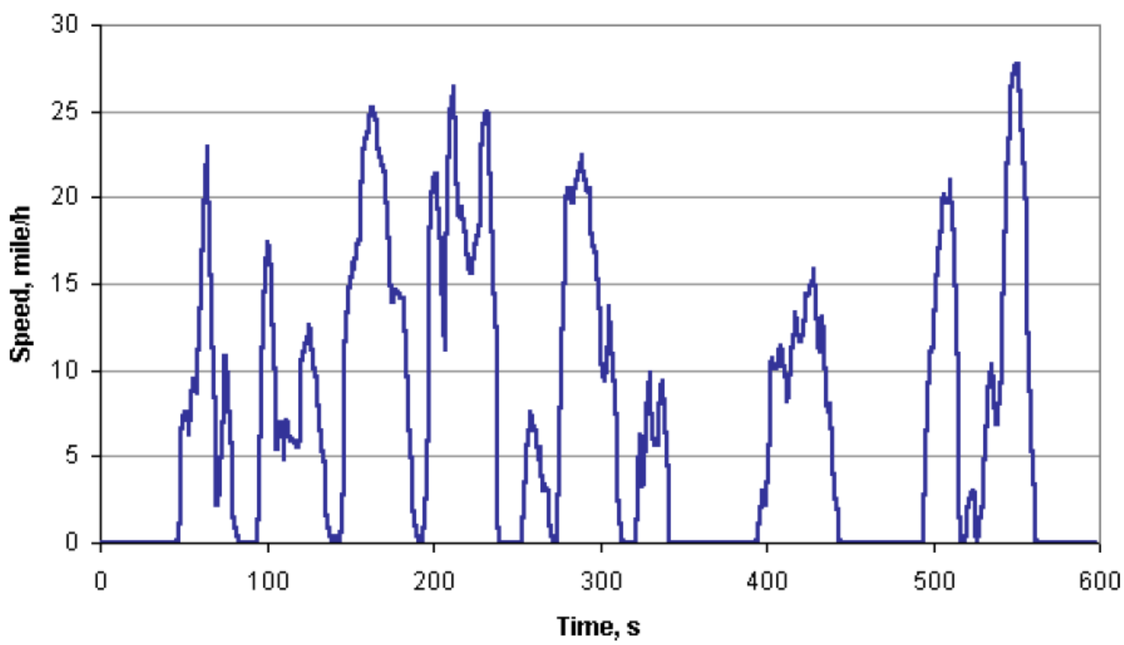


Figure 2.12 New York Driving Cycle (Larminie, 2003)

Table 2.6 The Energy Efficiencies for NYCC and ECE 15 Drive Cycles (Larminie, 2003)

Characteristics	**Unit**	**ECE 15**	**NYCC**
Distance	Km	0.9941	1.89
Total time	S	195	598
Average speed	Km/h	18.35	11.4
Maximum speed	Km/h	50	44.6

2.7 Simulation Modeling

AnyLogic® is an optimal software program to design system dynamics models, agent-based models, process models, and combinational models. This software program has been used in academia and industry (Borshchev & Filippov, 2004). AnyLogic® modeling delivers reliable results by providing various kinds of modeling library to model a fire, firefighting robot, sub-robots, and a fire hose.

In order to apply various vehicles in simulation models, a vehicle schedule simulation was presented by Merkuryeva and Bolshakovs (2010). This source shows that AnyLogic® can be used to model trucks delivering goods to shops with minimal usage and idle times. This sample library is very helpful to model the firefighting robot and sub-robots.

For the fire modeling, the agent scheduling is very helpful. Banerjee, Dasgupta, and Desai (2011) proposed how AnyLogic® can deal with staff scheduling. Shift schedules are able to express fire spread for both the fires and the fuels.

Agent-based modeling continues to become more powerful and reliable every year. Many simulation modelers would like to shift the agent-based approach because it is able to deal with very detailed modeling in simulation experiments and to manage thousands of agents at once. Bonabeau (2002) addressed the agent-based modeling for simulating complex interactions. Agent-based modeling helps a designer to simulate complex interactions among robots and fire; it deals with all kinds of models without limitation for spaces, heterogeneous population, and complex interactions among various agents.

Another important agent-based model was presented by Macal and North (2014). Agent-based modeling is used to one of four areas: flows, markets, organizations, or diffusion. The firefighting BMS modeling is a case of flow. The firefighting robot enters the buildings, go through multiple processes such as extinguishing fires and avoiding obstacles, and finalize the fire. Each robot, fire, building have different references for each agent modeling. This modeling is very powerful whenever all kinds of agents is able to be modeled.

2.8 Chapter Summary

This chapter summarized literature reviews on fire loss in the United States, firefighting robots, automatic water management system, multi robot energy saving system, fire modeling and firefighting robot drive cycle. The useful reviews applied to simulation models demonstrate how the novel robot systems and fire models are used to protect people and properties.

CHAPTER 3. METHODOLOGY

This chapter discusses the research framework, sample approach, tools of measurement, variables, and rules for assessment used in this dissertation.

3.1 Research Framework

This research uses simulation modeling to determine the optimal energy management by applying water management system, multi-robot systems, and energy efficiency evaluation for a firefighting robot. The research uses simulation modeling experiments that have been modeled by existing study investigation. The simulation software, AnyLogic®, is mainly used to design four simulation models: an automatic water management system (AWMS), a multi-robot energy saving system (MRESS), fire spread model, and firefighting robot drive cycles (FRDC). AWMS and MRESS show how the robot can save its energy, while the fire spread model and FRDC are used for validation of firefighting robot efficiency. The independent variables for each model are as follows:

- Automatic water management system
    - The presence of automatic T-valve system
    - The amount of water in a fire hose
    - The weight of the firefighting robot by advanced design
    - The firefighting robot energy efficiency by advanced design

- Multi-robot energy saving system
    - The robot energy efficiency by limit-cycle method
    - The robot energy efficiency by endrunning navigation method
    - The robot energy efficiency by MRESS
    - The length of fire hoses
    - The cover ranges of the firefighting robot

- Fire spread model
    - The fire development process
    - The fire spread probabilities on floors
    - The fire spread probabilities for walls
    - The fire spread probabilities from an area to other areas
    - The fire spread probabilities with or without sprinklers
    - Range setting for a Bayesian network validation

- Firefighting robot drive cycles
    - Different sizes of buildings to compare the robot efficiencies by combing systems
    - The total number of fires for the standard comparing
    - The statistical generating of fires for the statistical comparing

The independent variables for AWMS and MRESS are qualitative, and the independent variables for the fire spread are quantitative. FRDC variables are mixed method that has been performed to validate the advanced energy efficiency of the firefighting robot on the quantitative fire spread model. The dependent variables in the qualitative research are the firefighting robot weight, energy efficiency, and operating hours for the qualitative research. The dependent variables in the qualitative and mixed research are fire spread results and efficiency evaluation for each building. This research has several hypotheses to evaluate if the firefighting robot is able to operate more efficiently with AWMS and MRESS in small, medium and large fire areas.

- Because the firefighting robot is controlled by a person, it moves to destinations in an optimal navigation.
- To compare the performances of the robots, the same amount of fire is generated in the same areas.
- While discharging the amount of water in a fire hose, a fire hose is never folded or twisted.
- Because the burning building is a one-story building, some fuels such as wires on the ceiling of the burning building are not considered
- The amount of fire can be counted.

3.2 Sample Set

The different sample sets are applied for each agent models. The firefighting robot model is designed by the samples from FIRO M of Dongil Field Robot Co.,Ltd. (2010). The dimensions of this robot are 1100mm (L) x 710mm (W) x 900mm (H). The weight is 210 kilograms (463 pounds), and the speed is 4km/h. In addition, the operating time is 1.5 hours with a 24V/40Ah battery when the robot pulls the 65A fire hose-60 meters and 40A fire hose-90 meters. The control systems for this robot work by a wireless control which can control the firefighting robot up to 100 meters. The fire development has been studied by Babrauskas (1980) and DiNenno (2008). The fire process has the four phases: dormant, growth, development and decay. Takeda (2003) has developed a computer model to predict the fire resistance. The barrier failure probabilities and fire growth are estimated by Gaskin and Yung (1993), Webb et al. (2000).

3.3 Testing Environment

The testing environment is an agent-based model created within AnyLogic®. All of the agents are operated by each statechart. For the AWMS experiment, the firefighting robot agent and automatic T-valve are modeled by statecharts and are tested by using the automatic T-valve system and the novel designed firefighting robot. In the MRESS experiment, the sub-robot agent is modeled and added to the firefighting robot agent. The limit-cycle navigation and endrunning navigation methods are applied for the firefighting robot agent to validate its energy efficiency in a dangerous area that consists of the complicated obstacles. In order to predict the fire spread in buildings, the fire is defined by its statechart and is repeatedly tested in each building. For the FRDC experiment, all kinds of agents are working together in each building for energy efficiency validation.

3.4 Chapter Summary

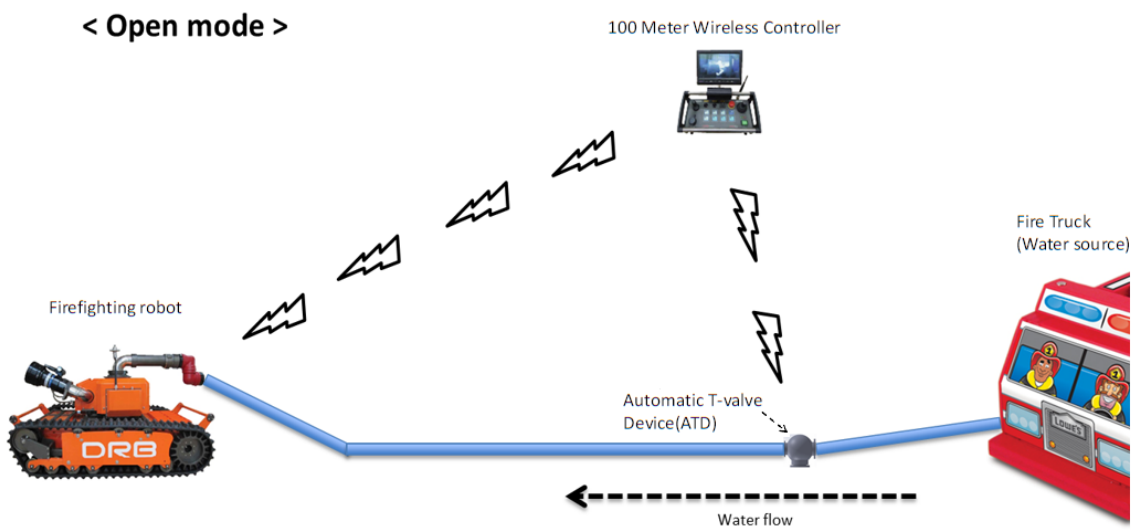
This chapter covers the merging research framework that is mixed the qualitative and quantitative research methods. The testing variables, hypotheses, and the agent models are introduced. In addition, the sample sets and testing environment are discussed.

CHAPTER 4. AUTOMATIC WATER MANAGEMENT SYSTEM

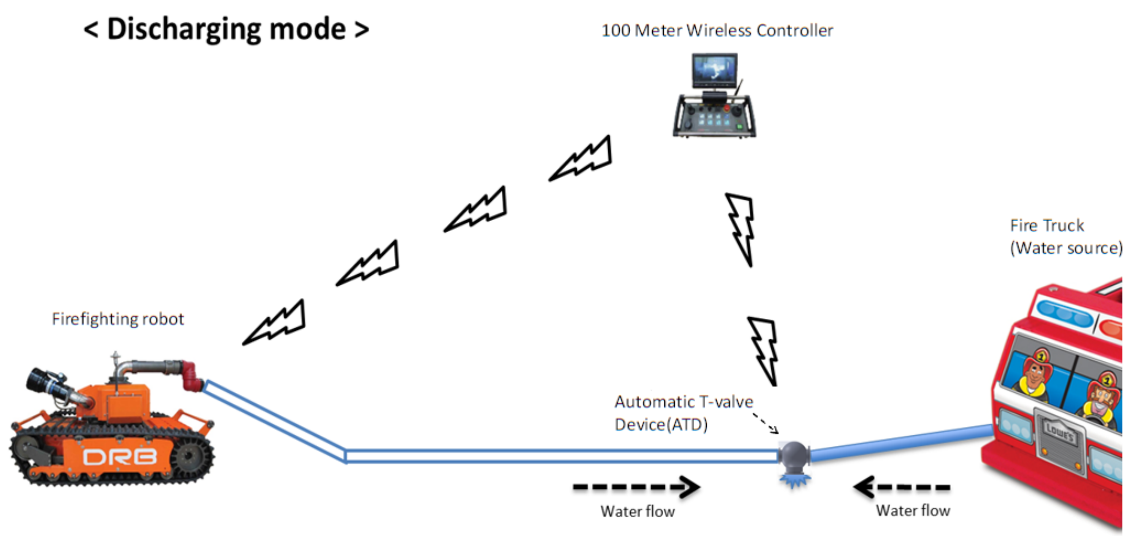
This chapter presents an automatic water management system (AWMS) for a firefighting robot battery management. The AWMS is intended to increase working hours of the firefighting robot so that the robot can effectively extinguish a fire while managing the amount of water in the robot and the fire hose. To do this, an automatic T-valve system (ATS) and a novel designed firefighting robot (NDFR) were designed from the original firefighting robot. Because the ATS and the NDFR are able to remove the water from the NDFR and the fire hose that is fully charged water, the robot could improve the traction efficiency and increase the operating time. Whenever the firefighting robot should move to other spaces, the AWMS will remove the water from the fire hose and the NDFR; thus, it helps the lighter robot to carry a lighter hose and operate for a longer time. In conclusion, the AWMS enables the firefighting robot and its fire hose to efficiently reach the desired destinations and successfully extinguish a fire for a longer duration by decreasing the use of energy.

4.1 Automatic T-valve System

The Automatic T-valve System (ATS) is one of the best solutions to increase operating time of the firefighting robot. A novel automatic T-valve device (ATD) for the ATS was designed and added to a fire hose for removing the water from the fire hose with fully charged water. The ATS can manage the ATD to discharge the water and to increase the working hours by increasing traction power for the firefighting robot. It helps the robot to carry a lighter hose and to operate for a longer time.



(a) ATS Open Mode



(b) ATS Discharging Mode

Figure 4.1 Operating the Robot and a T-valve Device by a Wireless Controller

Figure 4.1 displays the ATS operating with the firefighting robot. Whenever the wireless controller sends signals to firefighting robot and ATD at the same time, they are able to open and close the T-valve. Figure 4.1 (A) shows the open mode in which opened T-valve allows water to pass through the fire hose to extinguish a fire. And figure 4.1 (B) shows the discharging mode that involves rotated T-valve which stops water flow and allows the robot to operate to find other fires.

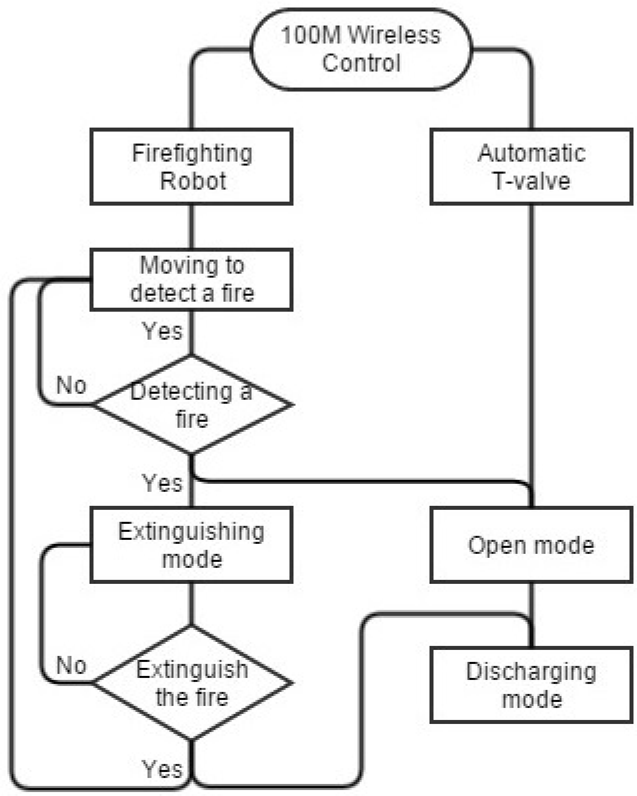
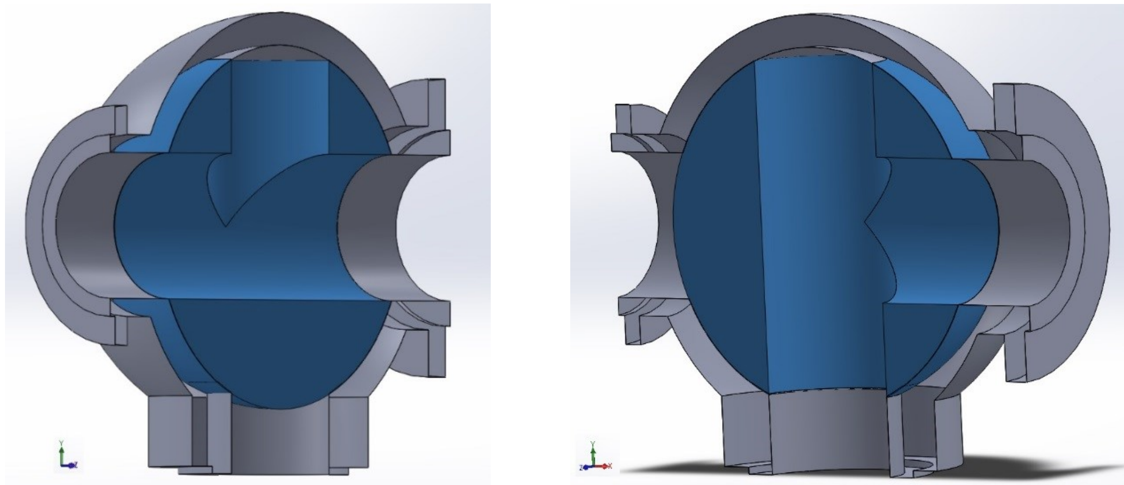


Figure 4.2 Flow Chart for the Firefighting Robot and ATD

Figure 4.2 shows a flow chart for the firefighting robot and ATD being operated by a wireless controller. First, the wireless controller starts to steer the firefighting robot to detect a fire while ATD is ready to rotate the T-valve. When the robot finds a fire, wireless controller sends signals to the firefighting robot and ATD to switch modes. At this time, the robot changes its mode from moving mode to extinguishing mode to shoot its water towards the fire. ATD also changes its mode into open mode, moving water from the water source to the robot. After extinguishing fires, wireless controller sends a signal to the firefighting robot to change the mode to moving mode so that it can find fires at other spots. ATD then changes its mode to discharging mode to expel water that remains in the fire hose.

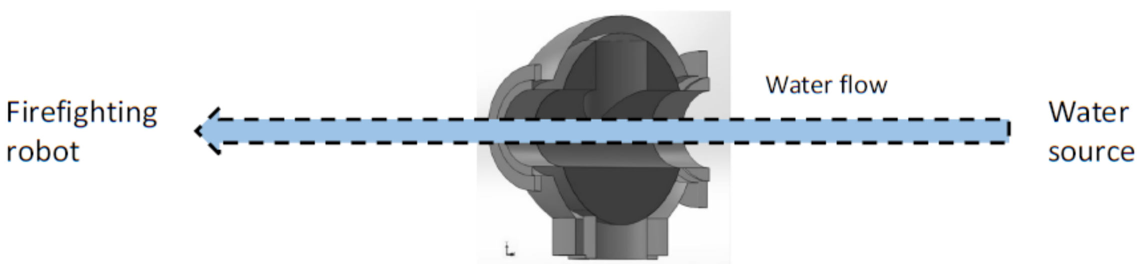
4.1.1 Automatic T-valve Device

The novel automatic T-valve device (ATD) in Figure 4.3 and Figure 4.4 is created on the basis of an existing T-valve and can be operated by a wireless controller. The ATD has two different modes: open mode and discharging mode. The open mode will allow water to pass through the ATD to extinguish a fire, whenever the wireless controller sends signals to the firefighting robot and the ATD. On the other hand, the discharging mode will expel water from a fire hose that is connected to the firefighting robot and will stop the water flow from a fire truck whenever the wireless controller signals the firefighting robot signals to move to other spots of fire. It helps the fire hose to expel the water from a fire hose, the robot is able to carry a lighter hose and operate for a longer time.

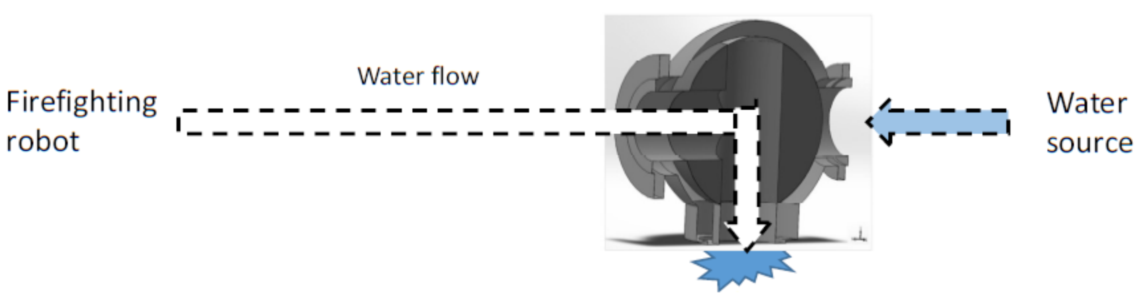


(a) Open Mode (b) Discharging Mode

Figure 4.3 Automatic T-valve Device (ATD)



(a) ATD Open Mode



(b) ATD Discharging Mode

Figure 4.4 Automatic T-valve Device (ATD) Operation

Since the ATD is operated by an actuator, total pressure loss in the fire hose should be calculated to set up the optimal actuator. Total Pressure Loss (TPL) consists of the sum of friction loss (FL), appliance loss (AL), and elevation loss (EL). In this research, the fire hose is 65A hose-60M that is a 200 feet section of 2.5” hose, so that the friction loss Coefficient (C) for a 2.5” hose is 2, as shown in table 2.3. If the flow rate (Q) sets up 300 gpm, the FL is able to be calculated, as below,

$$FL = 2 \times (300/100)^2 \times 200/100 = 36 \text{ psi} \tag{1}$$

When 300 gpm of water is passing through 200 feet section of 2.5” hose, the friction loss is 36.0 psi. Since the friction loss in small appliances is negligible, AL is not calculated. However, EL has to be considered because the fire hose connection point for the firefighting robot is higher than the water source. Up to 10-12 feet high, 0.434 psi should be calculated per 1 foot difference of the fire hose.

$$\text{EL for the fire-fighting robot} = 3(\text{ft}) \times 0.434 = 1.302 \text{ psi} \tag{2}$$

1.302 psi of elevation loss for 3 feet height of a fire-fighting robot will occur in the fire hose. In conclusion, when 300 gpm of water is passing through a 200 foot section of 2.5 inch hose, 36.0 psi of friction loss and 1.302 psi of elevation loss will occur in the fire hose. If the maximum pressure of water source is 400 psi, the actuator must overcome 362.698 psi to control a T-valve of the ATD.

4.1.2 Traction Efficiencies

The ATS is able to improve the traction efficiency for the firefighting robot. In order to use the differences of the traction efficiencies in simulation experiments, the frictional forces should be calculated with a fully charged fire hose and an empty fire hose. The sheath of the fire hoses in this research is made by rubber polymers; thus, frictional coefficient for rubber are 0.85 for the static frictional coefficient (μs), and 0.67 for the kinetic frictional coefficient (μk), as described in table 2.2. In case of the water mass, one liter of water is equivalent to approximately one kilogram between -7 degrees centigrade and 50 degrees centigrade. That means, in most cases, one liter of water is equal to one kilogram. In addition, the amount of water that fits inside of 200 feet of 2.5" hose is 198.9975 liters, and fire hose's weight is 56 kilograms. In conclusion, the total weight for the fire hose with water is 255 kilogram. The frictional force is able to be calculated as below:

Case 1: Fire hose including water.

$$F_s = 0.85 \times 255\text{kg} \times 9.8\text{m/s2} = 2124.15 \text{ N} \quad (1)$$

$$F_k = 0.67 \times 255\text{kg} \times 9.8 \text{ m/s2} = 1674.33 \text{ N} \quad (2)$$

$$W = 1674.33 \text{ N} \times 4000 \text{ m} = 24\text{V}/26.6\text{Ah battery use} \quad (3)$$

Case 2: Fire hose excluding water.

$$Fs = 0.85 \times 56\text{kg} \times 9.8\text{m/s2} = 466.48 \text{ N} \quad (4)$$

$$Fk = 0.67 \times 56\text{kg} \times 9.8 \text{ m/s2} = 367.696 \text{ N} \quad (5)$$

$$W \text{ (per one hour)} = 367.696 \text{ N} \times 4000 \text{ m} = 1470784 \text{ J} = 24\text{V}/5.841 \text{ Ah} \quad (6)$$

Thus, if the automatic T-valve system can clearly expel the water, the robot will be able to use only 24V/5.841 Ah power which economizes the power demand up to 78%. This means the robot can constantly move around up to 6.84 hours with an empty fire hose. Table 4.1 shows the compared results. In conclusion, if the firefighting robot uses this ATS system, the firefighting robot is able to decrease energy consumption. That means the robot would not need to be replaced with another robot or firefighters while charging its battery during fire extinguishment.

Table 4.1 Power Demand and Operating Time of the Firefighting Robot

	Maneuver without a fire hose	**Maneuver with a fire hose (with water)**	**Maneuver with a fire hose (without water)**
Power demand	24V/5Ah	24V/26.6Ah	24V/5.841Ah
Operating time	8 hours	1.5 hours	6.84 hours

4.1.3 Discharging Water

The formula for the discharging water is able to calculate the amount of discharged water as well as the amount of saved battery power. Due to the gap between firefighting robot's height and ground, the water in the first several feet of a fire hose will be easily discharged. However, if an ATD is used for 200 feet fire hose, some sections of the fire hose on flat ground would be twisted and folded by external influences including gravity, frictional force and etc. Therefore, the discharging rate of water and the consumption of power will be like Figure 4.5.

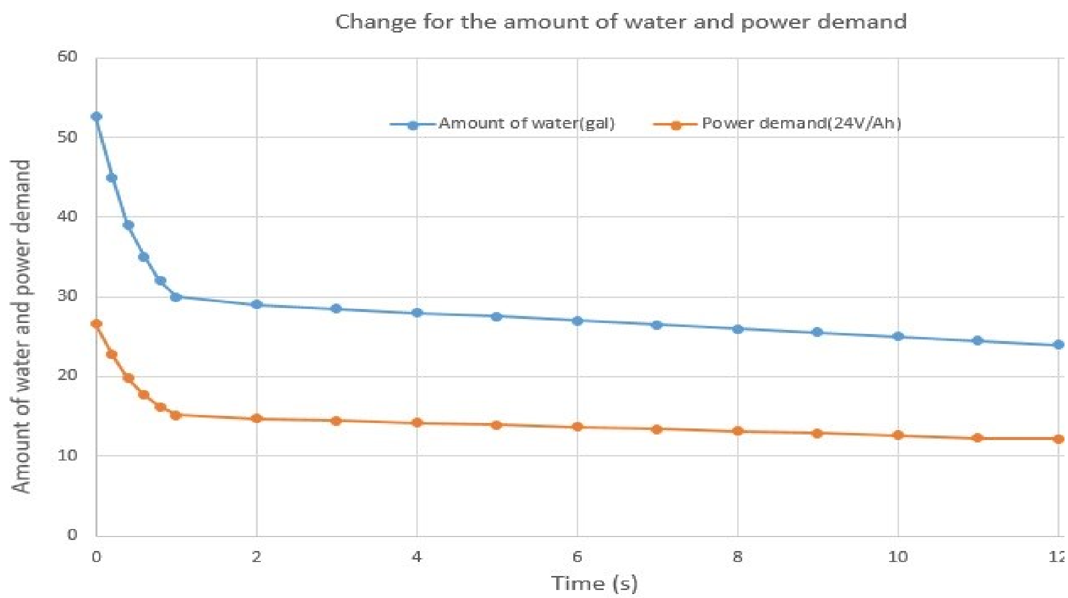


Figure 4.5 Change for the Amount of Water and Power Demand

As illustrated in Figure 4.5, the ATD could not discharge the full amount of water to save battery power. If the full amount of water is able to expel from the fire hose, the power demand is able to decrease up to 24V/5.841Ah. Whenever the ATDs are added on the fire hose, the probabilities of the fire hose closing is able to be decreased, as shown in Figure 4.6. With this solution, this research assumes that the fire hose in simulation experiments cannot be twisted and closed by external influences. Only obstacles can close the fire hose in the simulation experiments. In conclusion, the water in the fire hose is discharged completely and the power demand is also minimized, as shown in Figure 4.7.

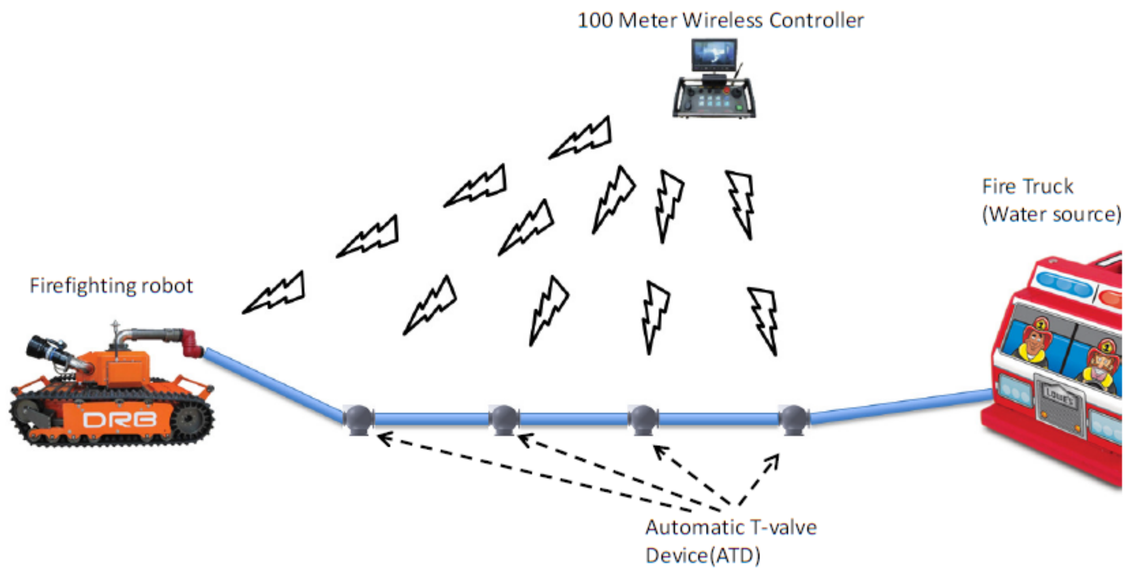


Figure 4.6 Operating the Robot and ATDs by a Wireless Controller

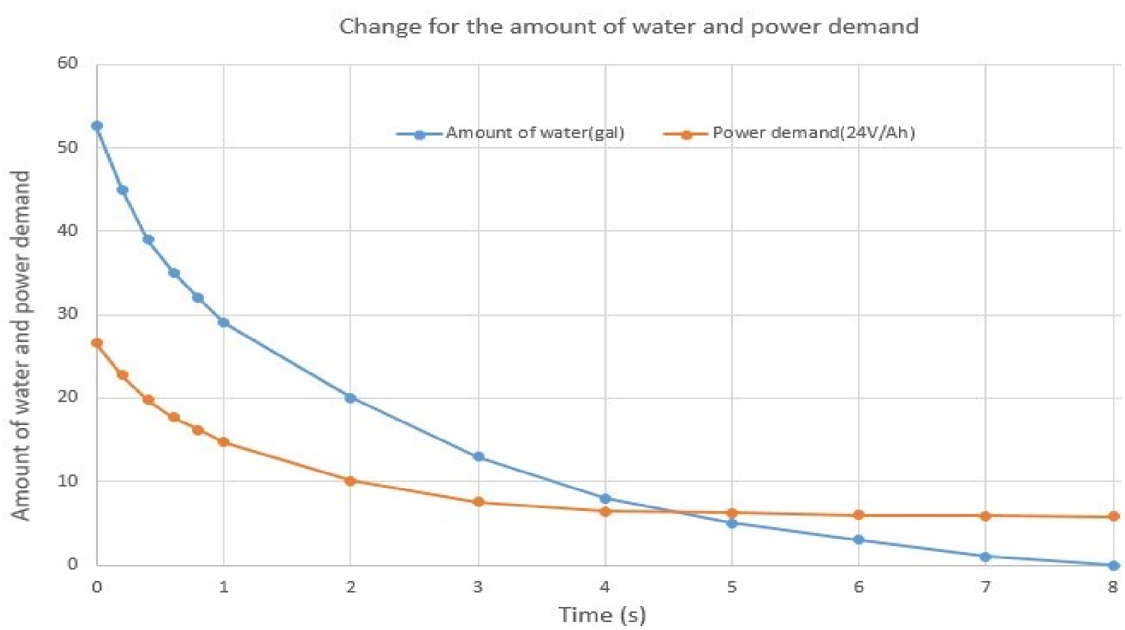


Figure 4.7 Change for the Amount of Water and Power Demand

4.2 ATS Firefighting Simulation Model

The firefighting simulation model with ATS consists of the firefighting robot agent modeling, the firefighting process modeling and a couple of fire areas. The basic information for the firefighting robot is shown in figure 2.3. The dimensions of this robot are 1100mm (L) x 710mm (W) x 900mm (H). The weight is 210 kilograms (463 pounds) and the speed is 4km/h. In addition, the operating time is 1.5 hours with a 24V/40Ah battery when the robot pulls the 65A fire hose-60 meters or 40A fire hose-90 meters. The power demands are 24V/5.841 Ah with an empty fire hose and 24V/26.6 Ah with a fire hose that is filled with water. The shooting water for 10 seconds or 40 seconds can extinguish a small fire or a large fire. The firefighting robot agent modeling is as shown in figure 4.8. The state chart displays the firefighting robot operating. When the robot detects the fire, the robot changes the mode from moving mode to extinguishing mode. After the firefighting is finished, the robot has to check its battery. If the battery is enough, its mode will be changed from extinguishing mode to moving mode. On the other hand, if the battery is not enough, the robot will be stopped.

In order to compare results between firefighting alone and firefighting with the ATS, two types of fire in AnyLogic® libraries are simply modeled in simulation experiments in figure 4.9. The shooting water for 10 seconds or 40 seconds is able to extinguish a small fire or a large fire. The process modeling shows the fire operating. If the fire gets the water over 10 seconds or 40 seconds, the fire will be extinguished. On the other hand, if the fire gets the water under their limits, they will come back alive.

In addition, two types of fire areas are modeled in figure 4.10 and figure 4.11. The fire in the first area is concentrated and the fire in the second area is scattered.

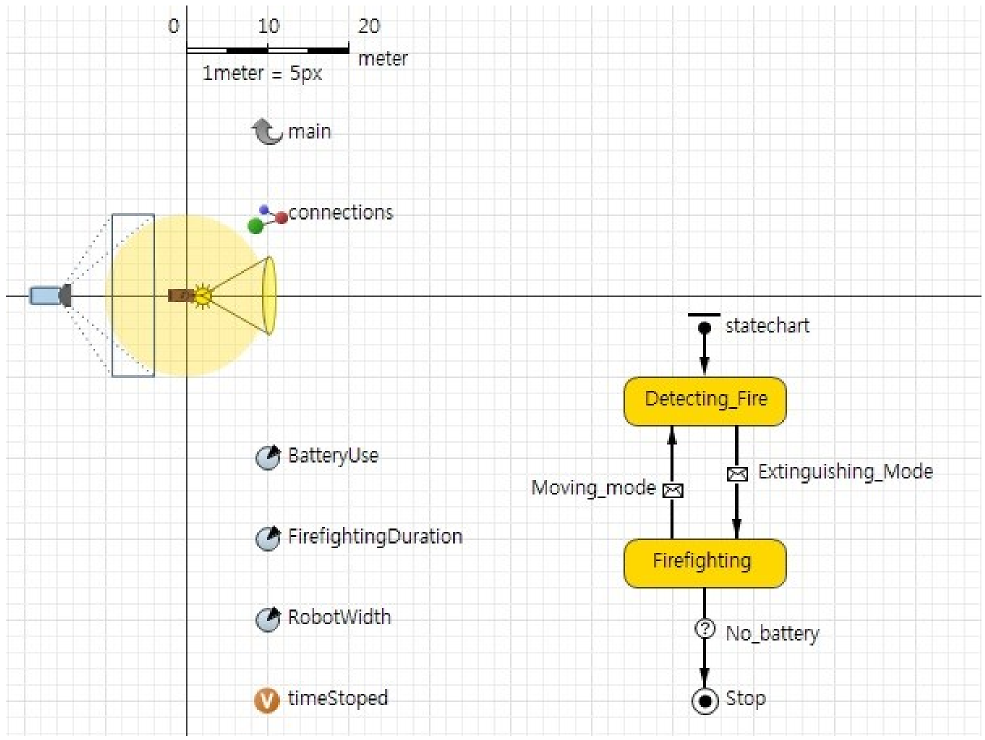


Figure 4.8 The Firefighting Robot Agent Modeling

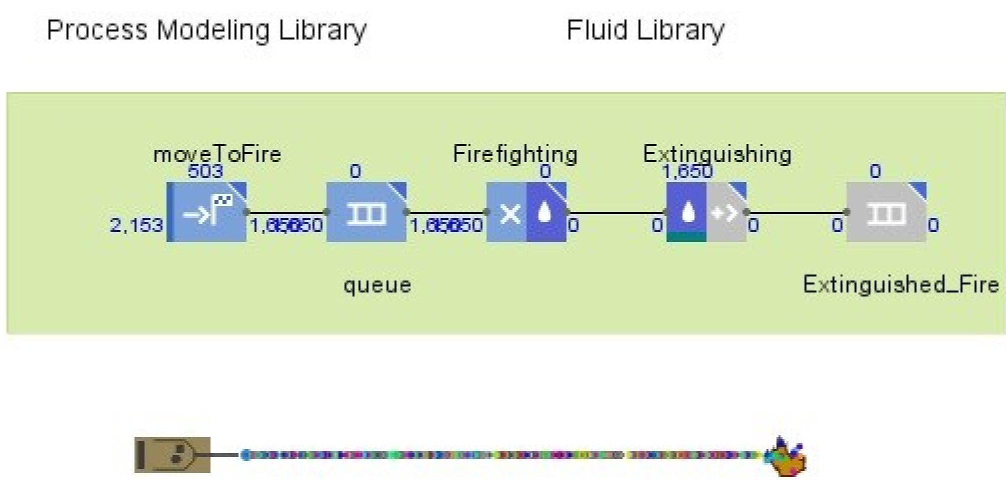


Figure 4.9 The Firefighting Process Modeling

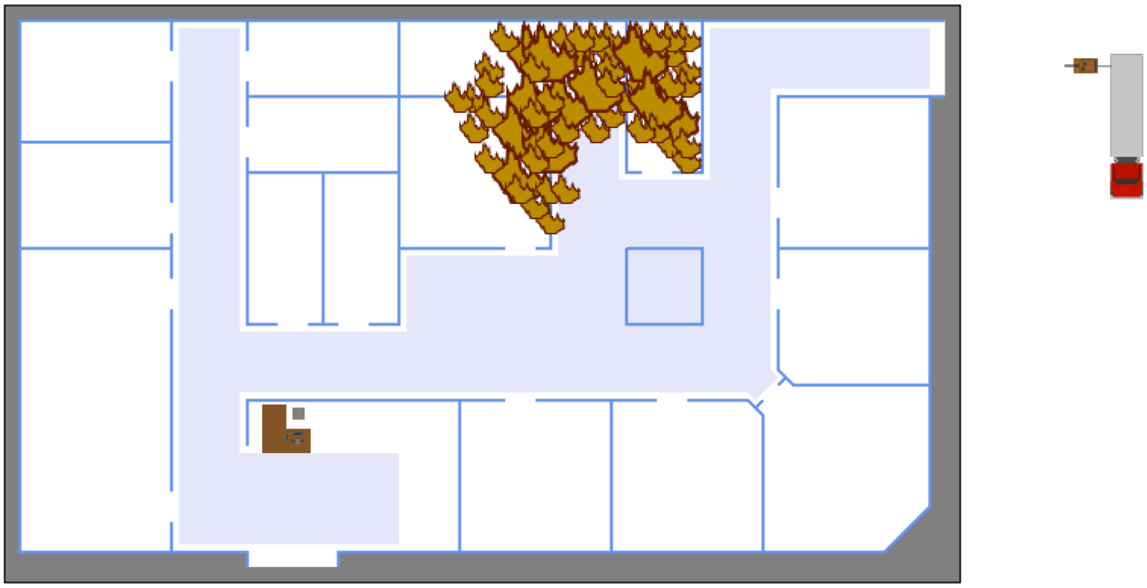


Figure 4.10 Concentrated Fires in a Fire Area

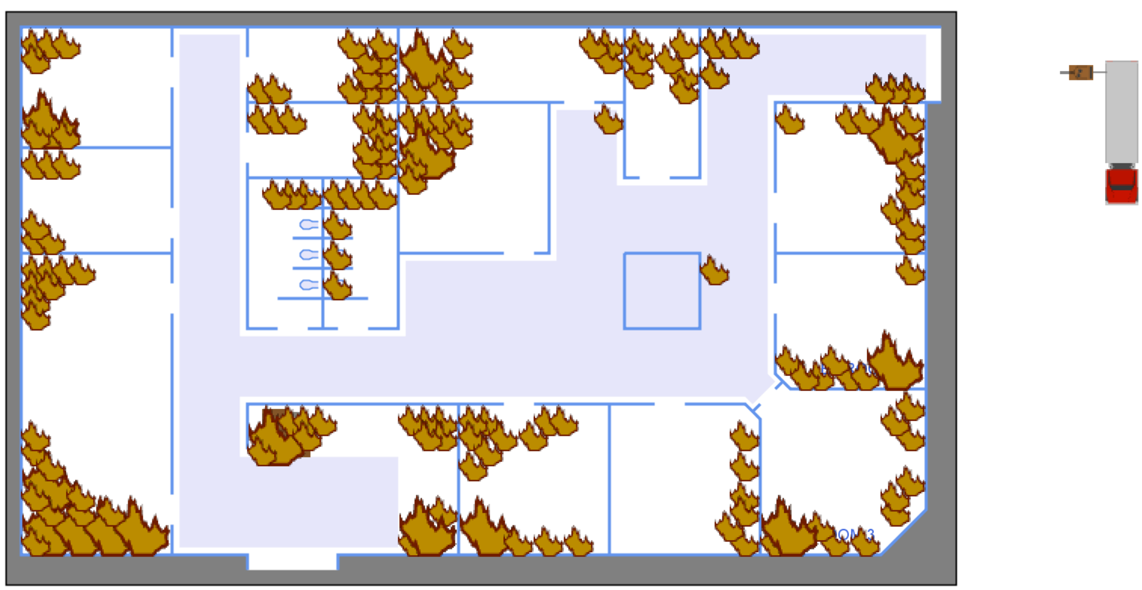


Figure 4.11 Scattered Fires in a Fire Area

Once all parameters for the firefighting robot agent modeling, the firefighting process modeling and fire areas are prepared, the model can be launched, as shown in figure 4.12. With a clicking the button labeled “Run the model”, the firefighting robot starts to extinguish fires.

Figure 4.12 First Screen for the Firefighting Robot Model

The simulation experiments in fire area with 520 concentrated fires show that there are no differences between firefighting alone and firefighting with the ATS until extinguishing all fires. But, the firefighting robot with the ATS is able to monitor other spaces for additional fire suppression after finishing firefighting. In the beginning, both robots move to a spot for firefighting that is about 38 meters away from the starting point.

And then they start to extinguish about 520 fires. Because the robots are able to extinguish up to 540 small fires with their maximum battery, their remaining battery is too low after firefighting. Therefore, the robot without ATS should come back to the starting point without energy consuming, because the robot can move up to 110 meters. On the other hand, the robot with ATS is able to monitor other spaces for the additional fire suppression because the robot can move up to 500 meters more although its remaining battery is too low.

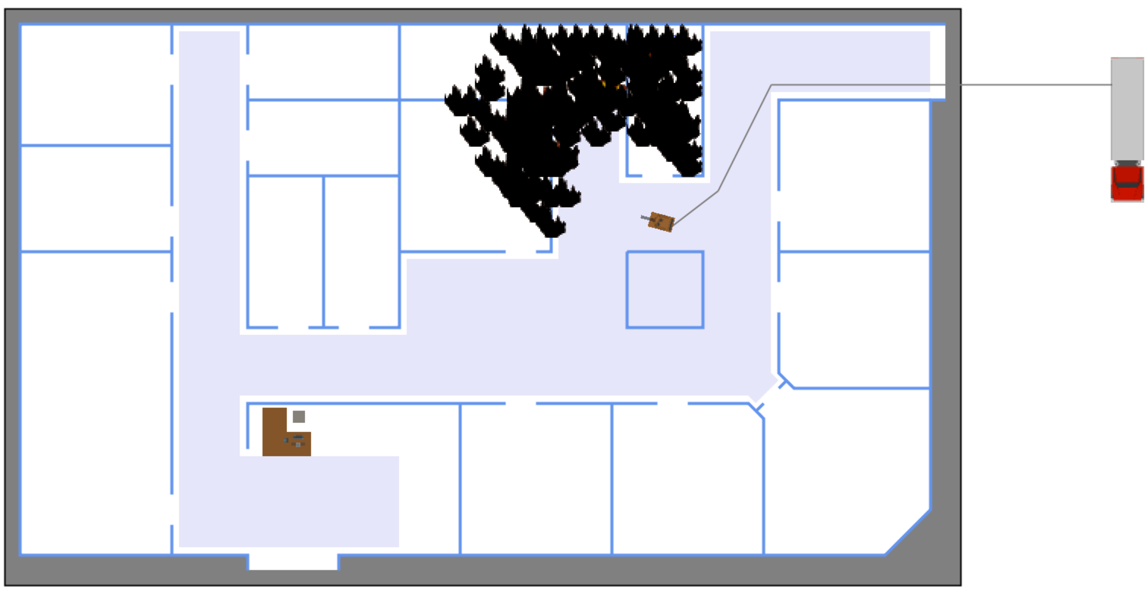


Figure 4.13 Firefighting for Concentrated fires in fire area

The ATS is actively able to work for the firefighting robot in fire area with scattered fires. In order to extinguish the scattered fires, the firefighting robot should frequently move to other spots. At this time, the ATS can expel the water from a fire hose, so that the robot is able to save the power demand from 24V/26.6Ah to 24V/5.841Ah. Figure 4.14 shows the firefighting without ATS. From the entrance, the robot should extinguish fires, so that a fire hose is filled with water. As a result, the robot always spends 24V/26.6Ah of the battery power for firefighting as well as movements with drawing a fire hose.

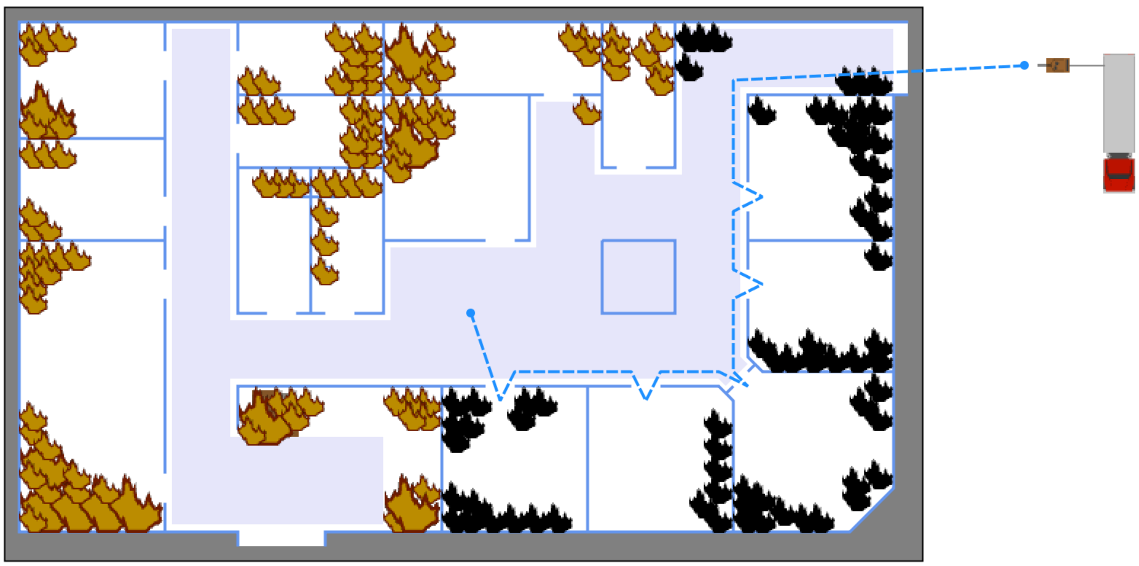


Figure 4.14 Firefighting without ATS in fire area with scattered fires

By contrast, the firefighting with ATS is able to save the battery demand up to 1/18 of battery power in figure 4.15. While the firefighting robot moves to other spots, the ATS has saved the battery power by expelling water. In conclusion, the robot with ATS extinguishes 30 more fires than before.

In these experiments, the ATS displays that it is able to save maximum 1/18 of battery power in small fire areas. As the fire areas get wider and the moving distance gets longer, the ATS can save more than four times the battery. In more detail, the robot without ATS is able to move up to 6,000 meters, but the robot with ATS can move up to 27,000 meters.

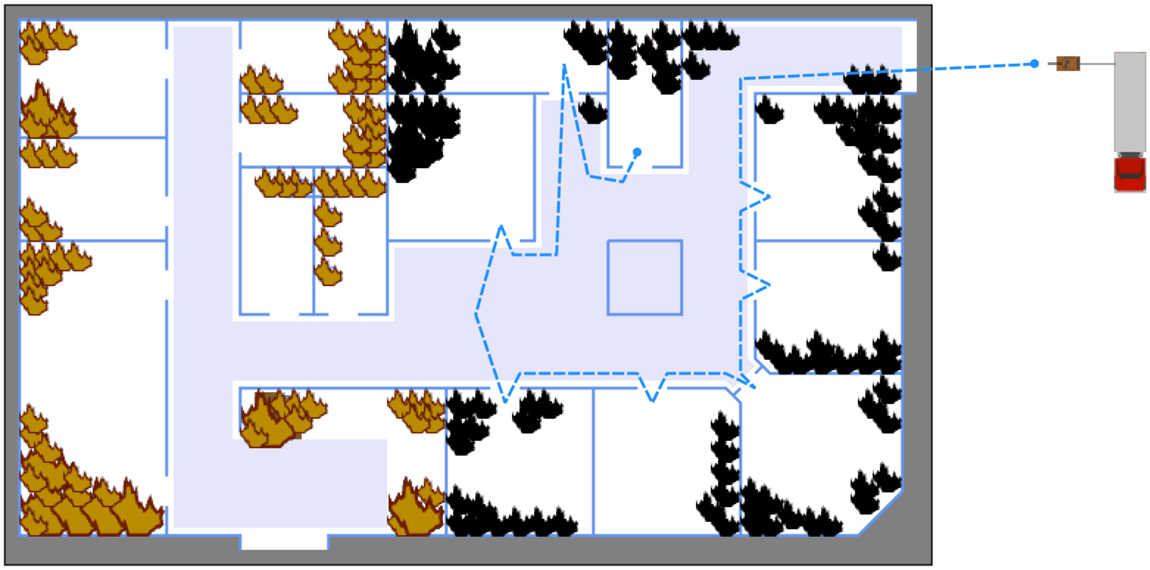


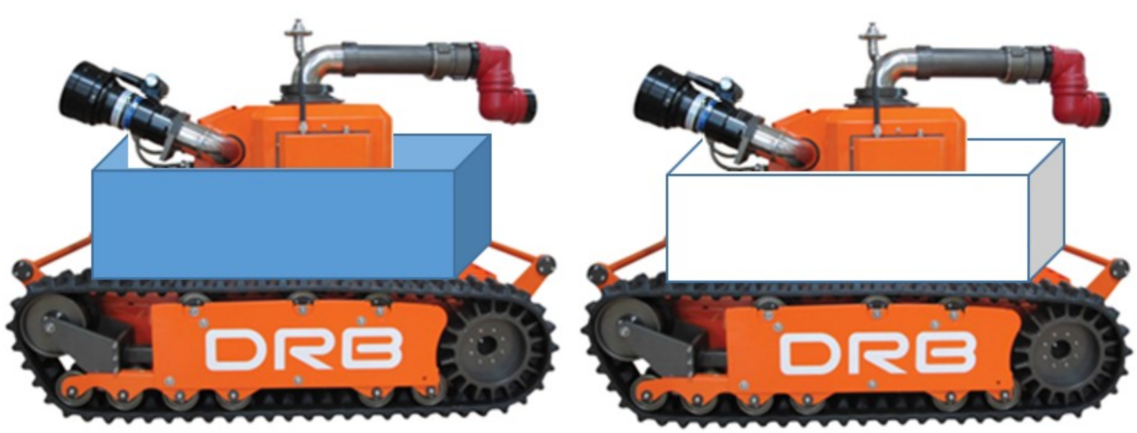
Figure 4.15 Firefighting with ATS in fire area with scattered fires

4.3 Novel Designed Firefighting Robot

The Novel Designed Firefighting Robot (NDFR) is designed to make the firefighting robot as light as possible by subtracting additional weight for stability so that the robot is able to bear the recoil from shooting water and the weight of a fire hose with fully charged water. Setting up an empty space in the robot makes the robot heavier or lighter temporarily by the ATS, whenever the robots want to change its modes from extinguishing mode to moving mode. Since the existing firefighting robot has been made very heavy for the robot stability, the decreasing weight of the robot with a fire hose is able to increase the energy efficiency of the robot. The NDFR is intended to enable the robot to increase operating hours and to effectively extinguish a fire while managing the amount of water in the robot and a fire hose. When extinguishing the fire, this charged water of the empty space in the robot could enhance the robot stability. And then, when a firefighting at a spot was finished, the ATS can discharge the water from a fire hose and a space in the NDFR robot.

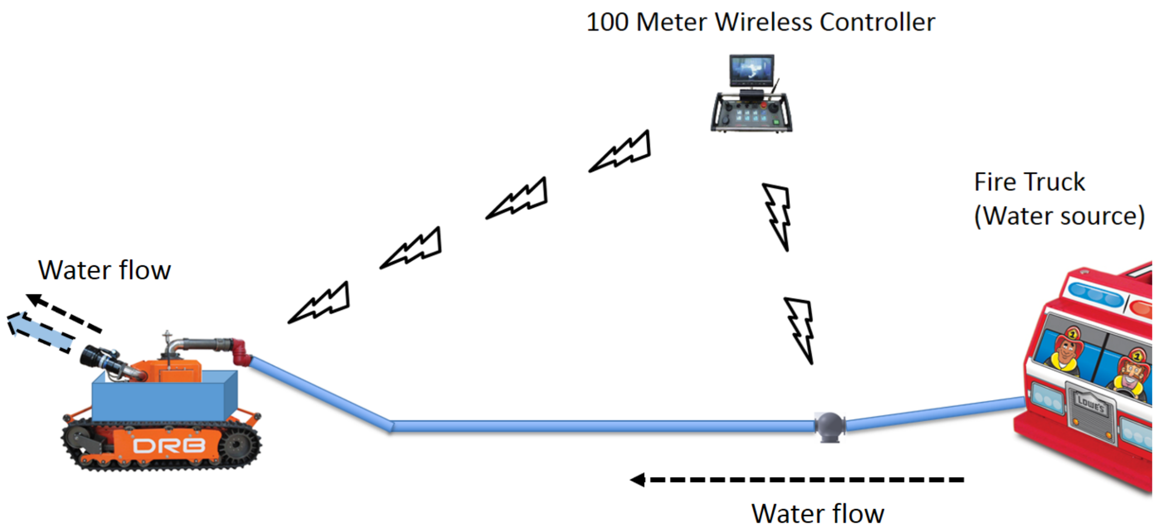
This NDFR robot is created on the basis of an existing ATS that can be operated by a wireless controller for the firefighting robot in figure 4.16 and figure 4.17. The NDFR has two kinds of modes that are a firefighting mode and a maneuvering mode. The first mode is NDFR firefighting mode. Whenever the wireless controller sends signals to the firefighting robot with the ATS to start to extinguish a fire, the ATS will be opened to allow water to pass through a fire hose and the empty space of NDFR that can be filled with water for extinguishing a fire. The second mode is NDFR maneuvering mode. Whenever the wireless controller sends signals to them for moving to other fire spots, the ATS discharging mode will expel water from the water space of the robot and a fire hose. Thanks for this working with ATS, the firefighting robot save more energy than the existing robot working with the ATS.

The NDFR with ATS as a solution to lower the weight of the fire hose and the robot helps the firefighting robot to operate for a longer time.

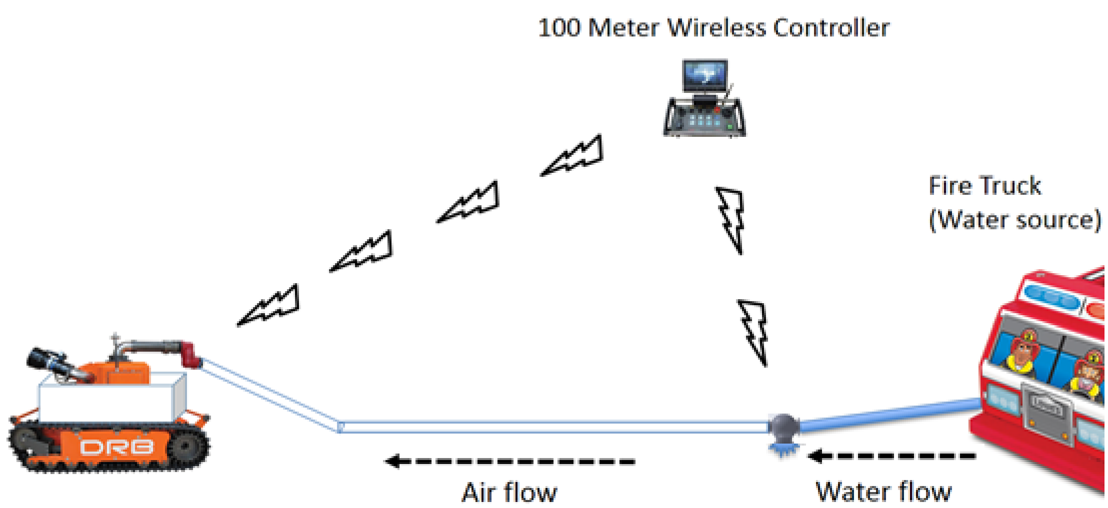


(a) NDFR firefighting mode (b) NDFR maneuvering mode

Figure 4.16 The Novel Designed Firefighting Robot (NDFR)



(a) NDFR firefighting mode



(b) NDFR maneuvering mode

Figure 4.17 Operating the NDFR and ATS by a wireless controller

4.3.1 Energy Efficiencies for NDFR

The NDFR is 30 kilograms lighter than the original firefighting robot from the subtracting of additional weight for robot stability. According to the study of the ATS, if the ATS can perfectly discharge the water from a fire hose, the robot could economize the power demand up to 78%. Therefore, the robot can consistently operate up to 6.84 hours with a fire hose. Moreover, if the NDFR works with ATS, the NDFR only uses 24V/5.121 Ah power. This result means that the robot could economize the power demand up to 81% and operate up to 7.81 hours with an empty fire hose. The results are compared in Table 4.2.

Table 4.2 Power Demand and Operating Time of the NDFR

The firefighting robot	**Power demand for movement (24V/Ah)**	**Robot moving hours (hours)**
Working alone	24V/5Ah	8
With a fire hose	24V/26.66Ah	1.5
With a fire hose and ATS	24V/5.841Ah	6.84
NDFR alone	24V/4.28Ah	9.3
NDFR with a fire hose and ATS	24V/5.121Ah	7.81

4.3.2 Firefighting Length Efficiencies for NDFR

The NDFR is able to cover a wider area than before, because it can increase the robot stability by charging more water. The existing firefighting robot has to use one of the regular fire hoses in order to avoid turning over as illustrated in Figure 4.18. However, the NDFR is able to use a longer fire hose because of the increased stabilities of the NDFR.

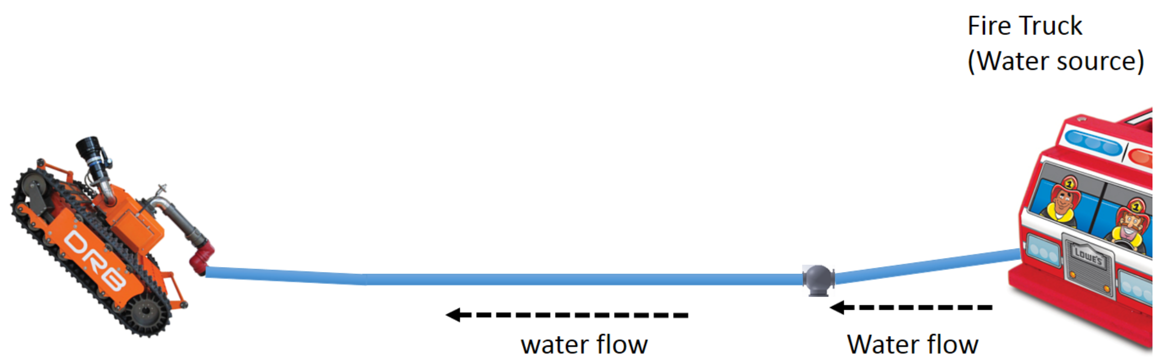


Figure 4.18 The firefighting robot flipped by a heavier fire hose

4.4 NDFR Firefighting Simulation Model

The NDFR simulation model consists of the same robot agent modeling that is shown in Figure 4.8, the firefighting process modeling demonstrated in Figure 4.9 and a couple of fireareas (in Figure 4.10 and Figure 4.11). The only difference is the power demand for movement that is decreased from 24V/5.841 Ah to 24V/5.121 Ah.

In fire area with 520 concentrated fires, the NDFR not only extinguishes all fires but also monitors for additional fire suppression, because its energy efficiency is better than the robot with ATS. In addition, the NDFR also operates for firefighting at the fire scene with scattered fires. Because the robot with ATD extinguished all fires in the maximum range of a fire hose, it is clear that the NDFR will extinguish the fires in same range of the fire hose. In order to ensure the NDFR operates optimally, the 60 meters limitation of the fire hose is removed in this experiment. In conclusion, the NDFR is able to work 3% more than the robot with ATS, so that one more compartment was cleared in Figure 4.19.

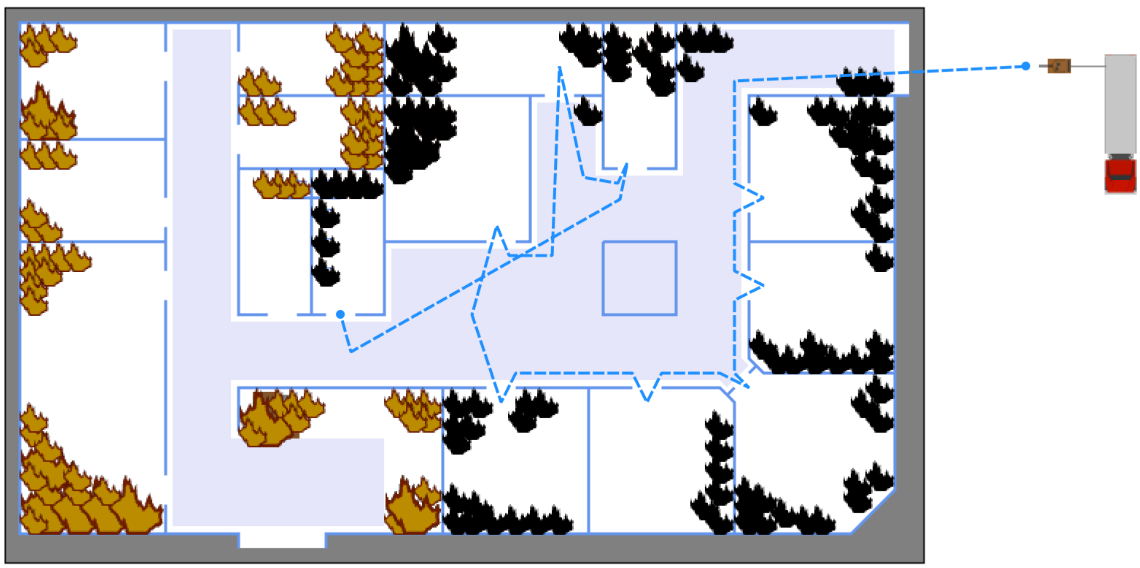


Figure 4.19 NDFR Firefighting in fire area with scattered fires

4.5 Discussion

In this chapter, the automatic water management system (AWMS) for a firefighting robot battery management was presented. An automatic T-valve system (ATS) and a novel designed firefighting robot (NDFR) increased the robot energy efficiencies and verified that the robot is able to work for a longer duration. In addition, the NDFR displays a possibility that the robot can expand its scope of use with renewed design. In conclusion, the AWMS increased the working scope and operation time from 1.5 hours to 6.84 hours or 7.81 hours.

Although the robot is able to move up to 60 meters due to the limitation of a fire hose, the wireless controller can manage the robot up to 100 meters. If the robot movement is longer, the robot should move in wider ranges, so that the efficiency of AWMS is increased. Thus, AWMS is more crucial for wider areas.

Even though the NDFR provides a solution that is able to increase the stability by upgrading its design, making an empty space for the robot is limited. Therefore, the next chapter will address multi robot systems that increase the working range by using the regular fire hose.

CHAPTER 5. MULTI ROBOT ENERGY SAVING SYSTEM

This chapter presents a multi robot energy saving system (MRESS) that minimizes the chances of energy loss while increasing firefighting time and range of a firefighting robot. This new robot system is able a firefighting robot with sub-robots to effectively move to desired destinations while extinguishing fires in an extended working range. In order to increase working time and range for robots, additional robot was designed based on the automatic T-valve system (ATS) and installed between regular fire hoses. The main goals of the sub-robot are expelling water from a fire hose for energy saving, and adding an additional fire hose to increase the working range. For the multi robot cooperation, the new system controls the robots by combining a tracking method, an endrunning navigation, and a limit-cycle system. The collaboration of limit-cycle navigation and a fire hose tracking method has outstanding merits including optimal path generating and faster data processing. Furthemore, the endrunning navigation system is able to decrease the collision chances. In conclusion, MRESS is able to robots to easily move to the goals with fast processing and to optimally move to their destinations without blocking by obstacles.

5.1 Robots Logic Model

For a multi-robot system, a sub-robot is designed based on the automatic T-valve system (ATS) and installed between regular fire hoses as shown in Figure 5.1. The sub-robot is able to discharge water for the energy efficiency and to extend the firefighting range by adding another 60 meters fire hose.

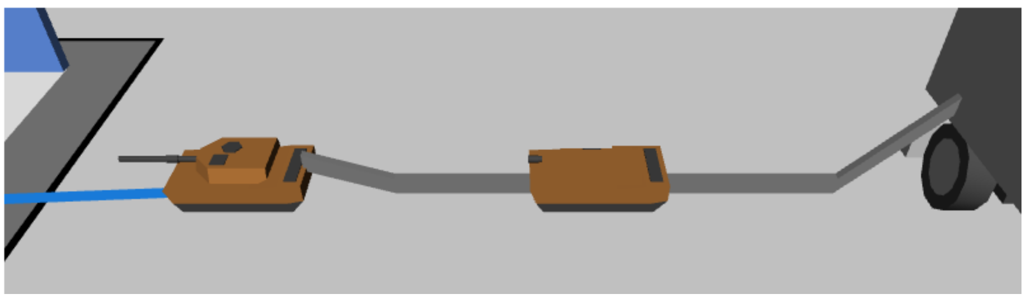


Figure 5.1 The Multi-robot Operation

The firefighting simulation model with MRESS is based on a firefighting robot agent modeling with ATS. This novel agent modeling with MRESS consists of not only the fire detecting and firefighting but also obstacle detecting, edge detecting, limit-cycle navigation and endrunning navigation. In the beginning, the firefighting robot enters to the fire area while the sub-robot is waiting for the first robot to reach the farthest area with a fire hose. Whenever the main firefighting robot detects fires, edges, and obstacles, the robot uses its technologies such as firefighting, limit-cycle and endrunning navigation. The state chart for the firefighting robot is illustrated in Figure 5.2.

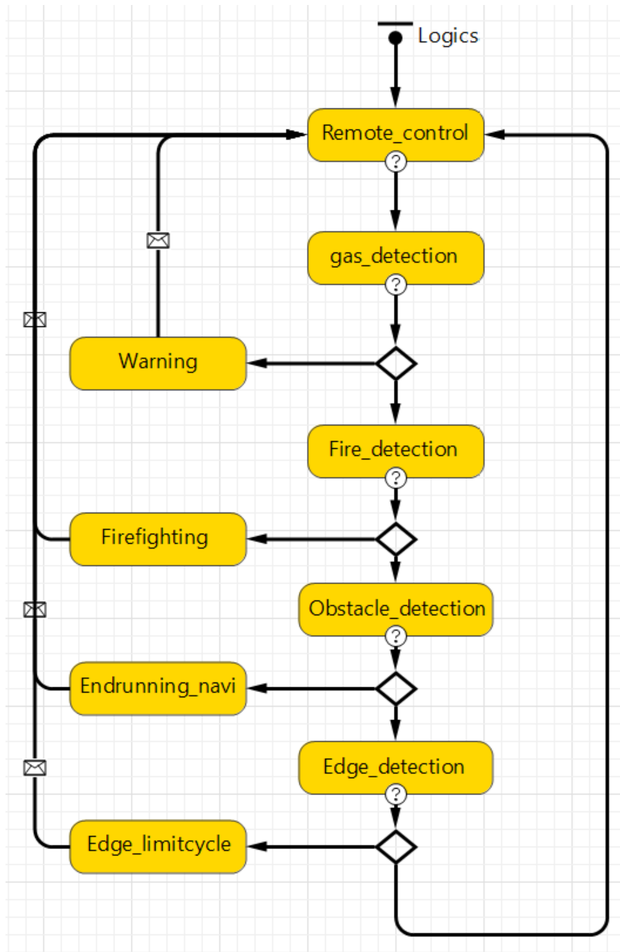


Figure 5.2 A state chart of the firefighting robot operating system

When the firefighting robot reaches the farthest area with a fire hose, the additional sub-robot starts to move along the fire hose for the working range extension of the firefighting robot. On the way to move to the main robot, the sub-robot also keeps detecting obstacles and their edges to avoid them. Because the firefighting robot already made an optimal path with endrunning, the sub-robot is able to simply follow the path. The state chart for the sub-robot is illustrated in Figure 5.3.

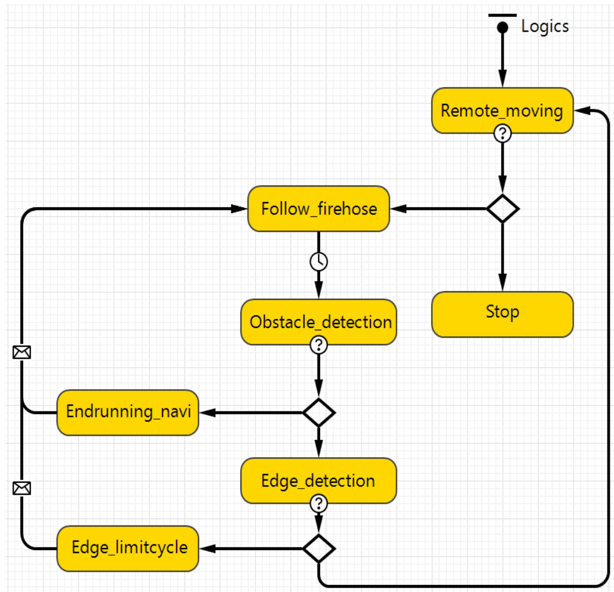


Figure 5.3 A state chart for the sub-robot with MRESS

5.2 Limit-cycle Simulation Model

The limit-cycle navigation system is able to transform all kinds of obstacles into circles. This method may be applied to not only static and polygonal obstacles but also dynamic robots in a flexible environment, such as soccer robot system for example. The proposed navigation method allows the firefighting robot and sub-robot to move easily towards desired destinations by exchanging the circle radius and the moving direction.

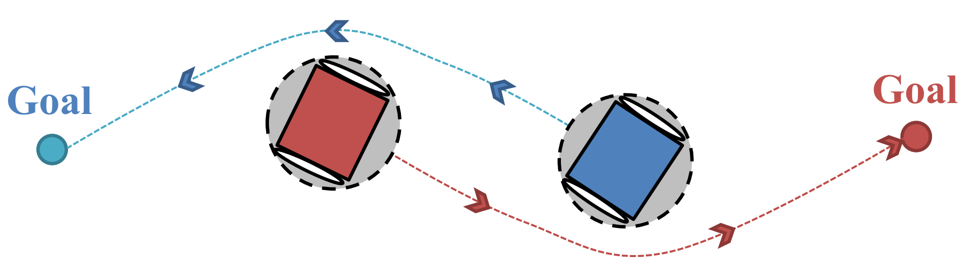
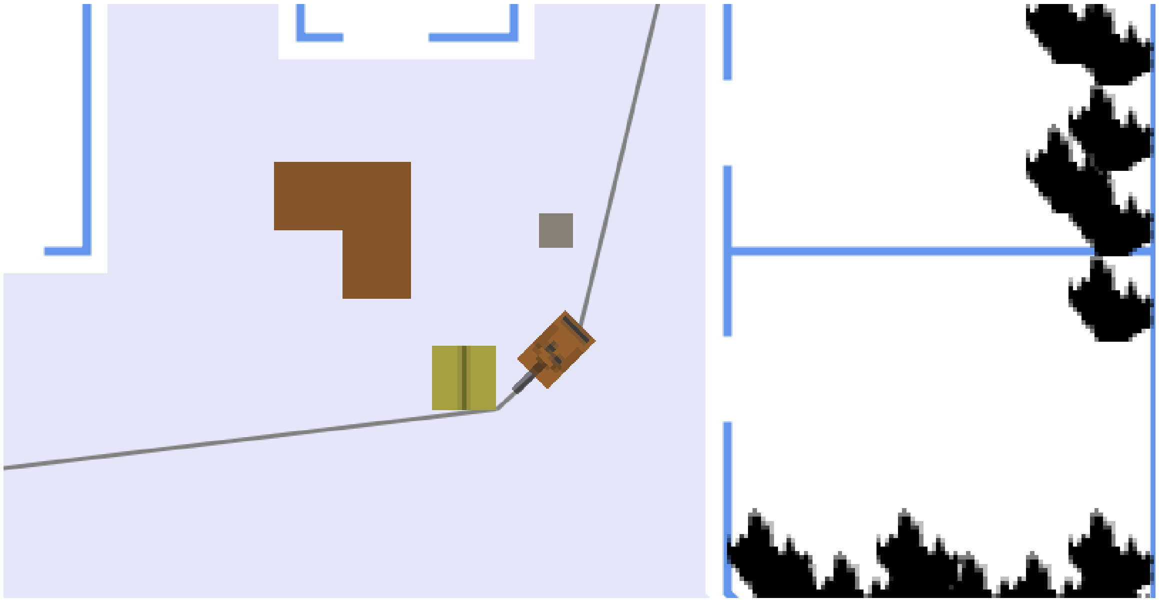


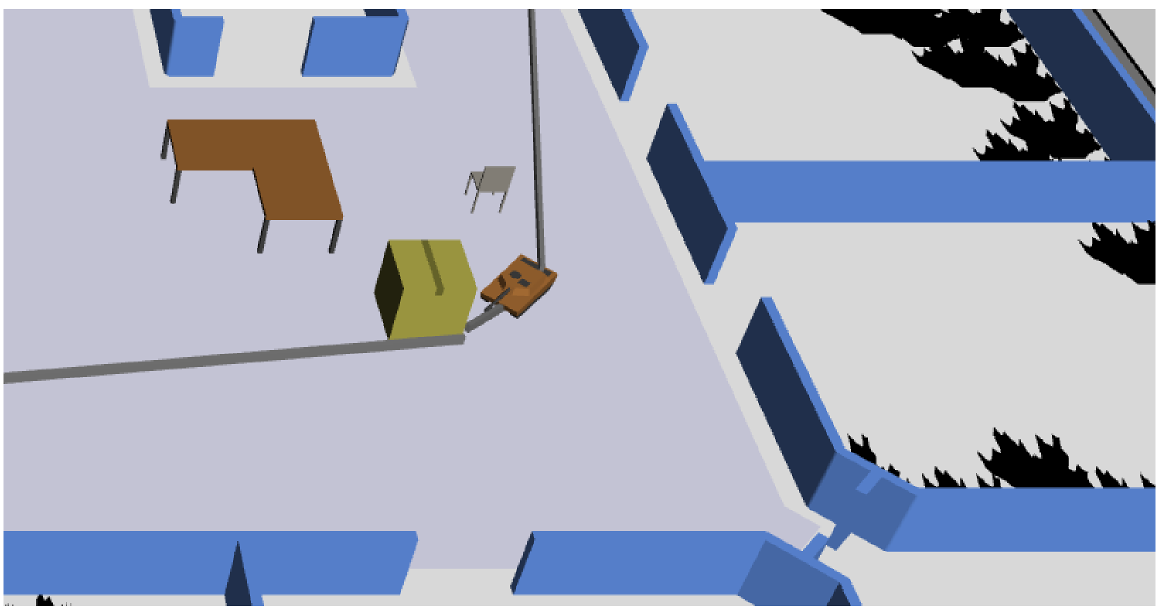
Figure 5.4 A Limit-cycle Navigation System (Kim et al., 2010)

The novel navigation system is very crucial for sub-robot operation. Since the main firefighting robot is worked by a person with a wireless controller, the robot is able to avoid all kinds of obstacles. On the other hand, the sub-robot is operated by automatic line tracking technology, so that it is easily able to be blocked by obstacles without limit-cycle navigation.

Figure 5.5 shows that a sub-robot following the fire hose. Although the shortest path is made for the robot by a person with wireless controller, the sub-robot sometimes cannot move to its goals due to blockage by obstacles. Whenever the following sub-robot is blocked by obstacles, the main robot should waste lots of battery power. This accident reduces the energy power of a firefighting robot, even though an additional sub-robot works to enhance main robot’s power as well as working range. On the other hand, a sub-robot with a limit-cycle system can follow the fire hose smoothly. Figure 5.6 shows that a sub-robot follows the fire hose by a limit-cycle system. Because the limit-cycle system cannot only transform all kinds of obstacles into circles but also make available spaces for the additional sub-robot to navigate to avoid obstacles, the robot can follow the hose freely. In conclusion, the limit-cycle system can help the sub-robot for the obstacles avoidance, so that the main firefighting robot can extend its working range and save battery demand.

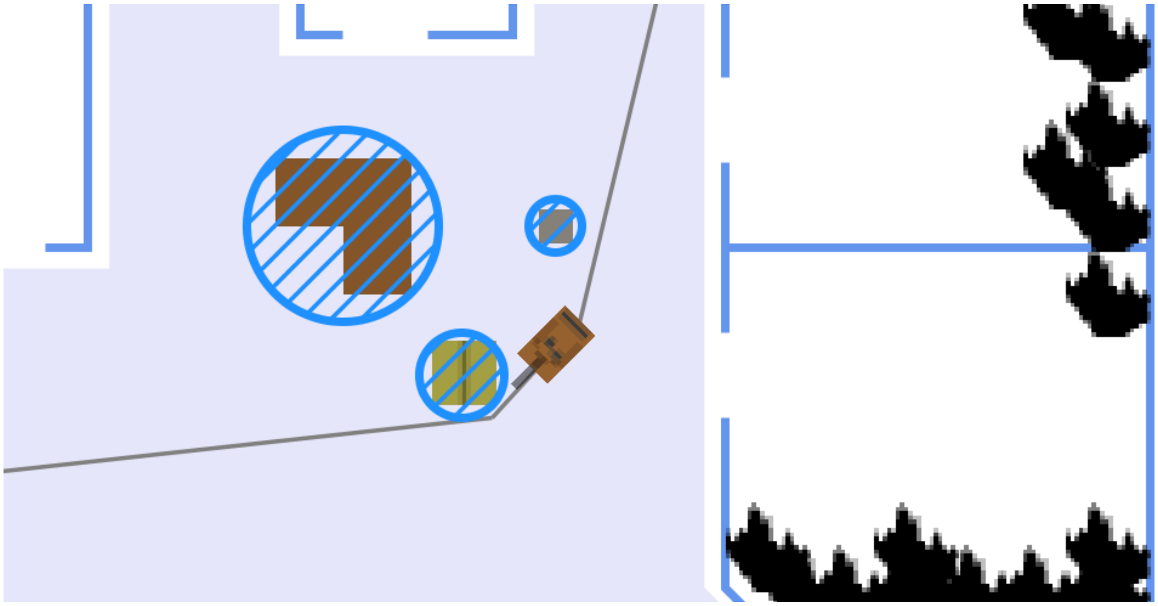


(a) 2D

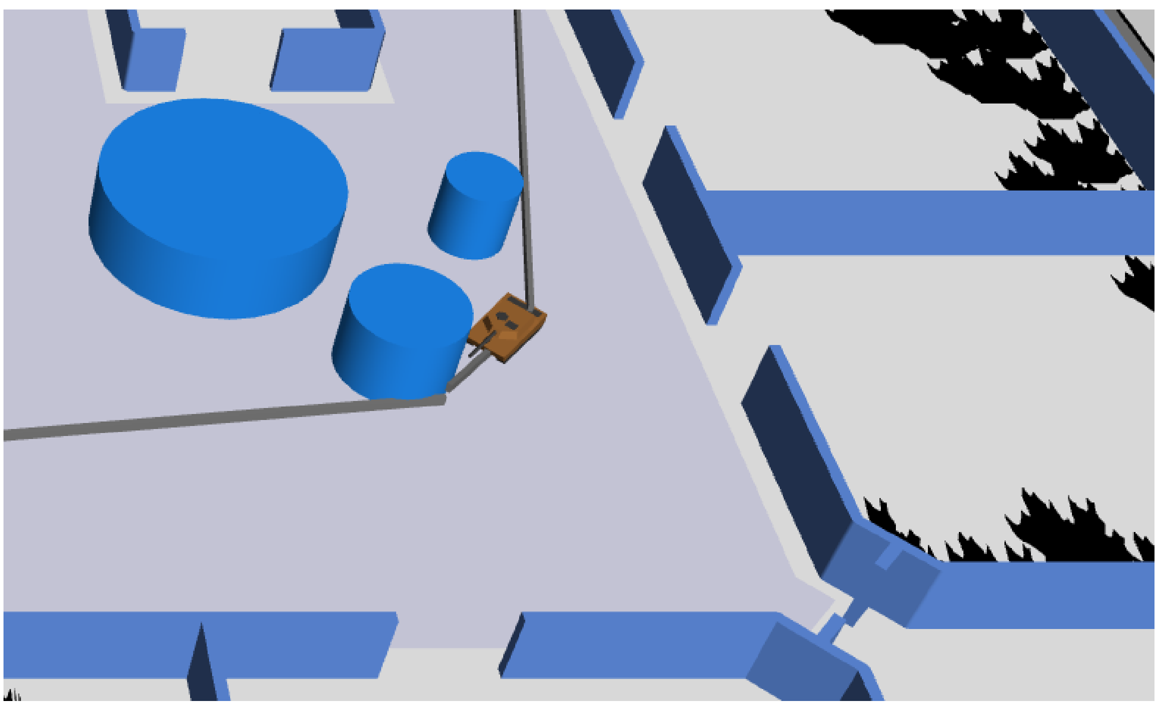


(b) 3D

Figure 5.5 A sub-robot operation without limit-cycle navigation method



(a) 2D



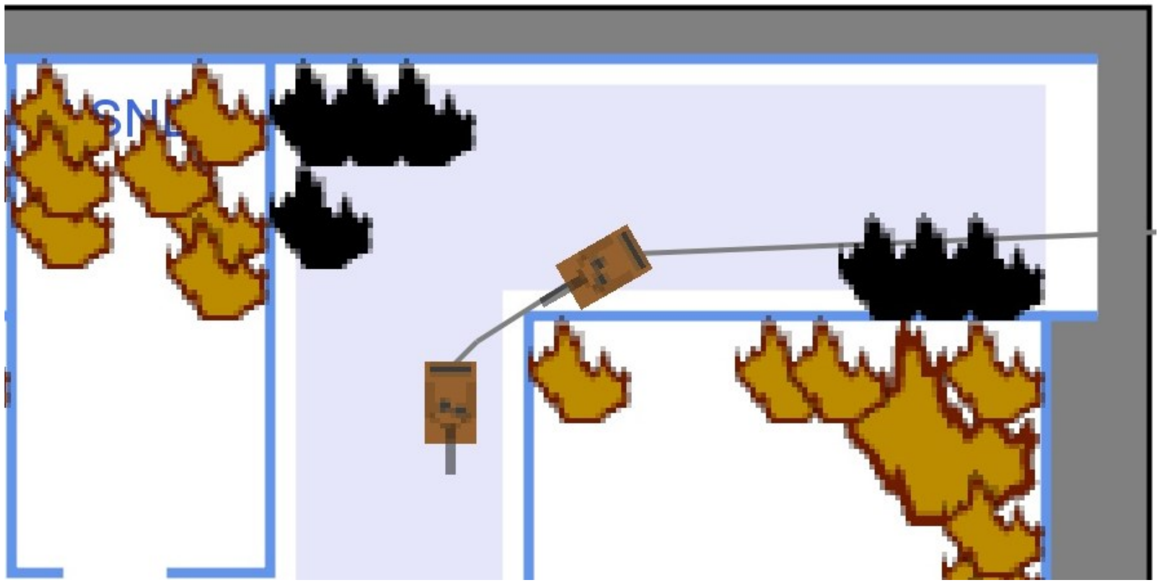
(b) 3D

Figure 5.6 A sub-robot operation without limit-cycle navigation method

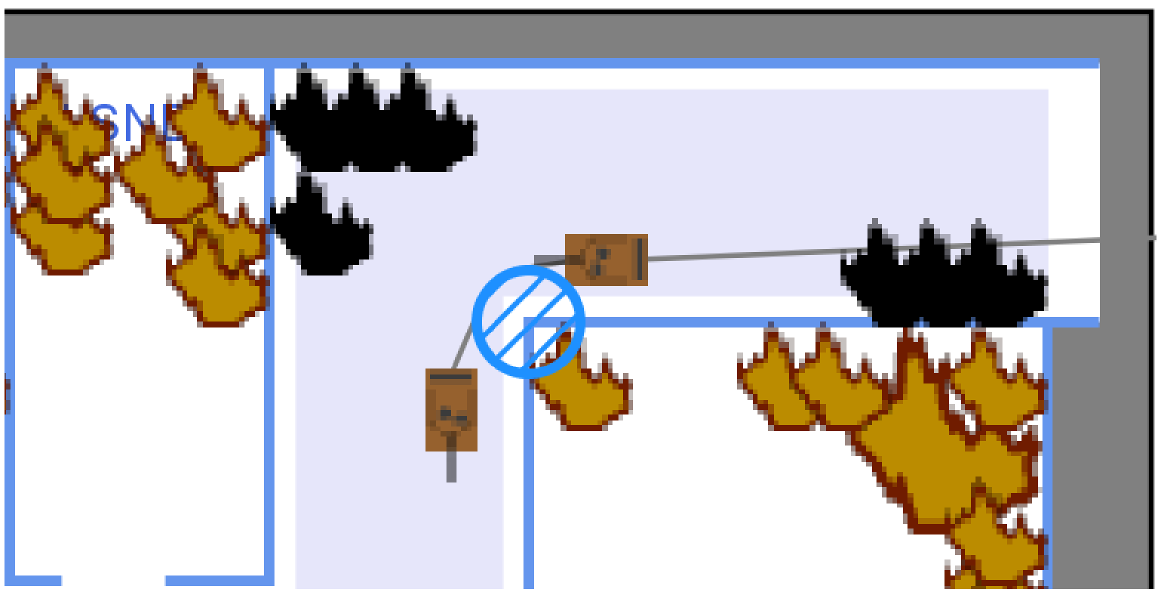
5.3 Edge Detecting Limit-cycle Simulation Model

The existing limit-cycle system is able to create a circular trajectory to make an optimal path. Whenever a robot detects an obstacle, the detecting system draws phase portraits of limit cycle based on the center of obstacles, which enable the robot to avoid the obstacles with an optimal trajectory. By using this fast process, robots are able to navigate while following optimal path in real time. On the other hand, the existing limit-cycle system can be used for regular polygonal obstacles since the circular path is able to be made on the center of obstacles. If the method applies to long-shaped obstacles like wall, the path will be very wide or go to infinity, leaving the robots confused. The edge detecting limit-cycle is able to overcome this confusing problem by combining an edge detection method and a limit-cycle navigation method. With this novel method, the robot is able to detect edges of obstacles as well as regular polygonal obstacles, and make an optimal path for all shapes of obstacles. In conclusion, the robot is able to avoid all shapes of obstacles smoothly.

Figure 5.7 illustrates the excellence of this edge detecting limit-cycle. In Figure 5.7 (a), the additional sub-robot is blocked by a wall while it is on its way to move the main firefighting robot, even though the firefighting robot made an optimal path. This problem leads to large energy loss for both firefighting robot and sub-robot because they use their maximum power to move to their destinations. On the other hand, a robot with edge detecting limit-cycle clearly moves to its destinations without interruption and energy loss, as shown in Fig. 5.7 (b). In conclusion, the sub-robot is able to help the firefighting robot to increase its working range and time.



(a) Blocked sub-robot by the edge of wall



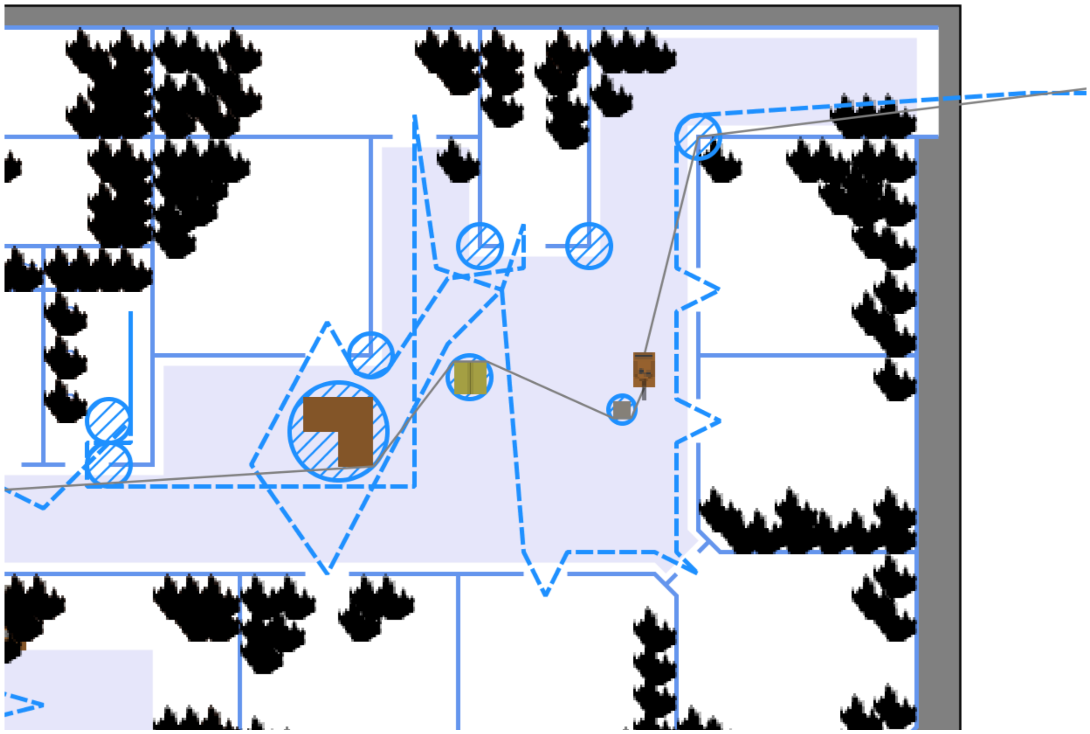
(b) Smooth following by edge detecting limit-cycle method

Figure 5.7 Edge Detecting Limit-cycle Method

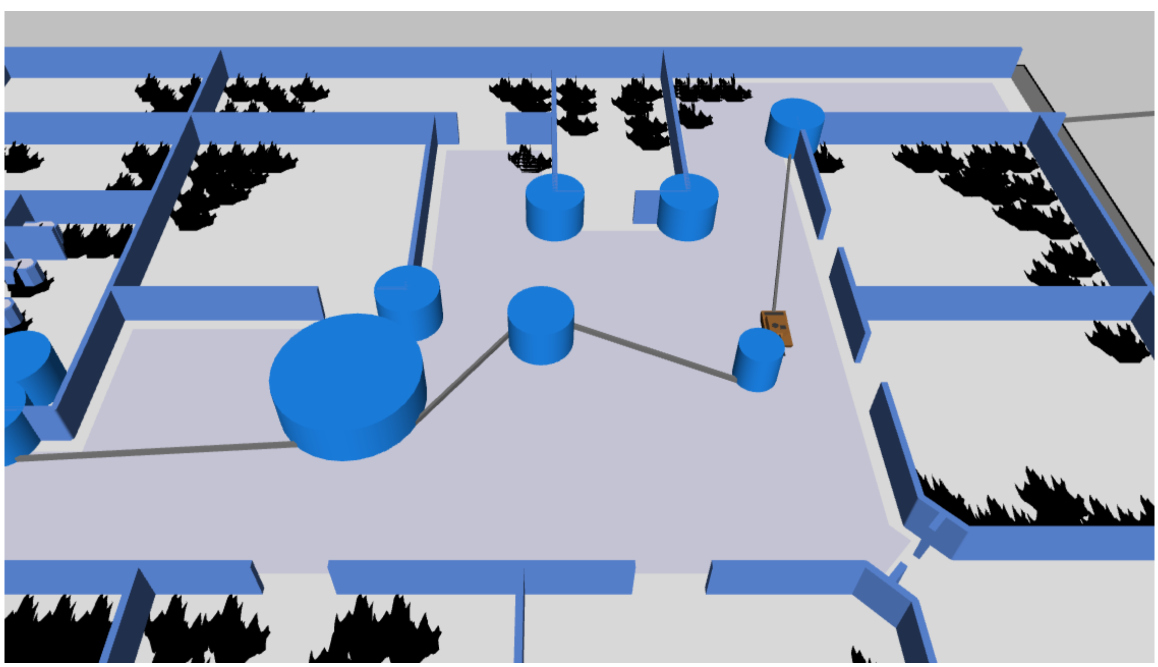
5.4 Endrunning Navigation Simulation Model

The endrunning navigation system is to enable firefighting robots to easily follow the optimal path and arrive at desired goals without interruption. The detail is that if firefighting robot with sub-robots approaches to the first obstacle, the first robot starts to give way by turning to the close direction to avoid a collision, Also, if the way is turning to the right, the robots keep turning right to avoid obstacles while they reach to the end of the alley. In addition, when the robots encounter in conflicting paths next to each other, the left robot turns right to yield.

Figure 5.8 shows the sub-robot operating without endrunning navigation method. The path trajectory made by the firefighting robot displays the robot freely moving to its destinations a lot with limit-cycle navigation method. Although the path trajectory is optimal, the fire hose has wastes some energy due to frictional force that occurs between the fire hose and three obstacles as well as a wall edge. In order to minimize the frictional force, the fire hose should decrease chances to meet obstacles. If the firefighting robot is able to use the endrunning navigation method, the chances of collision between a fire hose and obstacles could be minimized. Figure 5.9 shows the sub-robot operating with endrunning navigation. According to the rule of the endrunning navigation method, the firefighting robot will avoid the first obstacle by turning to the left, and the robot will keep avoiding other obstacles by turning to the left. In conclusion, the fire hose is able to avoid coming into a contact with an obstacle, so that the firefighting robot is able to minimize energy waste from frictional forces.

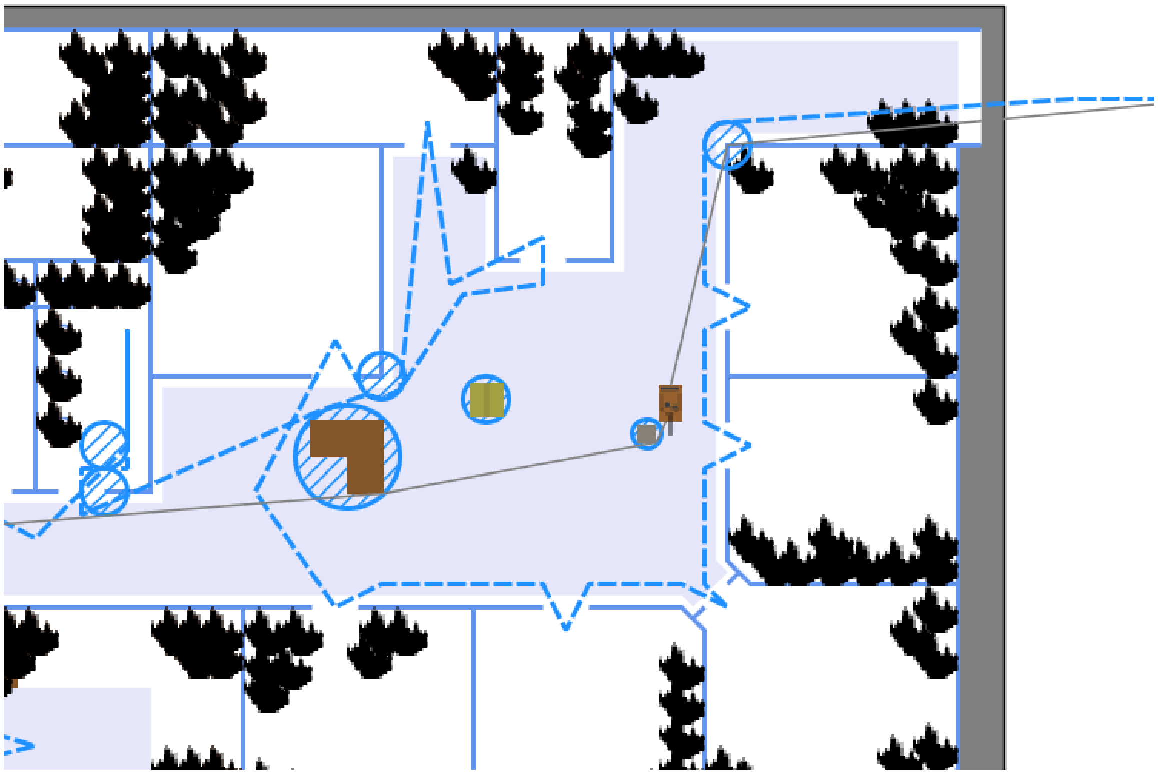


(a) With path trajectory in 2D

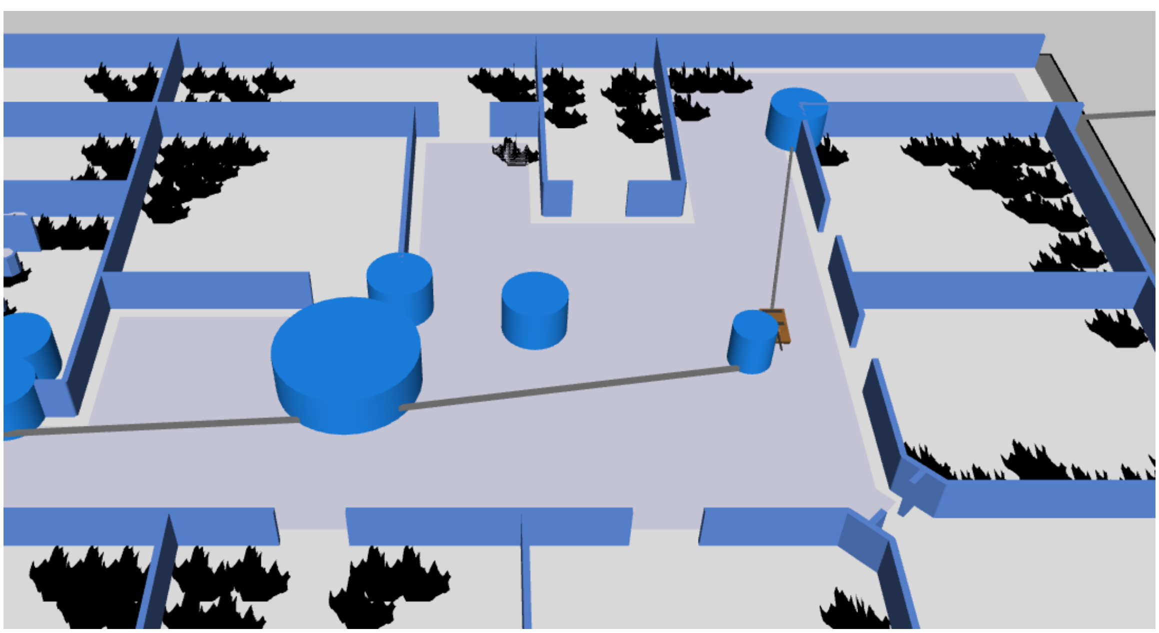


(b) Without path trajectory in 3D

Figure 5.8 Sub-robot operating without endrunning navigation method



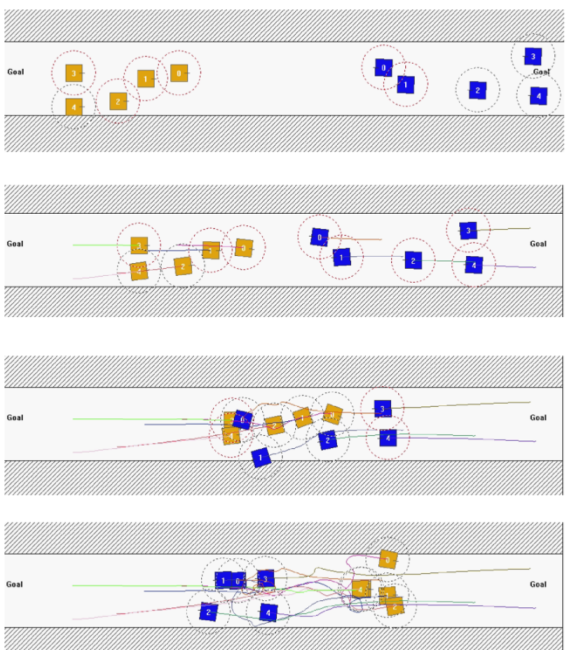
(a) With path trajectory in 2D



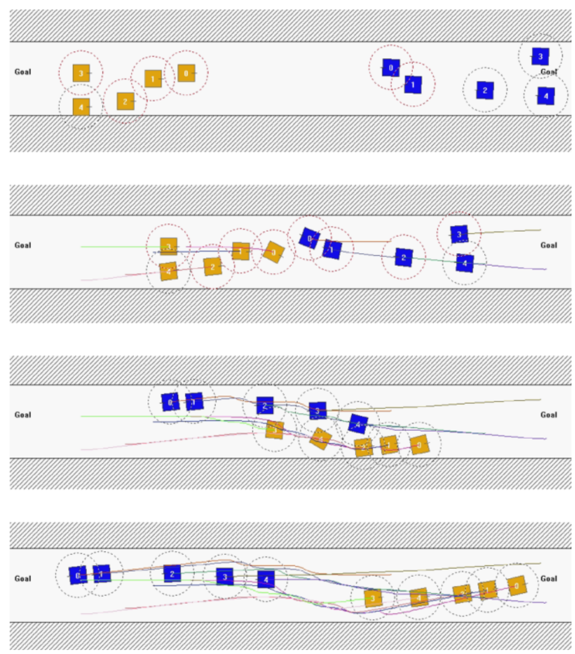
(b) Without path trajectory in 3D

Figure 5.9 Sub-robot operating with endrunning navigation method

The superiority of the endrunning navigation system is also verified by a soccer robot system in Figure 5.10. Because there are no static objects in this system, all robots are continuously moving toward their goals. Case 1 shows the shortest navigation method. Because all robots move to the close side to avoid obstacles, their trajectory is totally twisted. If fire hoses are connected among the robots, hoses will be twisted. On the other hand, Case 2 displays the endrunning navigation method. The first robot avoids the first obstacle, which is a robot coming from the opposite side, by turning to the right, and the robot keeps avoiding other obstacles by turning to right. As a result, a clear path for other robots is completed. Even if fire hoses connect the robots, all of them are able to avoid obstacles and reach the desired destination.



(a) Case 1: The shortest path



(b) Case 2: The endrunning path

Figure 5.10 An endrunning navigation method in soccer robot system

5.5 Discussion

In this chapter, the multi robot energy saving system (MRESS) that enhances firefighting time and range was presented. The limit cycle method, edge detecting limit cycle method and endrunning method decreased the chances of energy loss that results from being blocked and twisted by obstacles, so that the firefighting robot and sub-robot were able to extend their working range. As the range of fire becomes wider, the chance of a fire hose coming into contact with obstacles will be increased, Therefore, the fire hose could be held on the obstacles when the friction force is greater than the traction power of the firefighting robot. In conclusion, MRESS is very important for multi-robots system to save their energy and to extend the working range.

CHAPTER 6. FIRE SPREAD

This chapter presents a fire spread modeling to prepare for a fire situation. A fire spread model allows the optimal plan to be made by firefighters based on the fire spread to enable effective fire extinguishment in buildings. In this research, a statistical fire spread simulation modeling introduces a solution for fire accident prevention in a building. The fire spread is predicted by using statistical methods, such as bayesian network and decision tree. Additionally, the modeling methods are applied with various conditions: the fire ignition location, barrier failure probability, fire growth parameter, and backdraft. With the modeling, firefighters are able to expect the probability for location as well as growth of the fire. Particularly, firefighters are able to know the fire growth and spread in a layout exactly and economically. As a result, the firefighters are able to effectively suppress fires, leading to decreased mortality rate, property damages, and firefighting hours.

6.1 Statistical Fire Model

The fire spread can be designed by statistical information. When the information works with powerful prediction technology, the results are reliable. AnyLogic® is one of the powerful simulation software that allows exact prediction of the fire spread. Figure 6.1 shows the fire spread model. When a fire is ignited, the fire is able to spread in all directions. In order to set up this model, the directions are divided by eight directions.

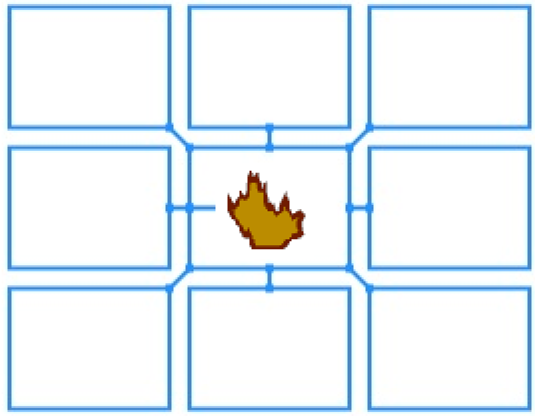


Figure 6.1 A fire spread

Figure 6.2 displays the fire spread process modeling. When the fire is ignited in the beginning, it moves to queue block to show the burning of the fire space. The burning activity in the queue block is managed by the delay1 block based on the fire growth parameter shown in Table 2.4. After the delay is finished, the probability will be decided by the elements of the new spots. The details are as below:

(1) The probabilities of barrier failure between the various building elements

- room to room (by wall) 0.81;
- room to room (by corridor) 0.84;
- room to stairwell, elevator (by wall) 0.57;
- room to stairwell, elevator (by corridor) 0.28;
- stairwell, elevator to room (by wall) 0.60.

(2) The probabilities of fire spread in compartment

- room 0.242
- stairwell, elevator shaft or duct 0.05.

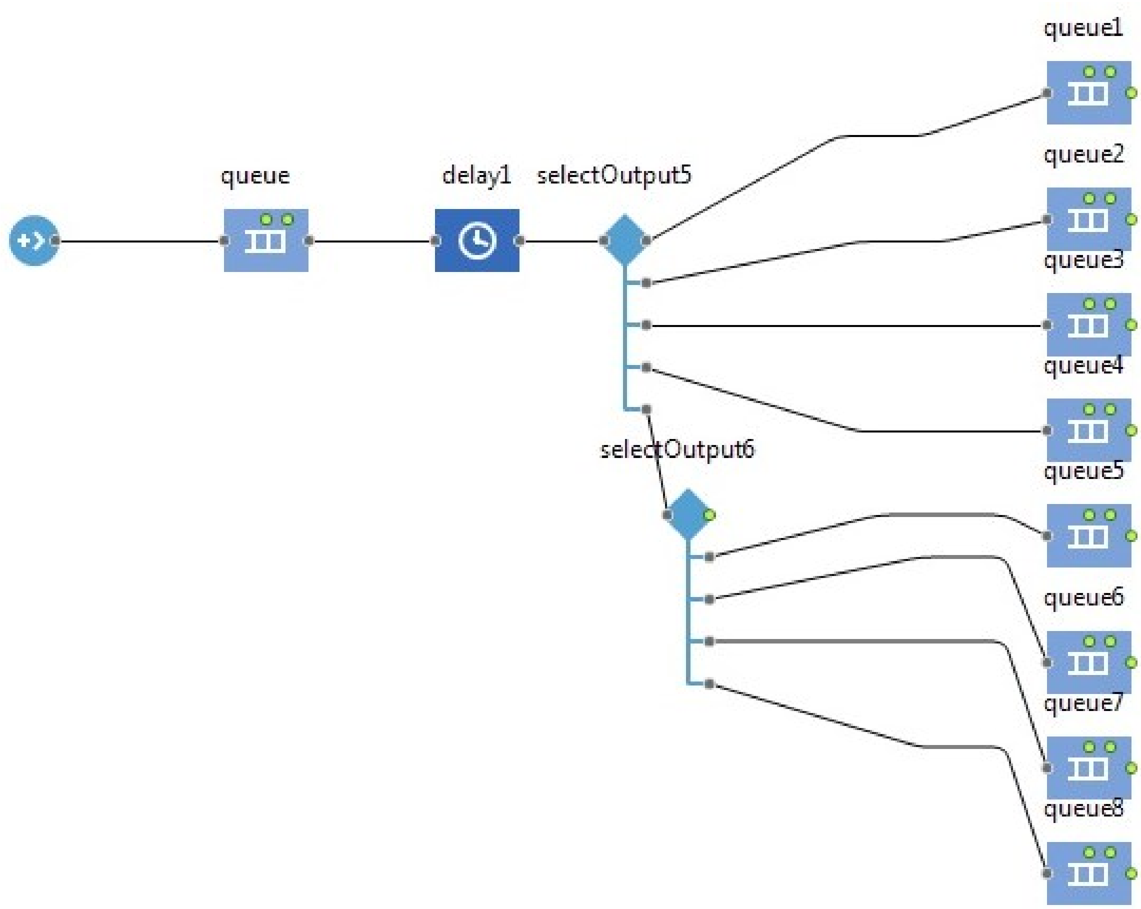


Figure 6.2 A fire spread process modeling

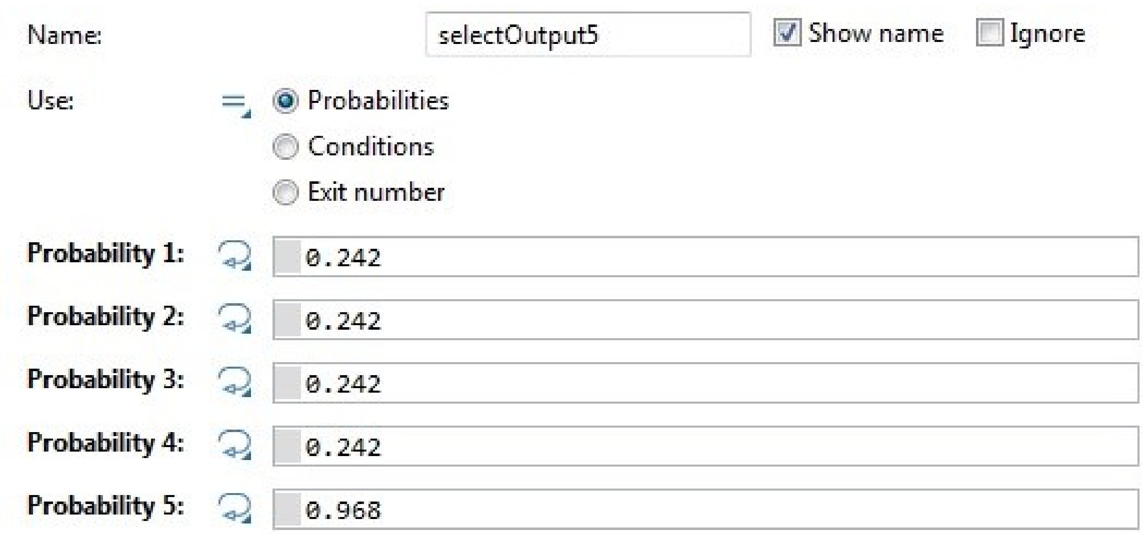


Figure 6.3 The probabilities of the fire model

Figure 6.3 shows the probabilities of the fire model. Because all elements of new spots are in the same room, the value of all probabilities are 0.242. Probability 5 represents the sum of queue 6, queue 7, queue 8, and queue 9, meaning that all directions are in the same room without fuel sources. Figure 6.4 displays the fire process modeling operation. The first space has 96 fires, and delay 1 block holds 8 fires to distribute the fires into eight directions. Selectoutputs block shows that how many fires move to each destination. The result shows that the fire spreads evenly because all destinations have same elements in the same room.

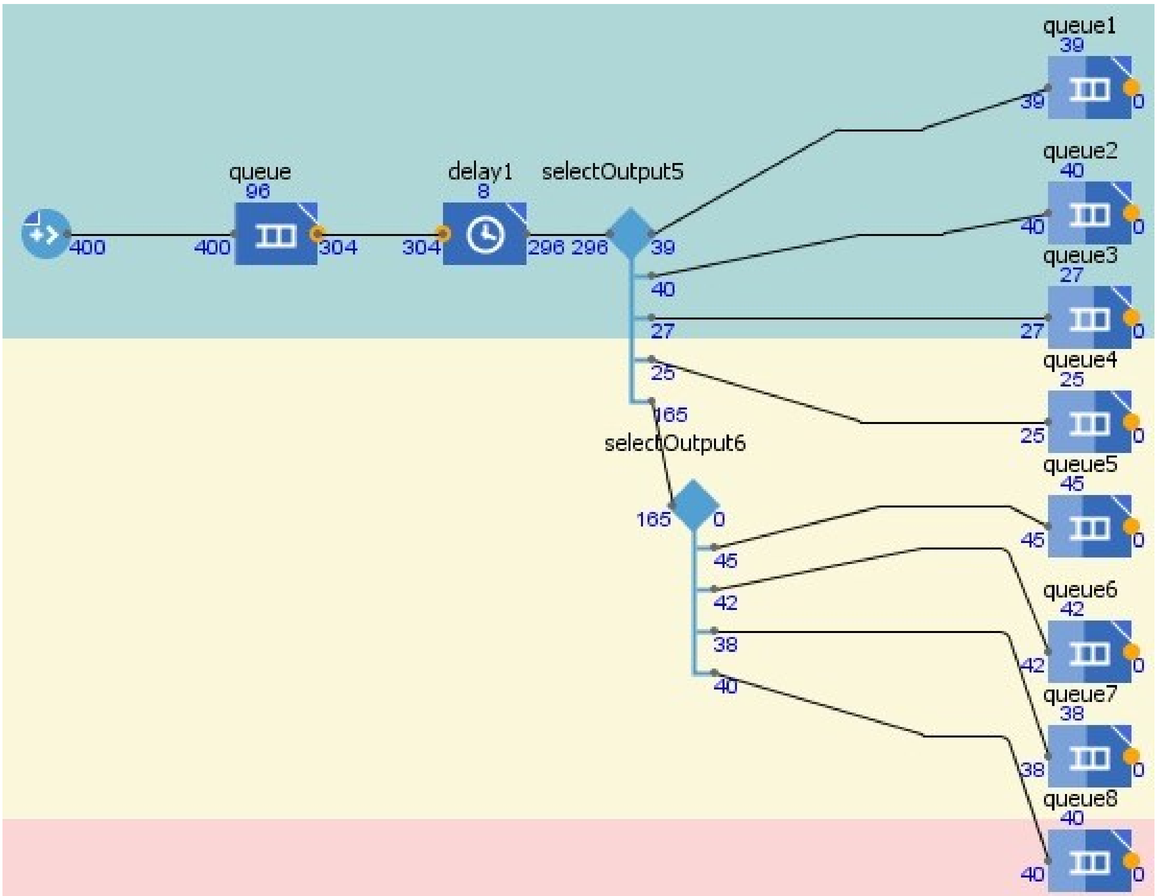


Figure 6.4 The fire process modeling operation

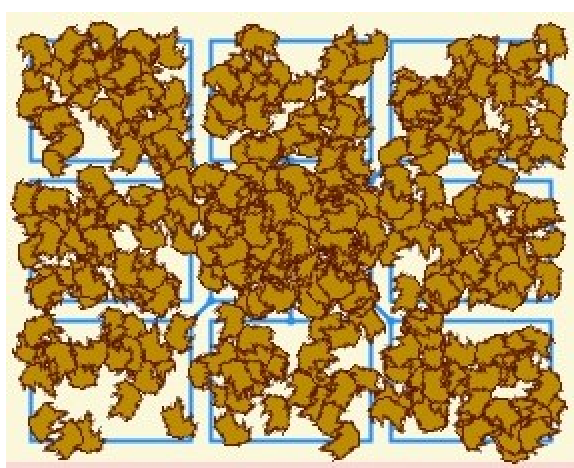


Figure 6.5 A fire spread result

6.2 Fire Agent Based Model

Anylogic® is one of the best software to design an agent based model. In order to prove excellence of the agent based model, two experiments were carried out for Anylogic® experiment and bayesian network. The experiment layout is shown in Figure 6.6.

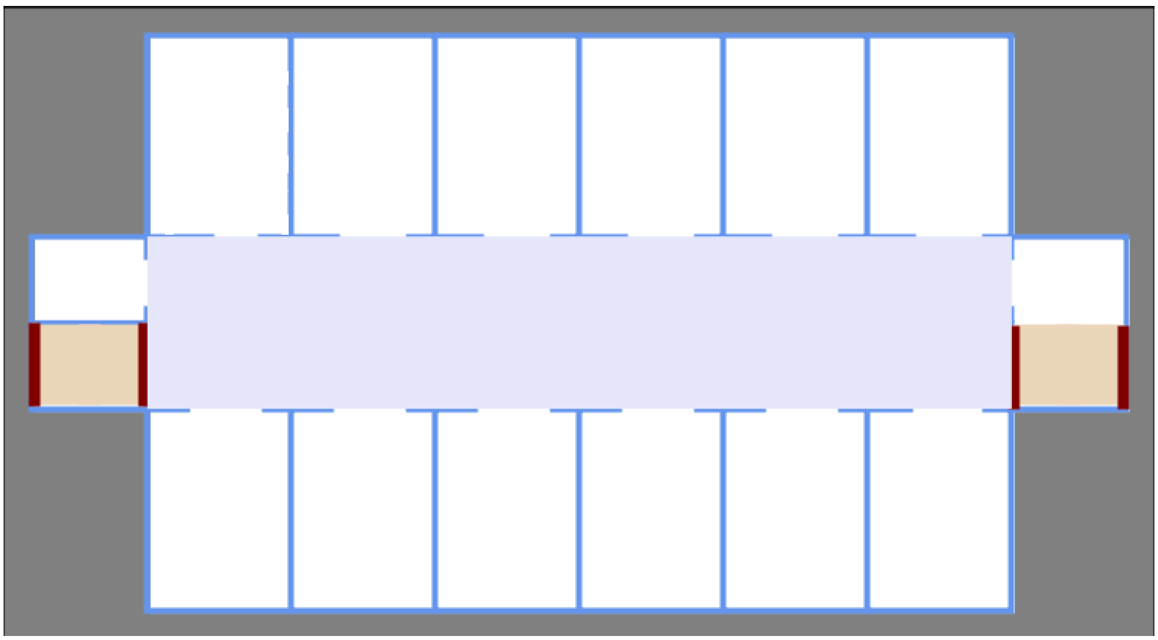


Figure 6.6 The floor layout of a building

First, the Bayesian network simplifies the layout, as shown Figure 6.7. Each compartment can be an element to spread fires, and the statistical information applies for the compartments. In conclusion, the Bayesian network makes results by calculating the probabilities between each compartment. The results are shown in Figure 6.8.

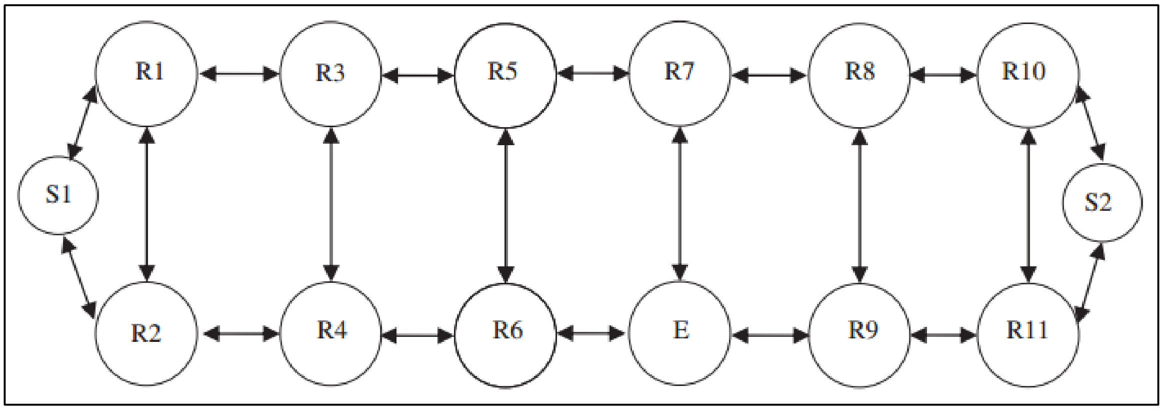


Figure 6.7 The simplified fire spread (Cheng et al., 2011)

Node	Fire spread probability
R_1	$P(r_1) = 1, P(\tilde{r}_1) = 0$
S_1	$P(s_1 \mid r_1) = 0.0285, P(s_1 \mid \tilde{r}_1) = 0$
R_2	$P(r_2 \mid r_1, \tilde{s}_1) = 0.20328, P(r_2 \mid \tilde{r}_1, s_1) = 0.1452, P(r_2 \mid r_1, s_1) = 0.226512, P(r_2 \mid \tilde{r}_1, \tilde{s}_1) = 0$
R_3	$P(r_3 \mid r_1, \tilde{r}_4) = 0.19602, P(r_3 \mid \tilde{r}_1, r_4) = 0.20328, P(r_3 \mid r_1, r_4) = 0.2346432, P(r_3 \mid \tilde{r}_1, \tilde{r}_4) = 0$
R_4	$P(r_4 \mid r_2, \tilde{r}_3) = 0.19602, P(r_4 \mid \tilde{r}_2, r_3) = 0.20328, P(r_4 \mid r_2, r_3) = 0.2346432, P(r_4 \mid \tilde{r}_2, \tilde{r}_3) = 0$
R_5	$P(r_5 \mid r_3) = 0.19602, P(r_5 \mid \tilde{r}_3) = 0$
R_6	$P(r_6 \mid r_4, \tilde{r}_5, \tilde{e}) = 0.19602, P(r_6 \mid \tilde{r}_4, r_5, \tilde{e}) = 0.20328, P(r_6 \mid \tilde{r}_4, \tilde{r}_5, e) = 0.1452, P(r_6 \mid r_4, r_5, \tilde{e}) = 0.2346432, P(r_6 \mid r_4, \tilde{r}_5, e) = 0.223608,$ $P(r_6 \mid \tilde{r}_4, r_5, e) = 0.226512, P(r_6 \mid r_4, r_5, e) = 0.23905728, P(r_6 \mid \tilde{r}_4, \tilde{r}_5, \tilde{e}) = 0$
R_7	$P(r_7 \mid r_5) = 0.19602, P(r_7 \mid \tilde{r}_5) = 0$
E	$P(e \mid r_7, \tilde{r}_9) = 0.014, P(e \mid \tilde{r}_7, r_9) = 0.0285, P(e \mid r_7, r_9) = 0.03452, P(e \mid \tilde{r}_7, \tilde{r}_9) = 0$
R_8	$P(r_8 \mid r_7) = 0.19602, P(r_8 \mid \tilde{r}_7) = 0$
R_9	$P(r_9 \mid r_8, \tilde{r}_{11}) = 0.20328, P(r_9 \mid \tilde{r}_8, r_{11}) = 0.19602, P(r_9 \mid r_8, r_{11}) = 0.2346432, P(r_9 \mid \tilde{r}_8, \tilde{r}_{11}) = 0$
R_{10}	$P(r_{10} \mid r_8) = 0.19602, P(r_{10} \mid \tilde{r}_8) = 0$
R_{11}	$P(r_{11} \mid r_{10}, \tilde{s}_2) = 0.20328, P(r_{11} \mid \tilde{r}_{10}, s_2) = 0.1452, P(r_{11} \mid r_{10}, s_2) = 0.226512, P(r_{11} \mid \tilde{r}_{10}, \tilde{s}_2) = 0$
S_2	$P(s_2 \mid r_{10}) = 0.0285, P(s_2 \mid \tilde{r}_{10}) = 0$

Figure 6.8 The fire spread result (Cheng et al., 2011)

On the other hand, Anylogic® software designs a fire agent model based on its size. If Anylogic® uses the simplified layout from the Bayesian network, the fire agent would be very big, as shown in Figure 6.9. In this case, the probabilities for all compartments also can be calculated, but it is not efficient for this software.

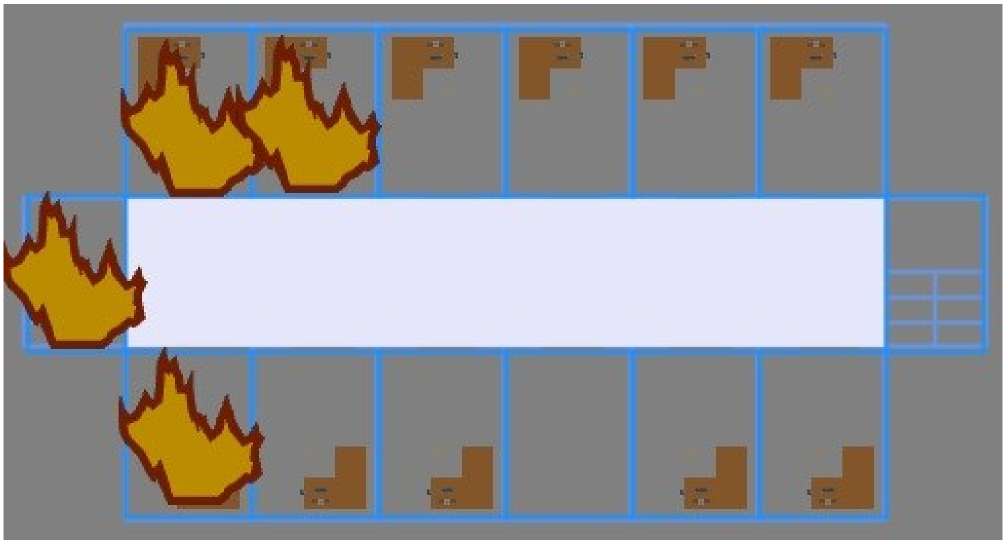


Figure 6.9 The AnyLogic® simulation by simplified layout

Although Anylogic® software designs the fire spread model among compartments, each compartment has lots of fire agents. The number of fires can demonstrate the flow and power of fires. The experiment result is shown in Figure 6.10.

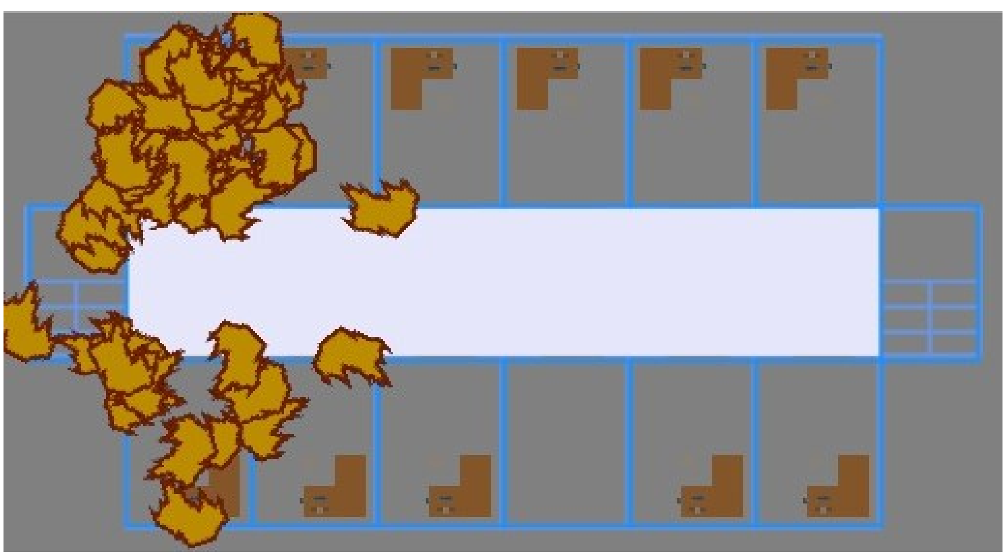


Figure 6.10 The AnyLogic® experiment on building floor

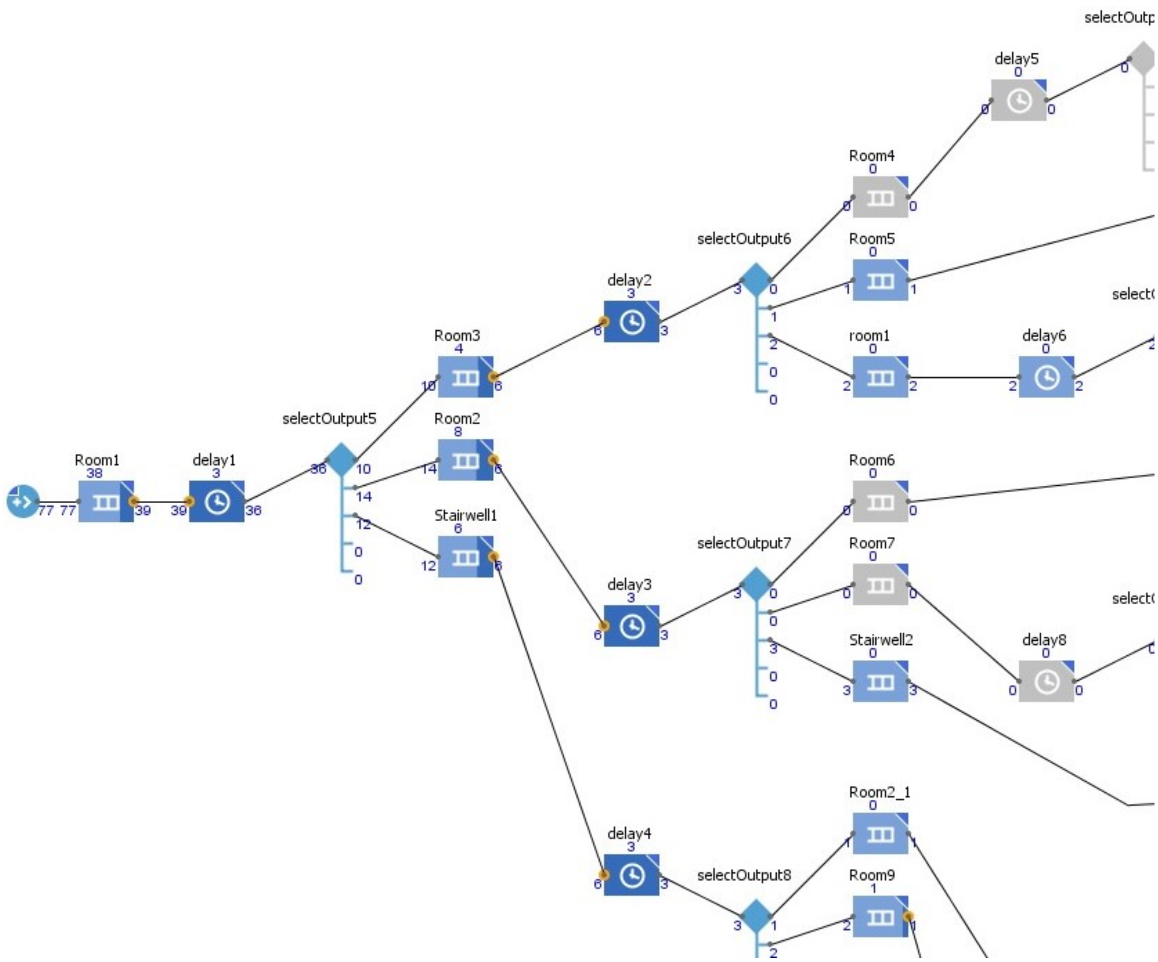


Figure 6.11 The fire spread process on floor

Figure 6.11 displays the fire spread process on floor. When the fire is ignited in room 1 in the beginning, delay1 block manages the speed of fire spread. Then, the seletoutput block spreads the fires to room2, room3, and stairwall1 by the statistical information. When the fire spreads to room2, room3 and stairwell1, they also start to work like room1. The fires continuously spread to adjacent compartments, and the results show not only fire spread probabilities, but also the amount of fires, the fire flow, and fire spread time.

6.3 Time Based Fire Model

Anylogic® agent based model is also good for time management. The management is controlled by delay block, as shown in Figure 6.12.

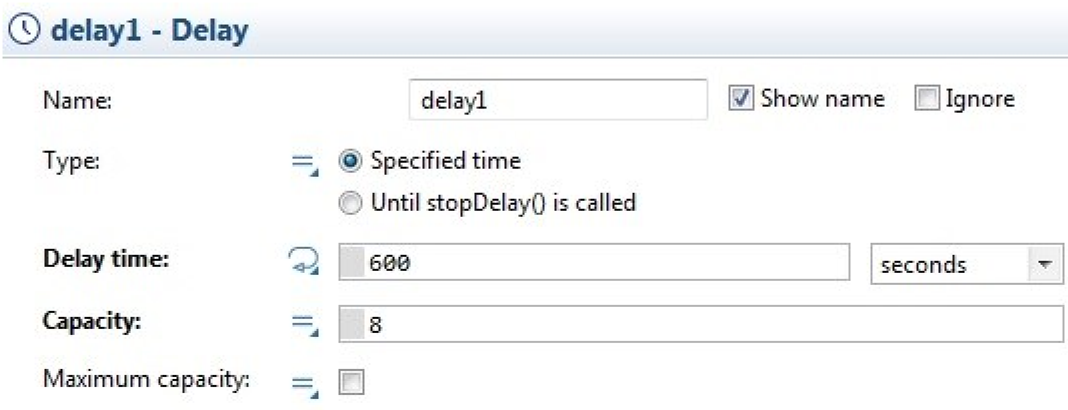


Figure 6.12 The delay block variables

The delay block controls not only delay time but also capacity. Therefore, fires are able to work for a designed amount of time and spread to adjacent blocks at the same time. In conclusion, fire spread per hour can be predicted. Figure 6.13, Figure 6.14 and Figure 6.15 address the fire spread in an interval of 20 minutes. Figure 6.13 shows that some of the fires accelerate their speed by fuels such as desk and chair. In addition, the fires on the wall try to penetrate walls. Because the fire spread probability of an outer wall is zero, the fires are able to penetrate toward walls of adjacent rooms. Figure 6.14 shows the fire spread after forty minutes. Although some fires moved to the stairway, fires on the right wall could not penetrate the wall. Figure 6.15 displays the fire spread after sixty minutes. Fires on the right side get enough speed by using the fuels. However, the fires on the left side maintain their speed due to absence of fuels.

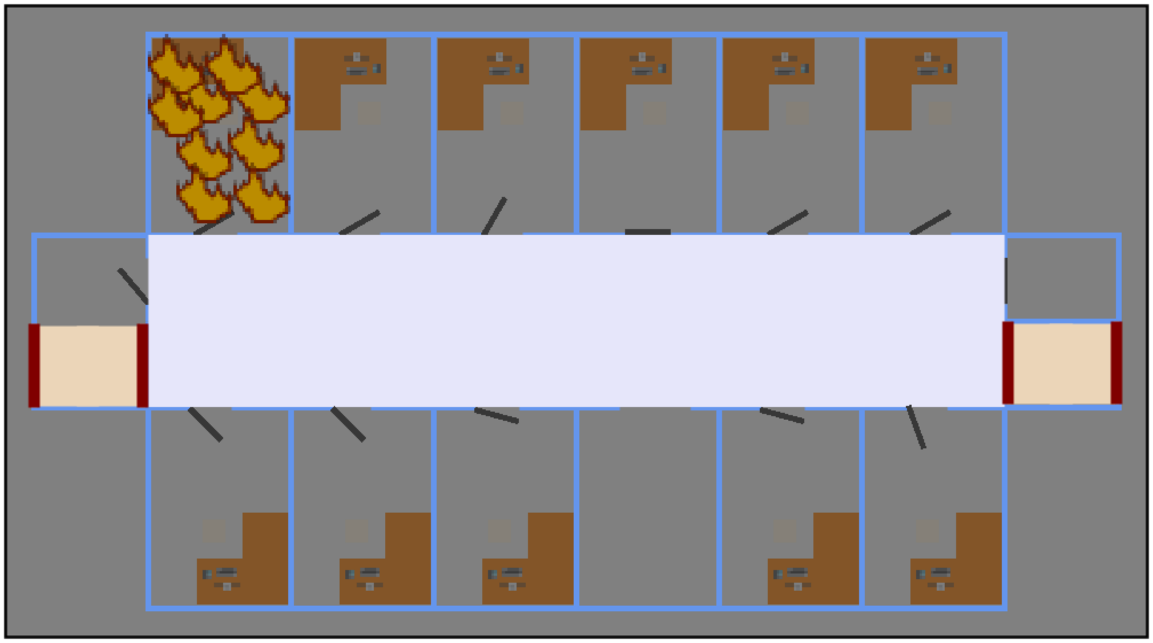


Figure 6.13 Fire spread for twenty minutes

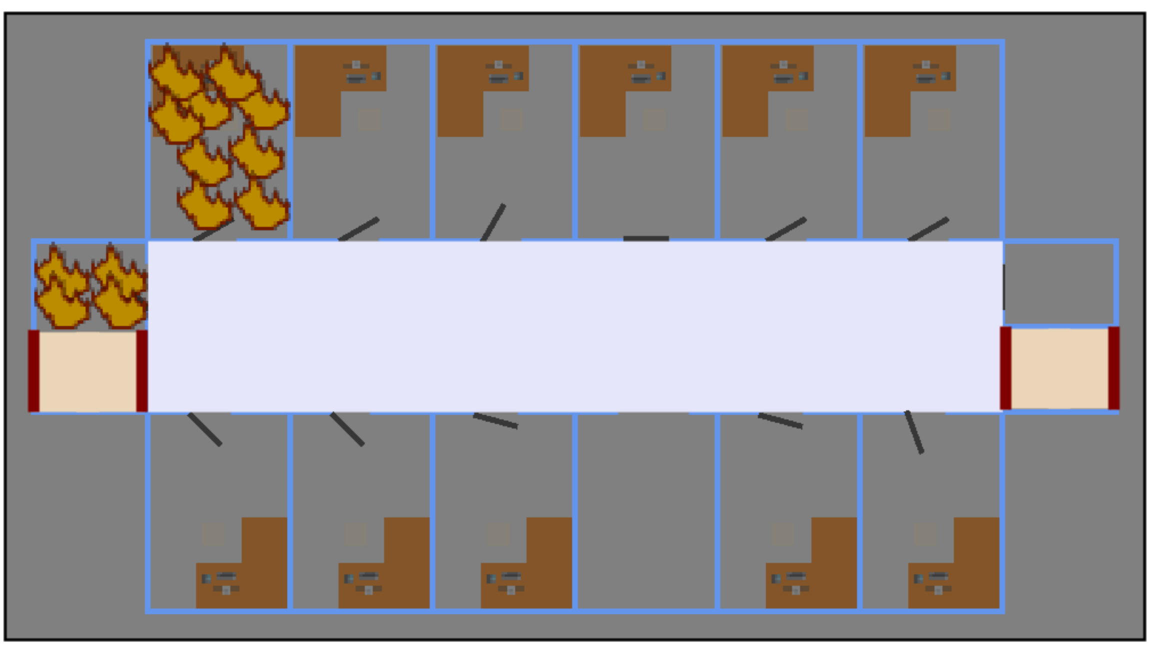


Figure 6.14 Fire spread for forty minutes

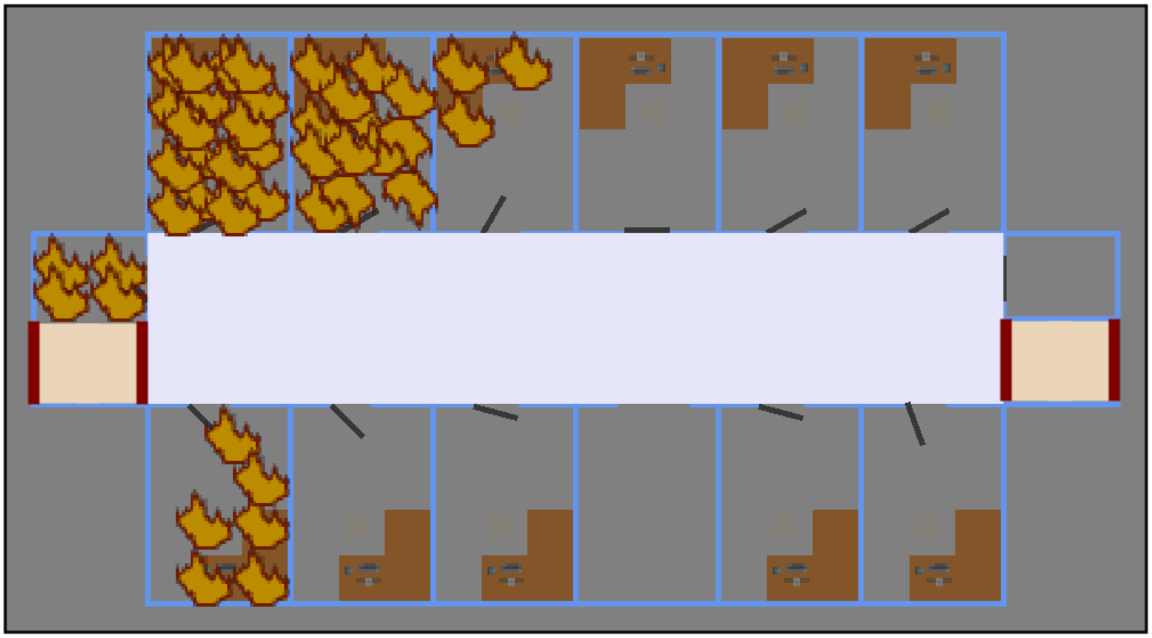


Figure 6.15 Fire spread for sixty minutes

6.4 Discussion

In this chapter, the statistical fire spread model was designed by Anylogic® software. The process based fire model provides reliable information, including not only probability but also the amount of fire, fire flow and fire spread time. If a building risk analysis system can be designed by Anylogic® software based statistical model, the building is able to prevent fire, and to overcome fire disaster.

CHAPTER 7. FIREFIGHTING ROBOT DRIVE CYCLES

Most vehicles usually repeat some patterns or routes while they are driving on various roads. Based on this information, vehicle companies set up the fuel efficiencies for their vehicles. Among the methods for determining fuel efficiency, the drive cycle is one of the best methods to evaluate the automobile efficiency (Martyr et al., 2011). The standard drive cycles such as the Los Angeles drive cycle and Highway Fuel Economy Test drive cycle are generalized cycles that can predict average fuel efficiencies of vehicles. A firefighting robot, however, has no standard drive cycles to determine the fuel efficiencies because it works in uncommon areas. Based on various firefighting robot experiment results, a novel drive cycle is able to be set up for a firefighting robot.

7.1 Concentrated Fires Experiment

The existing drive cycle has evaluated the fuel efficiencies based on distance, total time, average speed, and maximum speed. This is because the most vehicles only have one variable: a speed. On the other hand, the firefighting robot has two variables to evaluate its energy efficiency: energy use for movement and water shooting. Therefore, the novel drive cycle is completed based on distance, total time, and energy use for movement and water shooting. Figure 7.1, Figure 7.2, and Figure 7.3 demonstrate the energy use by the firefighting robot for three types of operation in concentrated fire area that was shown in Figure 4.10.

The original firefighting robot worked, as shown in Figure 7.1. In the beginning, the robot moved to a spot for firefighting that is about 38 meters away from the starting point. At this time, the robot used 24V/5.841Ah. Then, the robot extinguished about 520 fires and came back to the starting point with the battery use of 24V/26.6Ah. After the battery was discharged, the performance data for the robot's drive cycle was set up based on the firefighting robot operation, as listed below:

- Total distance: 90 meters
- Total time: 1.5 hours
- Energy use for movement: 24V/0.6Ah
- Energy use for water shooting: 24V/39.4Ah

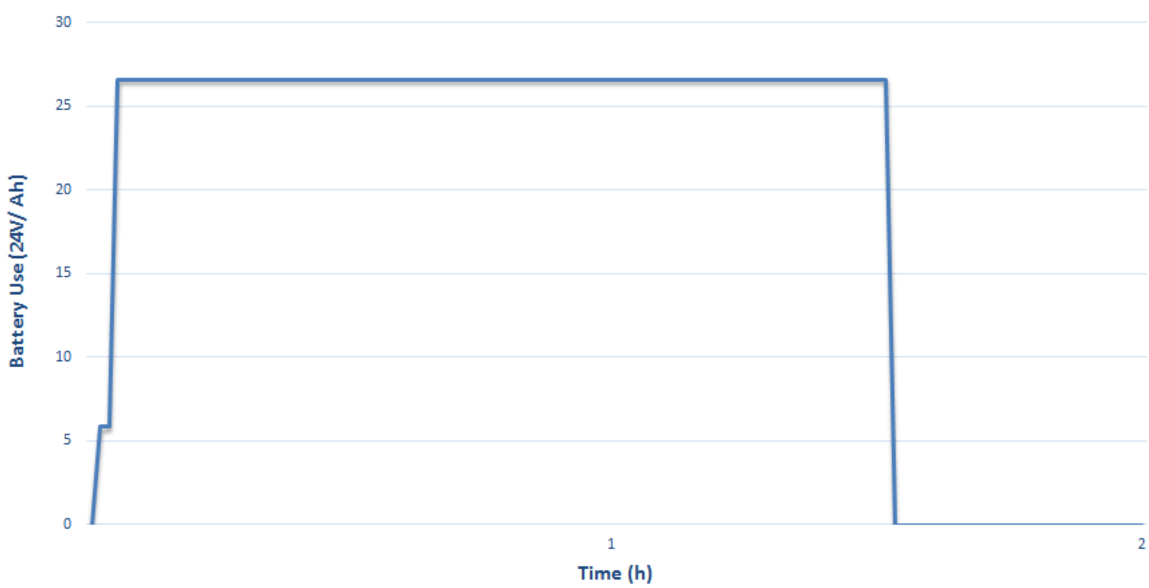


Figure 7.1 The Original Firefighting Robot Operation in Concentrated Fire area

Figure 7.2 shows the firefighting robot working with ATS. Like the original firefighting robot, the robot moved 38 meters from the starting point to a firefighting spot by using 24V/5.841Ah. Then, the robot extinguished about 520 fires with the battery use of 24V/26.6Ah. On the other hand, when the robot came back to the starting point, the ATS discharged water from the fire hose. This time, the robot only used 24V/5.841Ah of battery. As a result, the performance data to set up the drive cycle of the firefighting robot with ATS was determined, as shown below:

- Total distance: 300 meters
- Total time: 1.55 hours
- Energy use for movement: 24V/0.6Ah
- Energy use for water shooting: 24V/39.4Ah

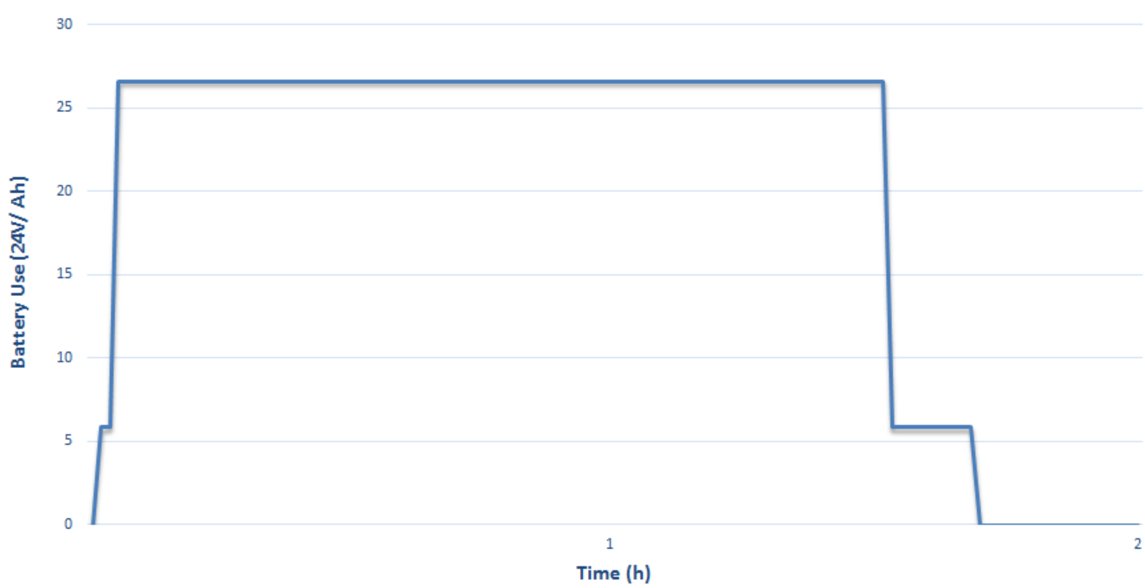


Figure 7.2 The ATS Firefighting Robot Operation in Concentrated Fire area

Figure 7.3 shows the NDFR working with ATS. This robot also moved 38 meters from the starting point to a firefighting spot, but using 24V/5.121Ah for movement. Then, the robot extinguished about 520 fires with the battery use of 24V/26.6Ah. When the robot came back to the starting point, the ATS also worked for discharging water from the fire hose, using 24V/5.121Ah of battery. As a result, the performance data for the NDFR with ATS is set up for its drive cycle, as below,

- Total distance: 315 meters
- Total time: 1.57 hours
- Energy use for movement: 24V/0.6Ah
- Energy use for water shooting: 24V/39.4Ah

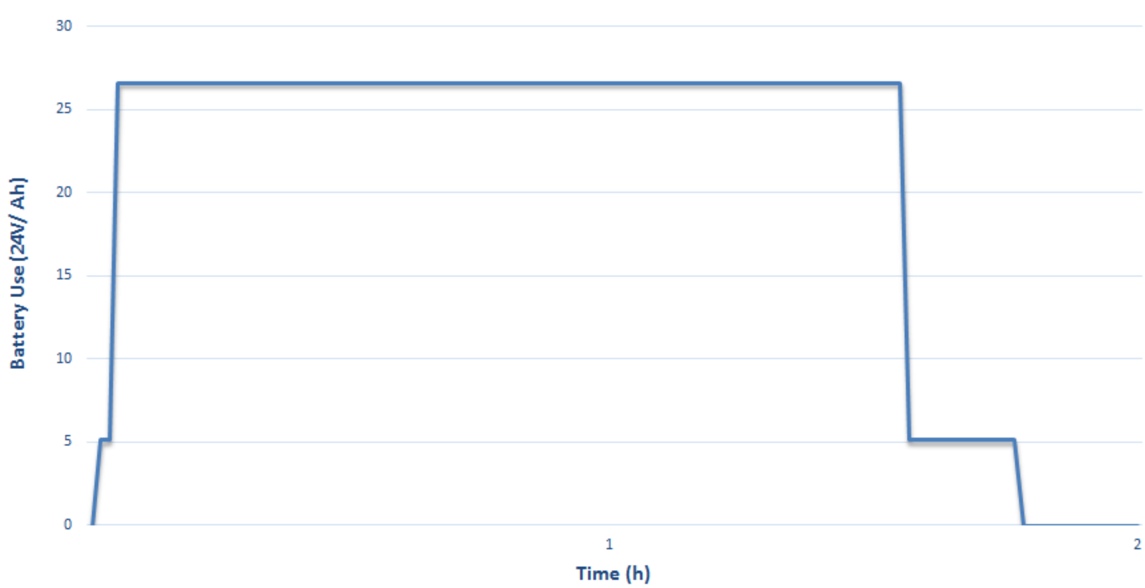


Figure 7.3 The NDFR with ATS Operation in Concentrated Fire area

7.2 Scattered Fires Experiment 1

Figure 7.4, Figure 7.5, and Figure 7.6 show the energy use by the firefighting robot for three types of firefighting robot operation in scattered fire area that was shown in Figure 4.11. Figure 7.4 shows the original firefighting robot operation. Because the robot should extinguish fires at the starting point, it had used 24V/26.6Ah of battery from start to finish. As a result, the performance data of the original firefighting robot was simply set up for its drive cycle, as listed below:

- Total distance: 40 meters
- Total time: 1.5 hours
- Energy use for movement: 24V/0.3Ah
- Energy use for water shooting: 24V/39.7Ah

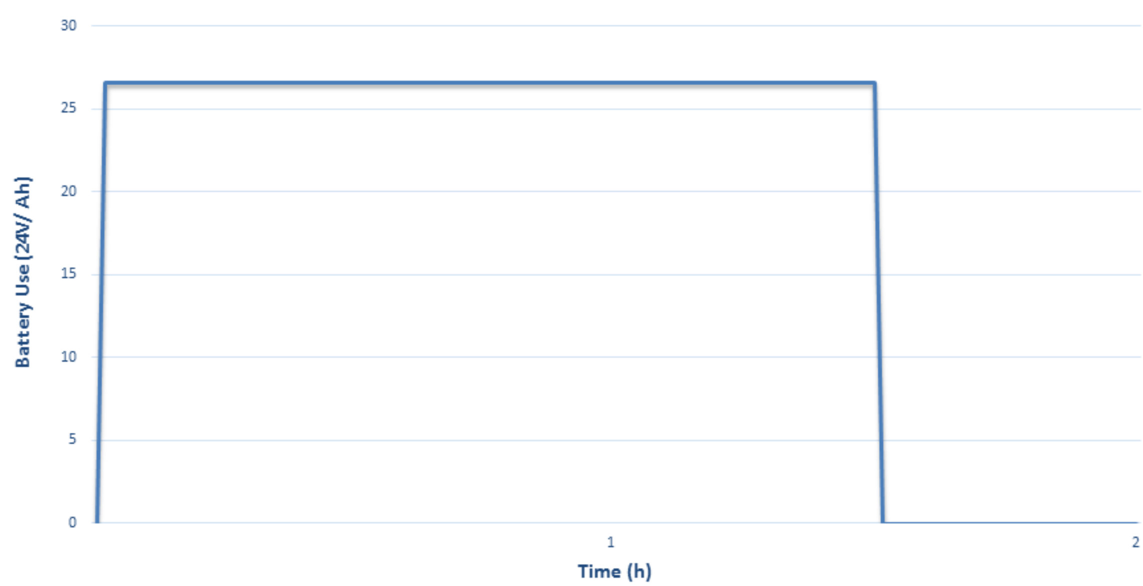


Figure 7.4 The Original Firefighting Robot Operation in Scattered Fire area

Figure 7.5 shows the firefighting robot working with ATS. Like the original firefighting robot, the robot should extinguish fires from the starting point. However, the ATS is able to expel the charged water out of the fire hose whenever the robot changes its mode from firefighting to moving, so that the robot can minimize its energy loss. A lot of curves in the figure prove the energy saving. As a result, the performance data for the robot with ATS is set up for its drive cycle, as below:

- Total distance: 50 meters
- Total time: 1.65 hours
- Energy use for movement: 24V/0.2Ah
- Energy use for water shooting: 24V/39.8Ah

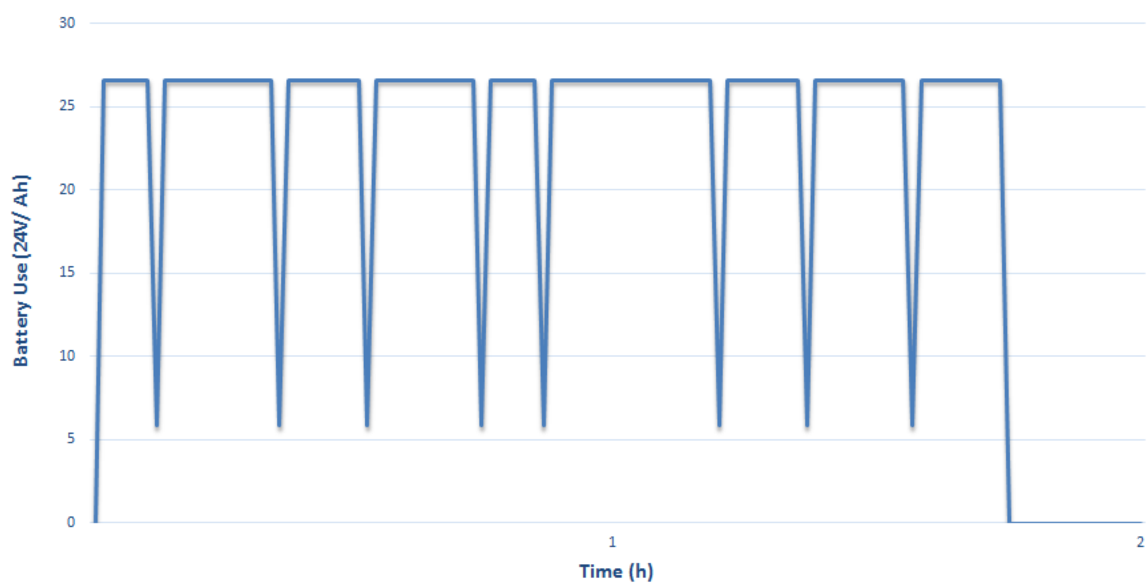


Figure 7.5 The Firefighting Robot Operation with ATS in Scattered Fire area

Figure 7.6 shows the NDFR working with ATS. Because this robot uses 24V/5.121Ah for movement, the robot moved 60 meters for firefighting. Like the ATS firefighting robot, the ATS is able to expel the charged water of a fire hose whenever the robot changed its mode from firefighting to moving, so that the robot can minimize its energy loss. In conclusion, the performance date for the robot with ATS is set up for its drive cycle, as below,

- Total distance: 60 meters
- Total time: 1.7 hours
- Energy use for movement: 24V/0.15Ah
- Energy use for water shooting: 24V/39.85Ah

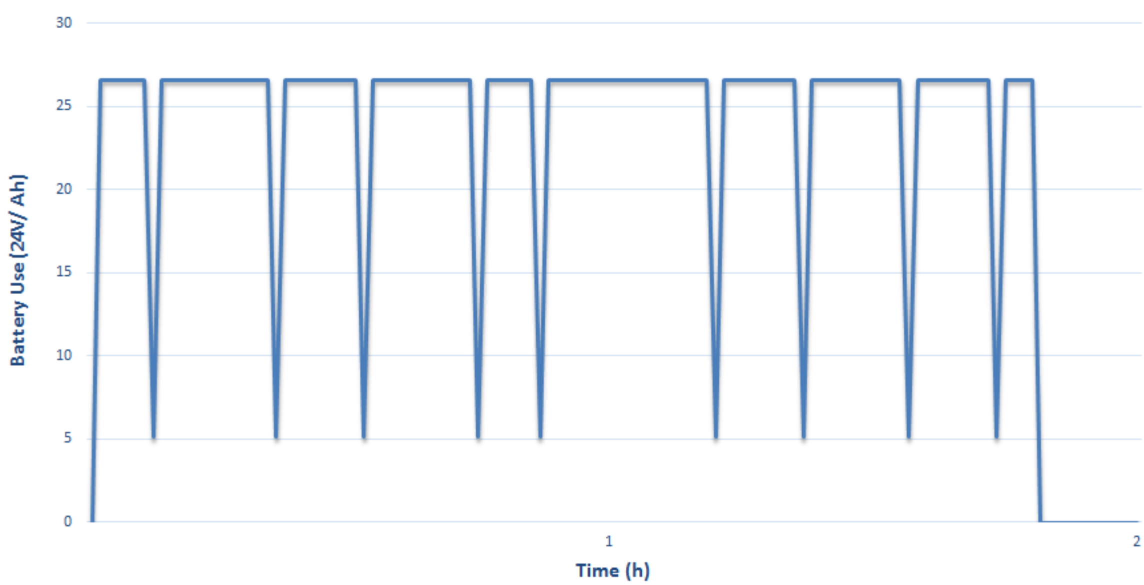


Figure 7.6 The NDFR Operation with ATS in Scattered Fire area

7.3 Scattered Fires Experiment 2

Figure 7.7 and Figure 7.9 illustrate new layouts to prove the energy saving for robot movement. Because the number of fires are decreased, the firefighting robot is able to extinguish all fires and operate for a longer time. In addition, the robot is able to operate for additional fire suppression in a large area. Figure 7.8 displays the operation of the NDFR with sub-robot. Because the robot extinguishes fires in a short time, the robot is able to patrol for additional fire suppression by using 24V/5.121Ah of battery power. In conclusion, the performance date for the robot with sub-robot is set up for its drive cycle, as below:

- Total distance: 17 km
- Total time: 4.3 hours
- Energy use for movement: 24V/20Ah
- Energy use for water shooting: 24V/20Ah

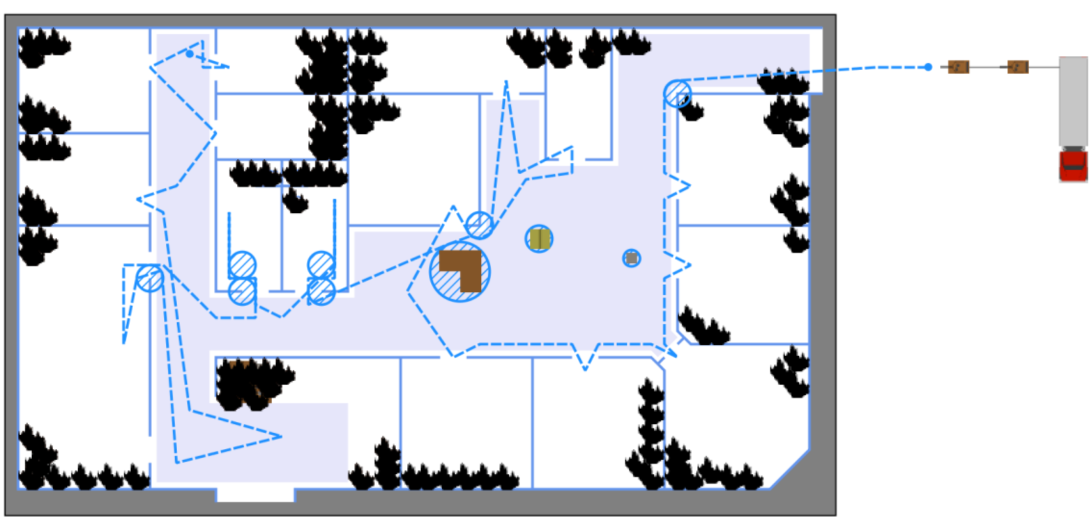


Figure 7.7 The NDFR Operation with sub-robot in Scattered Fire area

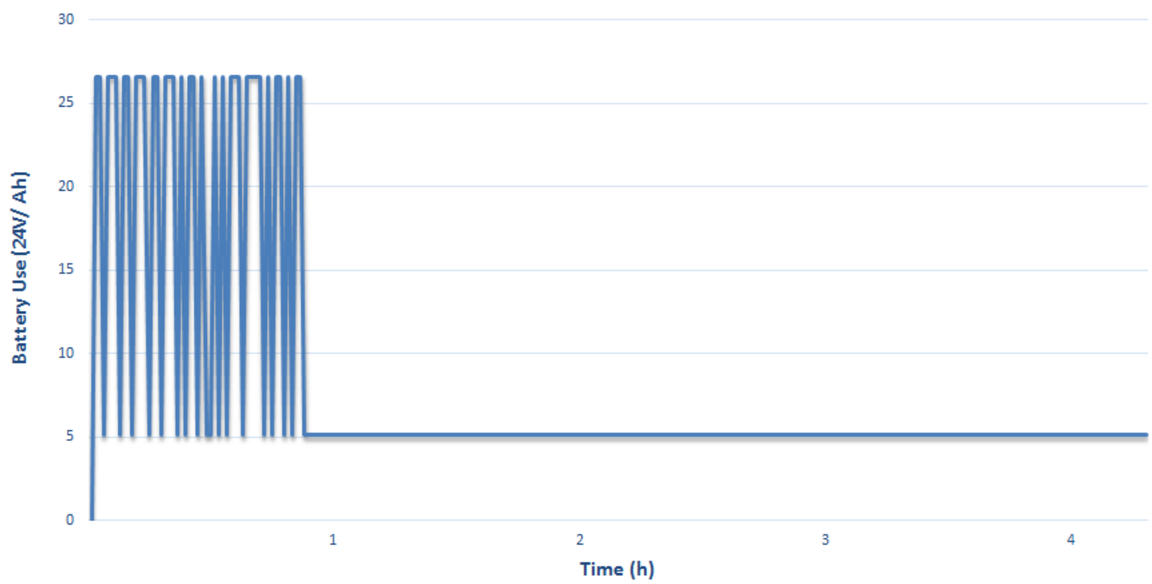


Figure 7.8 The drive cycle for NDFR with ATS in Scattered Fire area

Figure 7.9 has no fires. Therefore, the firefighting robot with sub-robot is able to focus on the patrol, so that it operates for the longest time. The robot has moved only for additional fire suppression using 24V/5.121Ah of battery power. Because the sub-robot used MRESS, there was no energy loss from being blocked by obstacles. In conclusion, the performance data for the robot with sub-robot is set up for its drive cycle, as below:

- Total distance: 31.24 km
- Total time: 7.81 hours
- Energy use for movement: 24V/40Ah
- Energy use for water shooting: 24V/0Ah

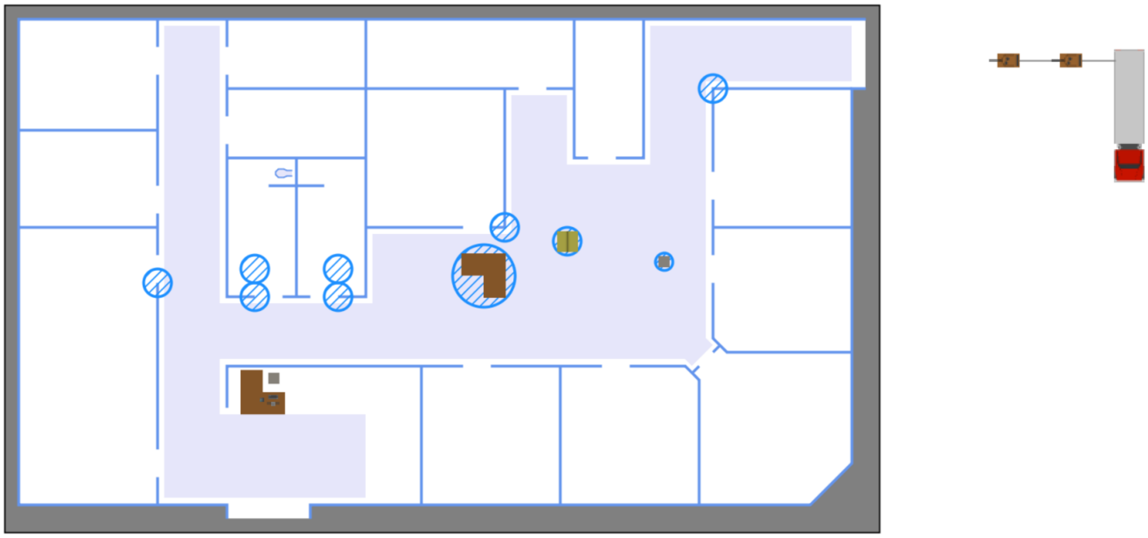


Figure 7.9 The NDFR Operation with ATS in empty Area

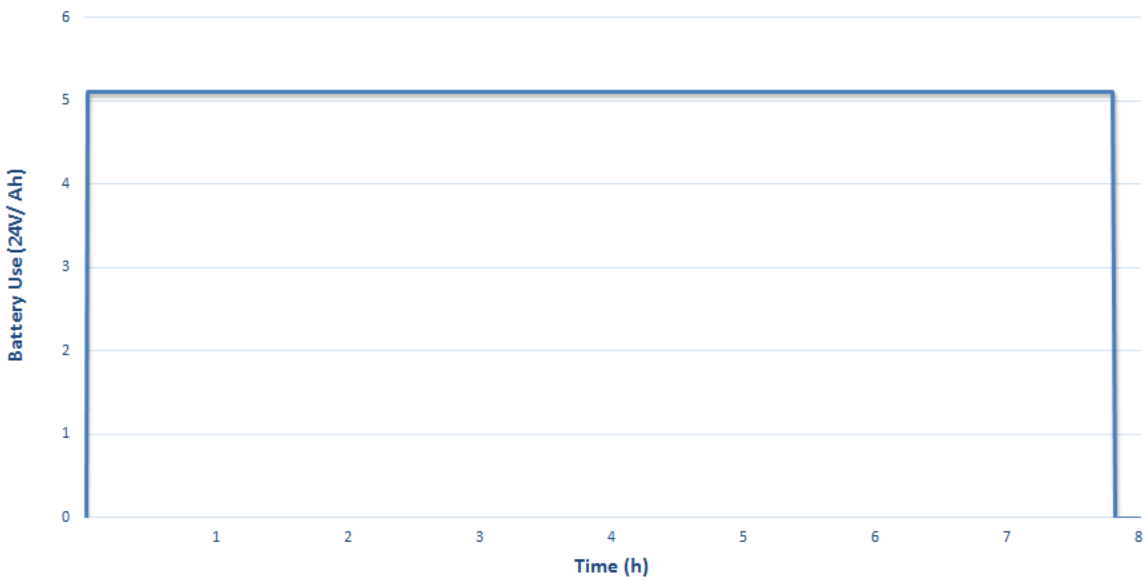


Figure 7.10 The drive cycle for NDFR with ATS in empty Area

7.4 Discussion

The firefighting robot drive cycle is studied in this chapter. Because the existing drive cycle has difference values of fuel efficiency for different speeds, it needs to check the difference in fuel efficiency from a couple of areas. One the other hand, the fuel efficiency of the firefighting robot is not affected by the speed or water shooting. The robot just has a fixed speed of 4 km/h for movement and a fixed energy use of 24V/26.66 Ah for water shooting. Therefore, the average fuel efficiency by drive cycle is easily determined, as shown in Table 7.1.

Table 7.1 The Firefighting Robot Drive Cycles

Characteristics	**Unit**	**Original firefighting robot**	**With ATS**	**NDFR with ATS**
Maximum working distance	Km	6	27.36	31.24
Maximum working time	H	1.5	6.84	7.81
Movement energy	24V/ Ah	26.66	5.841	5.121
Water shooting energy	24V/ Ah	26.66	26.66	26.66
Average fuel efficiency	24V/ Ah	26.66	16.25	15.89

CHAPTER 8. CONCLUSION

In this research, the battery management systems (BMS) for firefighting robots are studied. The BMS are intended to enable firefighting robots to increase operating time and to effectively extinguish a fire while managing the amount of water in a fire hose and cooperating with sub-robots. To increase the working hours by enhancing the traction power for the main firefighting robot, a novel automatic T-valve device and sub-robots were designed and added to fire hoses. The main goal of the BMS for firefighting robots is to lower the weight of the fire hose and to increase traction power by working with sub-robots. Whenever a firefighting robot wants to move to other locations, the battery management systems will remove the water from fire hoses and draw the empty fire hoses; thus, they allow the main robot to carry lighter hoses and to operate for a longer time.

8.1 Result Analyses

The firefighting robot model showed changes in energy efficiency for each robot. Figure 8.1 shows the operating hours and ranges for each firefighting robot. Since all robots are able to move at a speed of 4km/h, the original firefighting robot is able to work up to 1.5 hours and as far as 6 km. When the robot sets up a ATD on its fire hose, the robot is able to increase its working hours up to 6.84 hours. Therefore, the robot can move up to 27.36 km, if the robot focus on moving for fire monitoring. In addition, the NDFR is able to decrease energy loss by making a space in the robot. Therefore, the robot is able to work up to 31.24 km, if the robot focuses on moving for fire monitoring.

Table 8.1 Operating Time and Range for the Firefighting Robot

Characteristics	Time(hours)	Range(km)	Radius(meters)
The firefighting robot	1.5	6	60
Working with T-valve	6.84	27.36	60
NDFR with T-valve	7.81	31.24	60
With a sub-robot	7.81	31.24	120

For the firefighting in the large area, the length of the fire hose is very crucial. Therefore, the sub-robot was designed and added onto a fire hose. The sub-robot is able to draw additional fire hose of 60 meters, and follow the firefighting robot. Therefore, the working radius for the sub-robot increases by 60 meters per one unit of sub-robot. These superior results are from AWMS and MRESS.

An automatic water management system (AWMS) has worked for a firefighting robot battery management. The AWMS is intended to increase working hours of the main robot so that the robot can effectively extinguish a fire while managing the amount of water in the robot and the fire hose. To do this, an automatic T-valve system (ATS) and a novel designed firefighting robot (NDFR) were designed from the original firefighting robot. Because the ATS and the NDFR removes water from the robot and the fire hose that is fully charged with water, the robot is able to improve the traction efficiency and increase the operating time. Whenever the main robot needs to navigate to other spots, the AWMS will remove water from the fire hose and the NDFR; thus, it helps the lighter robot to carry a lighter hose and operate for a longer time.

Table 8.2 Operating Time and Weight of the Firefighting Robot and Fire Hose

Characteristics	**Time(hours)**	**Robot(kg)**	**Fire Hose(kg)**
The firefighting robot	1.5	210	255
Working with T-valve	6.84	210	56
NDFR with T-valve	7.81	180	56

Figure 8.2 displays the operating hours and weight for each firefighting robot. The original firefighting robot weighs 210 kilograms and the fire hose weighs 56 kilograms. When the fire hose is completely filled with water, it weighs 255 kilograms. Thus, the robot should waste lots of energy to draw this heavier fire hose, so that the robot is able to operate up to 1.5 hours. On the other hand, the robot is able to work up to 6.84 hours if the AWMS help to remove water from the fire hose. In addition, the NDFR can operate up to 7.81 hours because the AWMS discharges water from the robot and fire hose.

The multi robot energy saving system (MRESS) minimizes the chances of energy loss while increasing firefighting time and range of a main robot. Multi robot system enables robots to effectively move to desired destinations while extinguishing fires in an extended working range. In order to increase firefighting time and range of the main robot, an additional robot was designed based on the automatic T-valve system (ATS) and was installed between regular fire hoses. The main goals of the sub-robot are to expel water from a fire hose to avoid energy loss and to add an additional fire hose to increase the working range. For the multi robot cooperation, the new system controls the robots by combining a tracking method, an endrunning navigation, and a limit-cycle system. The collaboration of limit-cycle navigation and a fire hose tracking method has outstanding merits including optimal path generating and faster data processing. Furthemore, the endrunning navigation system is able to decrease the collision chances.

The statistical fire spread modeling is used to prepare for a fire situation. A fire spread model allows the optimal plan to be made by firefighters based on the fire spread to enable effective fire extinguishment in buildings. In this research, a statistical fire spread simulation modeling introduces a solution for fire accident prevention in a building. The fire spread is predicted by using statistical methods, such as bayesian network and decision tree. Additionally, the modeling methods are applied with various conditions: the fire ignition location, barrier failure probability, fire growth parameter, and backdraft. With the modeling, firefighters are able to expect the probability for location as well as growth of the fire. Particularly, firefighters are able to know the fire growth and spread in a layout exactly and economically.

Lastly, the firefighting robot drive cycle is studied in chapter 7. Because the existing drive cycle has a big difference in fuel efficiency according to the speed, it needs to check the difference in fuel efficiency from a couple of areas. One the other hand, the firefighting robot has no difference in fuel efficiency according to the speed. The robot just has a fixed speed of 4 km/h and battery use that changed the amount of water in a fire hose. Therefore, the drive cycle is easily completed

For the firefighting robot BMS, the AWMS and MRESS worked for the firefighting robot with a fire hose to optimally generate a planned path with fast data processing and to successfully move to the desired destinations without blocking the fire hose. In addition, fire spread model made the firefighters effectively suppress fires, so that the mortality rate and property damages, as well as the firefighting time, can be decreased. Lastly, the firefighting robot drive cycle completed the robot's evaluation.

As a result, the battery management systems for firefighting robots enable the firefighting robot to successfully extinguish a fire for a longer time and to efficiently reach the desired destinations. In addition, all of the simulation results were demonstrated by a computer simulation program, called AnyLogic®.

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