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# Intelligent robot-assisted evacuation: A review

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***Abstract*****—**Mass gathering in places such as shopping mall, concerts, sport events etc. is a necessity but may pose threat to the occupants during emergency. This paper presents a review of the different approaches of the crowd evacuation problems which can be classified into classical and modern methods. The classical methods have been widely used which basically depends on prior evacuation warnings or human in assisting an emergent evacuation scenario. Nonetheless, with the lack of important information such as the location of the safest exit, the consequence can be catastrophic. As a result, classical evacuation method becomes tough even though many people might able to assist the evacuees during such situation. Overcoming this, researchers have developed intelligent robots-assisted evacuation systems as a modern approach to manage crowds more systematically and simultaneously during emergency, which will be reviewed in this paper. Finally, this review paper aims to give a broad scope of the reliable evacuation system management to ensure the safety of the evacuees during emergency evacuation**.**

***Keywords:*** Evacuation management, robot-assisted evacuation, search and rescue, pedestrians' regulation and navigation.

## 1. Introduction

Public congregation is a necessity and unavoidable occurrences in daily life. It is no doubt that it brings several benefits, however there is also potential for injury to happen due to the dynamic of crowd behaviour. Boukas et al. [1] has stated some of recent disasters such as in Angola and the Ivory Coast on New Year's Eve 2013, India on January 2011, Cambodia at water festival in 2010, and in China on Mihong Bridge in 2004. All these accidents have caused hundreds of human casualties and thousands of injuries. Among the reasons why emergency evacuation possibly happen are because of natural disasters, fire, traffic accidents, building structural failure, earthquake, panic and so on as stated by [2]. There are many developed approaches to assist crowd evacuation such static and dynamic signage evacuation systems, by use of agents or authority, and mobile robot. Robotics hasplayed significant roles in industrial applications and have been used widely for public safety. Hence, significant number of researches have been conducted in the field of robotics during the last decadesfor evacuation applications such as robot-assisted evacuation, search and rescue, and regulation of the pedestrians.

New approaches have been developed by introducing robot-assisted evacuation that guides evacuees to reach their destination via the optimal and safe exit. The conducted researches on robot-assisted evacuation can be classified according to its function and purpose into three categories: guide as beacon, search and rescue, or regulating the pedestrians.

Robinette et al. [3] expressed: *Evacuees have a little time to make decisions or select optimal paths, so they rely on existing technology, such an emergency exit signs and evacuation maps, as well as information gleaned from authority figures, to find the best way out. As robots become more pervasive in everyday life, we can expect them to one-day guide evacuees in emergencies.*

The use of robots to assist during emergencies should be made a reality with current advanced technologies. Kim et al. [4] suggested that a robot-assisted evacuation should be equipped with temperature protection, waterproofing, and impact resistance mechanisms. Applying intelligence inside robots lead to a promising result of evacuation. Combining intelligence and robotics make the system better since it has been proven to expand robots' functionality, efficiency and performances due to enabling the robot to sense and react with the environment. This broadly increases the scope of the robots' tasks as they can recognize specific objects despite of its spatial location. Furthermore, a proper combination of monitoring and control technique, as well as proper computing technologies will assure better automated evacuation system. Several reviews, which includes robots, have provided deep insight into the crowd evacuation such as Zhou et al. [5] who have reviewed the guided crowd evacuation while Sakour et al. [6] reviewed the deployed technologies in the simulation of crowd evacuation. However, robots-assisted crowd evacuation has not yet been reviewed. Main contributions of this review work are summarized as follows: 1) A classification of crowd evacuation approaches into two different types, which includes classical approach such as signage, and authority, and modern approach known as intelligent robots-assisted evacuation; 2) A comprehensive analyses of intelligent robots-assisted crowd evacuation.

This paper is organized into six sections as follows: Section 2 presents a review of all conventional method while the modern methods are discussed in Section 3. Section 4 shows the comparison and specifications of each robot. Section 5explains the limitations of the modern technology. Finally, in Section 6, a brief conclusion and ideas for future work are drawn.

## 2. Evacuation prior to robot

Thus far, evacuation has been carried out in a conventional way which only involve the occupants inside the buildings. People depend on the evacuation signs, markers, plans or the authority of the building. However, people tend to get panic when emergency takes place and fail to notice the evacuation plans provided in the buildings. The followings are some of the conventional method utilized:

### *2.1. Signage*

Signage systems are widely applied to the most of public places such as buildings, offices, stations, airports and hotels as guidance in normal situation to various paths and exits. Chen et al. [7] proposed a heuristic algorithm based on the Lagrangian algorithm to establish clear standards for optimizing location of emergency signages considering the effect of light-occlusion on the evacuation efficiency while Zhang et al. [8] proposed a location model to determine the minimum number of signages with the optimal location for guidance while evacuating. Zhang et al. [9] proposed an intelligent lighting and indicators as guidance for evacuees during emergency evacuation. In the meantime, EXIT signages and emergency lights have been equipped in most local buildings to assist people in the building finding a way out if any emergency happens such as fire, tsunamis, hurricanes, or any natural disasters. However, the visibility of the signs is limited and could be categorized as inefficient since it might not give us the expected results towards the evacuees of the buildings due to impaired visibility. Thick smoke produced by the fire for example will occupy the higher ceiling first before it fully spread to the whole room. Hence, the signs might not clearly visible by the evacuees and they might run anywhere they feel safe. The technical report of photometric and psychophysical measurements of exit signs through smoke written by Rea et al. [10] and handbook of fire protection engineering written by DiNenno et al. [11] have discussed the visibility impairment during smoke. Both authors have carried out an experiment respectively to observe the visibility of emergency signs in smoky condition. The outcome for both experiments indicates that the visibility of the signs has been reduced when smoke surrounds the respective area. This might be due to the smoke density which is increasing by time or ambient light whereby the light has been scattered to the surrounding before bouncing towards human eyes. In addition, Ibrahim et al. [12] mentioned that using visual aids such as emergency lighting and evacuation indicatory system are inefficient even though it saves cost due to limited data obtained regarding the condition of the evacuation area and congestion information. To solve this, Galea et al. [13] proposed a dynamic signage combined with a voice alarm to inform evacuees about availability of an exit or indicating alternative exits for redirecting.

### *2.2. Authority*

Zhou et al. [14] proposed a hybrid bi-level model to optimize the number, initial locations, and routes of leaders during the evacuation in subway stations. Wang et al. [15] has conducted a research on emergency evacuation in which the research focused on four fundamentals of evacuation which are crowd evacuation theory, crowd evacuation modelling, evacuation decision-making, and evacuation risk evaluation. According to Wang et al. [15], there are three types of decision-making in evacuation which are pre-decision, during and post-decision evacuation. Here this review focused only on making decision during evacuation. The assignment targeted for a large scale of evacuation within limited time whereby a group of people were assigned to each evacuation route. This is to ensure those who are involved in any emergency situations can be saved within limited time and the number of people in each refuge could be lessen as it is not achieve its maximum capacity. The demand for travel will decrease according to the paths available thus lessen the traffic and blockage during emergency evacuation. The motion of the human crowd will be faster and the time taken to evacuate will be shorter. Ibrahim et al. [12] stated that the crowd management authorities are expected to take immediate evacuation steps during emergency situations. Wang et al. [15] also stated a way to overcome traffic problem is through a “generous resource allocation” which will make the evacuation runs smoothly. The authors also highlighted the important aspect of the study of large-scale evacuation decision-making which is to have the logical allocation of each refuge and using all available emergency resources to the maximum. Therefore, evacuation through the authority is important as the traffic of human crowd could be controlled efficiently as mentioned by both authors. Considering the emotion of those occupants of a building who are in panic, they might take a wrong decision or a wrong route when evacuation take place.

To overcome these problems such an unseen signage due to smoky condition or wrong decision by a building authority, a better way is to consider introducing robots to lead the evacuation. Compared to classical evacuation guidance such as signages and authority, robot-assisted crowd evacuation systems have received a considerable attention lately due to the recent advances in the surveillance and wireless communication.

## 3. Evacuation using robot

Living in the fourth industrial revolution, the dependency of people towards information and technology increases gradually each year due to the progress advancement of technologies. Recent Intelligent robots, equipped with more advanced sensors, are attracting more attentions. Hence, robots are proposed and developed to evacuate people during emergency to overcome the evacuation problems of classical approaches. Compared to conventional evacuation, robot-assisted evacuation has many advantages when an emergency happens, such as approaching the evacuees quickly, guide them efficiently to the shortest and safest route, and accessing the dynamic change in an environment in real time such as pedestrians’ density and flow, as stated by Tang et al. [16].The robots will require very different capabilities, so it is mainly equipped with camera, sensors, human tracking and navigation, and controller. All these specifications of each reviewed robot are discussed on the next sections.

### *3.1. Camera*

Camera provides more details of the environment, so it is widely used in robotics to ease the authority in capturing the evacuation environment and thus directing the evacuees to the optimal emergency exit. Most reviewed robots are built with cameras as the users could stay updated with the robot’s surroundings. This can assist the firefighters to help those who are trapped inside a building. In addition, the firefighter could see directly the condition of the surroundingincluding obstacles and the density of the crowd, therefore enabling them to recommend to the evacuees with the optimal routes. However, more generated data by the camera means more computational analysis is required.

### *3.2. Sensors*

A robot needs to be equipped with sensors to ensure more efficient, safer and concise evacuation guidance of the evacuees in real time. A sensor can measure some aspects of the environment. There are many types of sensors that can be used inside an evacuation robot. For example, having temperature sensor could detect the surrounding temperature. Thus, the change of temperature could be observed and interpreted. Having wireless communication sensor could ease the process of transferring data. Hence, time to obtain data or information could be shorter.

### *3.3. Human Tracking and Navigation*

Human tracking and navigation are very important mechanisms for an evacuation robot. Without human tracking, the suggested routes provided for evacuees might be inefficient leading to more time to evacuate. A mobile robot must navigate in its environment. The complexity of the environment can have a major influence on the robot’s task performance. In addition, since the time for evacuation is limited, human tracking system should be equipped in an evacuation robot in order to reduce the time. Avoiding obstacles and self-localization are parts of the navigation. The robot could navigate the evacuees to the appropriate location to protect them from any harm caused by the emergency evacuation. Operating evacuation robots in an unknown and dynamic environment leads to time consumption with high computational cost. However, during the evacuation, most of robots use static map and deals with the dynamic changes of the environment, while it performs route planning and localization.

### *3.4. Controller*

Robots should make desired decisions rapidly based on the detected details of environment by the sensors. Controlling a robot could be in various ways. Evacuation robot can be controlled via Bluetooth, joystick, remote internet and so on. Bluetooth uses low power for transferring data over short distances as it has short wavelengths, therefore it has been used widely in communication services before the emergence of Internet and it still used until today. Joystick and remote internet have higher range distances compared to Bluetooth, but it requires line of site transmission.

## **4. Discussion**

Several reviews have been done to assist researchers in modelling the evacuation robot and the crowd behaviour when emergency happens. Chen et al. [17] proposed an empirical study of human-robot interaction in an uni-directional exit corridor. Kim et al. [4] proposed a portable evacuation robot that can explore and gather information in a fire site and evacuate people. Meanwhile, Shell et al. [18] described and suggested an implementation of audio beacons, easily localized and identified by the auditory system of human, to assist in evacuation tasks. Ferranti et al. [19] studied the impact of topology features on the quality of evacuation routes.

Each robot reviewed might has different functions. Kim et al. [4] have also reviewed several robots such as BEAR, Jet Fighter, Fire Searcher, Tehzeeb, Mobile Robot Systems, ROB-1, and Wever C1. BEAR is developed by Theobald [20] and mainly used for rescuing purposes such as evacuating injured people to safe place when natural disasters happen. It has the capability to explore hazardous area, and to lift and carry weights up to 225 kg. However, the use of this robot is limited due to the high cost of development and thus can only be used for military and research purposes. Jet Fighter is introduced by Tokyo Fire Department and acts like a fireman. Meanwhile, Fire Searcher robot is a scouting robot used in environment with high temperature and poisonous gas to monitor the victims. Tehzeeb is also considered as a rescuing robot as BEAR. Ko et al. [21] presented a prototype of a Mobile Robot with wireless sensor network that can navigate into rubbles autonomously for rescue purpose. Compared to previous robots, ROB-1 and Wever C1 are developed for hand carrying and indoor security respectively. Although these robots have a compact size, they are not suitable for missions of rescue and evacuationin extreme fire sites due to its nondurable construction. Mori et al. [22] developed Jack and Cutter Robots suitable for heavy-duty rescue where disasters categorized into three scenarios: collapsed house, collapsed building rubble, and traffic accidents.

One part of this research endeavour of the robots-assisted evacuation is focused on the pedestrian regulation during normal evacuation or emergencies that occur due to panic or disaster.The robot-assisted evacuation for pedestrians' regulation performs either as a leader to direct evacuees towards the destination, or as a shepherd to regroup evacuees. Tang et al. [16] proposed a robot to guide evacuees to select automatically an exit with the minimum escape time. Boukas et al. [1] proposed a robot as guidance to redirect evacuees towards a less congestive exit. Whereas Liu et al. [23] proposed multiple robots to assist and evacuate humans efficiently and safely.

Studies have been reported on robot-assisted evacuation for the purpose of pedestrian regulation in scenarios, such as crossing pedestrian flows by Yamamoto et al. [24] and unidirectional pedestrian flow in an exit corridor by Jiang et al. [25] who proposed an autonomous mobile robot as dynamic obstacles at indoor corridor exits which interacts with pedestrians efficiently based on social force model so that the flow of regulated pedestrian tracks a desired velocity. They proposed an adaptive dynamic programming (ADP) method which provides feedback control with online learning and control capability. However, the pedestrian features such as pedestrian positions and velocities were extracted from the image of the environment. Wan et al. [26] proposed a deep neural network (DNN) to improve the learning capability of complex interactions between human and robots. The robot motion planner was trained using a deep reinforcement learning algorithm to maximize the pedestrian outflow. Wan et al. [26] addressed the challenge of feature representation and evaluated the proposed approach in a 3-D continuous environment constructed by the Unity 3-D engine.

Chen et al. [17] deployed a mobile robot which is only to record and analysis individual and collective motions of pedestrians. It consisted of tracking system made of 5 Microsoft Kinect sensors and 6 computers connected to a local area network. Schöner et al. [27] mentioned two fundamental requirements of autonomous robots in which the robots need to structure their behaviour based on sensory system information that they themselves acquire and go beyond the sensor-driven nature of control systems. This is supported by Langley et al. [28] whereby the authors stated that the autonomous robot must be able to explain its decisions and actions. This leads to the importance of autonomous robots in evacuation to handle the human crowd in emergency. Autonomous robot can be very complex where the robotperforms an autonomous mapping in case of unknown environment, locate suitable exits including any emergency exits and newly created exit points such as windows with ladders and reduce the level of complexity by providing the robot with only necessary information. The specifications of each robot differ from one to another. For example, Jet Fighter has camera and obstacle avoidance sensors to prevent itself from being crashed and wireless communication system for monitoring task. Fire Searcher could be controlled by using remote and transmit the data collected using an applied manipulator. Tehzeeb can localize itself by using laser scanner module, manipulators and map generation algorithms even in high smoke density area. The Mobile Robot developed by Ko et al. [21] has been equipped withthermal array sensor to detect living human by body heat, wireless sensor network to track the robot. ROB-1 uses Bluetooth sensor to allow the user to control. It is also equipped with camera while Wever C1 uses face detection or voice recognition sensors and can be controlled via mobile phone and remote internet. The robot proposed by Kim et al. [4] is equipped with camera and uses temperature sensor, CO sensor, $O2$ sensor, and wireless RF modules for data transmission. Shell et al. [18] equipped the proposed robot with camera, wireless communication and localization. Ferranti et al. [19] proposed a robot made of camera, sensory nodes, and long-range wireless communication. Boukas et al. [1] equipped the robot with a wide and a narrow stereoscopic camera. It is also equipped with a beacon along with voice instruction to attract the evacuees towards availability of an exit. The robot involved in a static environment and deals with the dynamic changes, while performing path planning and localization. Jiang et al. [25] optimized the robot motion control parameter based on real-time camera observation of pedestrian flow. An overview of the functions and specifications of each reviewed papers on robots-assisted evacuation is presented in Table1 and Table 2. BrainOS is a software that could be installed within the robot. It is a tool for robots to provide an efficient way in navigation. It provides advanced technology of self-driving by using computer vision and AI libraries. This software enables online learning whereby the inputs obtained from the trainer could be merged with internal instructions that have been implemented in the system. Hence, the robots could be taught with new configurations from certain location. According to Grotmol et al. [29], this software also enables the users or instructors to remove a portion of the learned behaviors inside the robots' system through time machine operation. Therefore, implementing BrainOS inside an evacuation robot might give effective results compared to other navigation systems. Ultrasonic sensor is a sensor that transmits waves into the air and detects reflected waves from an object therefore it is a great fit for many applications. Among the advantages of the ultrasonic sensor is that the reading is not affected by the color or transparency of the object detected. It can also be used in low visibility environment such as due to smoke or darkness thus making it advantageous to be applied in intelligent evacuation robot.

**Table 1.** Simulation studies of robot-assisted crowd evacuation

| **Author** | **Year** | **Scale** | **Movement Model** | **Influenced mode** | **Scenario** |
|---|---|---|---|---|---|
| Yamamoto *et al* | 2013 | Macroscopic behavior of flow | Particle model | Collision avoidance, pedestrian flows | Crossing pedestrian flows |
| Liu *et al* | 2018 | Microscopic and Macroscopic | Stochastic differential equation model | Environment and crowd density | Exits |
| Tang et al | 2016 | Microscopic | Panic model includes Social Force Model | Density, egress flow speed. panic level, threat perception | Exits of shopping mall |
| Wan et al | 2018 | Macroscopic | Deep Neural Network Model | Pedestrian velocities and outflow | Two merging pedestrian flows through a bottleneck exit |

**Table 2.**Overview of reviewed robots

| Author(s) | Name of Robot | Functions | Outdoor / Indoor Normal / Threat | Autonomous | Specifications | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Camera | Sensors | Human Tracking / Navigation | Controller |
| Chen et al (2018) | mobile robot | Detection and tracking | Indoor, normal | N/A | N/A | 5 Microsoft Kinect sensors | Y | N/A |
| Theobald (2010) | BEAR | Search and rescue injured people, lifting | Outdoor and indoor, normal and threat | Semi | Y | N/A | N/A | Remote human operator |
| Kim *et al* (2009) | Jet Fighter | Fire extinguisher | Outdoor and indoor, threat | Y | Y | Obstacle avoidance, wireless communication | Y | Remote user |
| | Fire Searcher | Scout in fire sites | Outdoor and indoor, threat | N/A | N/A | N/A | N/A | Remote |
| | Tehzeeb | Rescue while exploring in lightless area | Outdoor and indoor, threat | N/A | N/A | Laser scanner | Y | N/A |
| | ROB-1 | Playing music, shooting images | Indoor, normal | Y | N/A | Bluetooth | N/A | Mobile phone |
| | Wever C1 | Home security | Indoor, normal | Y | Y | Face detection or voice recognition | N/A | Mobile phone and remote internet |
| | Unnamed | Evacuation | Outdoor and indoor, normal and threat | Y | Y | Temperature, $CO, O_2$, gas, wireless RF modules | Y | Joystick and remote controller |
| Ko and Lau | Mobile Robot | Explore through | Outdoor and indoor, | Y | N/A | Wireless sensor network, | Y | N/A |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| (2009) | System | wireless communication | normal and threat | | | Thermal sensor | | |
| Mori *et al* (2006) | Jack and Cutter Robots | Rescue operations, cutting obstacles | Outdoor and indoor, normal and threat | Y | N/A | N/A | N/A | N/A |
| Shell and Mataric (2005) | Unnamed | Locate, treat, rescue | Outdoor and indoor, normal and threat | Y | N/A | Wireless communication | Y | N/A |
| Ferranti and Trigoni (2008) | *Agents* | Explore and collect data of victims and surrounding | Outdoor and indoor, normal and threat | Y | N/A | Stationary sensor nodes, long-range wireless communication | N/A | N/A |
| Jiang *et al* 2017 | Mobile robot | Regulate pedestrian | Indoor exit corridor, normal | Y | Y | N/A | | Adaptive dynamic approach |
| Boukas et al 2015 | Mobile robot | Guide pedestrian | Indoor, normal | Y | Y | Beacon along with voice instruction | Y | N/A |

## 5. Limitations

Here, some of the limitations of building an intelligent evacuation robot are listed down which remain as a challenge to this research area.

### *5.1. Navigations*

#### *5.1.1. Collecting enough real data*

Being in an environment with dynamic changes such as moving peoples, animals, or obstacles will lead to a challenge in precise execution of the data. This is one of the main reasons for the lack of robot usage during emergency evacuation. Practically, the autonomous navigation system cannot function well since each location has different architecture, therefore most of the robots are developed only for research purpose.

#### *5.1.2. Creating precision motion control*

When the size of the robots is too big, it is more difficult to control with high precision motion as some place might have a narrow space to evacuate. Hence, the robots must be able to avoid the obstacles by maximizing the amount of floor or path provided.

### *5.2. Sensors*

#### *5.2.1. Temperature*

Most of the accuracy of sensors are affected if the temperature suddenly drops or rises within 5-10 degrees or more. This will create a certain problem for evacuation robots in places such as fire sites, where high temperature is inevitable.

#### *5.2.2. Human detection*

This is one of the most crucial sensors in evacuation robots, since the fundamental function of the robots is to help the evacuees to evacuate in emergency. The robot should be able to differentiate between humans and objects to meet its function.

#### *5.2.3. Limited detection range*

A sensor needs to have high range so that it can detect hazardous situation far ahead. This is essential part for the sensors because the robots need to guide the evacuees by avoiding the risky path during evacuation.

### *5.3. Emotions*

Craig et al. [30] suggested that communication with robots will be more intuitive if robots not only can convey emotional content but also recognize emotion cues in humans and adapt to their behaviour accordingly. This is to ensure that the robots can interact with human specifically in an emergency, by being able to boost up the confidence and trust of humans per se.

### *5.4. High Cost*

One of the main disadvantages of evacuation robot also the high cost involved in building the system i.e. mechanical parts, hardware, software, maintenance as well as cost for training to users etc. which makes it not conducive for commercialization. Furthermore, the system of the robots needed to be updated frequently to suit the changing requirement. In case of breakdown which is inevitable due to its application in hazardous area, the cost for repair will be too expensive and to restore the lost data will be a cumbersome task.

### *5.5. Physical Appearance*

During an emergency, evacuees tend to look front, hence a larger/taller robot is preferable to be spotted easily. However, a bulky robot will be difficult to be controlled in a tight route. For this, the size of the robot should be optimized; so it will be visible by the evacuees and at the same time can manoeuvre through the narrow spaces easily. Although some robots have been well designed for evacuation tasks in extreme fields, they are still too heavy and massive for ease of transportation.

## 6. Conclusion

This paper presented a review on firstly, classification of crowd evacuation approaches into classical approach such as signage and authority, and modern approach known as intelligent robots-assisted evacuation. Then, this review also provided a comprehensive analyses of intelligent robots-assisted crowd evacuation. In the operation of evacuation, there are two ways which are with and without using robots. Evacuation prior to robot that discussed in this paper is by using signage or by authority. The most of the reviewed intelligent robot-assisted crowd evacuation systems were developed to guide as beacon, research and rescue, or regulate pedestrians. However, many problems arise due to limitations of the current robots such as navigations precision and data, non-compatible sensors, lack of emotions, high cost of maintenance and the physical appearance. Therefore, we perceive future avenues should focused overcoming these limitations in order to realize safe and fast evacuation under normal and threat conditions.

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