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Application of Fuzzy Logic for Actor Node Selection in Wireless Sensor and Actor Networks: Implementation and Performance Evaluation of Proposed Intelligent Simulation Systems and a Testbed

by

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Contents

List of Figures

List of Tables

Abstract

The Wireless Sensor and Actor Networks (WSANs) are composed of sensors and actors. The sensors gather information about the physical events, while actors perform appropriate actions based on the sensed data from sensors. In order to provide effective sensing and acting, we need a coordination mechanism among sensors and actors. Also, there are many issues for WSANs such as energy saving, routing efficiency, sensor-actor coordination and actor node selection to carry out a job. However to deal with these problems should be considered many parameters, which make the problem NP-Hard. Thus, the heuristic and intelligent algorithms are good solutions. In this research work, we focus on actor node selection problem in WSANs. We consider and propose new parameters and implement different intelligent systems based on Fuzzy Logic (FL) to select the actor nodes in order to perform the required tasks. The proposed systems can be used in different environments and applications. We carried out many simulations and found that the performance of implemented systems is good. The implemented systems improves the energy saving and congestion situation and they can be used for mobile WSANs. We also compared the complexity of different fuzzy-based systems and found that when we use many parameters the complexity is increased, but the performance also is increased. We implemented a testbed and performed experiments in real environment. The experimental results show that the implemented testbed makes a good decision for actor node selection. This thesis contributes in the research field as following: 1) Proposal of new parameters for actor node selection in WSANs. 2) Proposal and implementation of intelligent systems based on FL for making appropriate actor node selection in WSANs. 3) Performance evaluation of implemented systems for different scenarios. 4) Comparison of implemented intelligent simulated systems. 5) Implementation of a testbed for WSANs and its application in a real scenario. 6) Give insights about future developments and application of WSANs as an important technology for wireless communications. The thesis has 8 Chapters.

Chapter 1 presents the background, motivation and thesis structure. Chapter 2 introduces general aspects of wireless networks and describes Wireless Sensor Networks (WSNs), Mobile Ad-hoc Networks (MANETs) and Wireless Mesh Networks (WMNs) as related work. In Chapter 3, we introduce the architecture, challenges and applications of WSANs. In Chapter 4, we present FL, Fuzzy sets and Fuzzy memberships functions. In Chapter 5, we present our proposed fuzzy-based simulation systems for actor node selection in WSANs. In Chapter 6 are shown the performance evaluation results of proposed simulation systems. In Chapter 7, we show testbed implementation and evaluation. In Chapter 8, we conclude this thesis and give the future work.

Keywords: Wireless Networks, Wireless Sensor Networks, Wireless Sensor and Actor Networks, Fuzzy Logic, Intelligent Algorithms, Intelligent Systems.

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Chapter 1

Introduction

1.1 Background

Recent technological advances have lead to the emergence of distributed Wireless Sensor and Actor Networks (WSANs) which are capable of observing the physical world, processing the data, making decisions based on the observations and performing appropriate actions[1].

With the advancement of new technologies such as 5G [2, 3] and ZigBEE [4], WSANs have emerged as a variation of WSNs. WSANs are capable of monitoring physical phenomenons, processing sensed data, making decisions based on the sensed data and completing appropriate tasks when needed. WSAN devices deployed in the environment are sensors able to sense environmental data, actors able to react by affecting the environment or have both functions integrated [5]. For example, in the case of a fire, sensors relay the exact origin and intensity of the fire to actors so that they can extinguish it before spreading in the whole building or in a more complex scenario, to save people who may be trapped by fire.

Unlike WSNs, where the sensor nodes tend to communicate all the sensed data to the sink by sensor-sensor communication, in WSANs, two new communication types may take place. They are called sensor-actor and actor-actor communications. Sensed data is sent to the actors in the network through sensor-actor communication. After the actors analyse the data, they communicate with each other in order to assign and complete tasks. To provide effective operation of WSAN, is very important that sensors and actors coordinate in what are called sensor-actor and actor-actor coordination. Coordination is not only important during task conduction, but also during network's self-improvement operations, i.e. connectivity restoration [6, 7], reliable service [8], Quality of Service (QoS) [9, 10] and so on.

Sensor-Actor (SA) coordination defines the way sensors communicate with actors, which actor is accessed by each sensor and which route should data packets follow to reach it. Among other challenges, when designing SA coordination, care must be taken in considering energy minimization because sensors, which have limited energy supplies, are the most active nodes in this process. On the other hand, Actor-Actor (AA) coordination helps actors to choose which actor will lead performing the task (actor selection), how many actors should perform and how they will perform. Actor selection is not a trivial task, because it needs to be solved in real time, considering different factors. It becomes more complicated when the actors are moving, due to dynamic topology of the network.

1.2 Thesis Purpose and Contribution

In this thesis, we propose and implement four fuzzy-based systems to solve actor node selection problem in WSANs. In WSANs, sensors gather information about the physical events, while actors perform appropriate actions upon the environment, based on the sensed data shared by sensors. In order to provide effective sensing and acting, a distributed local coordination mechanism is necessary among sensors and actors.

In this work, we focus on actor selection problem and we propose a meta-heuristic platform based on fuzzy-logic in order for actors to decide whether they will perform required tasks, refuse or call other actors for help, based on data supplied by sensors and actual actor condition.

We propose and implement four fuzzy-based systems. In the first Fuzzy-Based System for Actor Node Selection 1 (FBSANS1), we use 3 input parameters: Job Type (JT), Distance to Event (DE), Remaining Energy (RE). The output parameter is Actor Selection Decision (ASD). In the second Fuzzy-Based System for Actor Node Selection 2 (FBSANS2), we used as input parameters Job Type (JT), Distance to Event (DE), Remaining Energy (RE), Actor Node Speed (ANS) and as output Actor Selection Decision (ASD). In the third Fuzzy-Based System for Actor Node Selection 3 (FBSANS3), we added Density of Actors (DOA) as fourth parameter. In the fourth Fuzzy-Based System for Actor Node Selection 4 (FBSANS4), we added

Congestion Situation (CS) parameter. Comparing complexity of FBSANS1 with FBSANS2, FBSANS3 and FBSANS4, the three systems with four parameters are more complex than FBSANS1. However, they are more flexible than FBSANS1. Our contributions are summarized in following:

- Proposal of new parameters for actor node selection in WSANs.
- Proposal and implementation of intelligent systems based on FL for making appropriate actor node selection in WSANs.
- Performance evaluation of implemented systems for different scenarios.
- Comparison of implemented intelligent simulated systems.
- Implementation of a testbed for WSANs and its application in a real scenario.
- Give insights about future developments and application of WSANs as an important technology for wireless communications.

1.3 Thesis Outline

This thesis consists of 8 chapters and its structure is given in Fig. 1.1.

The thesis is organized as follows.

Chapter 1 presents the background, motivation and thesis structure.

Chapter 2 introduces general aspects of wireless networks and describes Wireless Sensor Networks (WSNs), Mobile Ad-hoc Networks (MANETs) and Wireless Mesh Networks (WMNs) as related work.

In Chapter 3, we introduce the architecture, challenges and applications of WSANs.

In Chapter 4, we present FL, Fuzzy sets and Fuzzy membership functions.

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In Chapter 7, we show testbed implementation and evaluation.

In Chapter 8, we conclude this thesis and give the conclusions and future work.

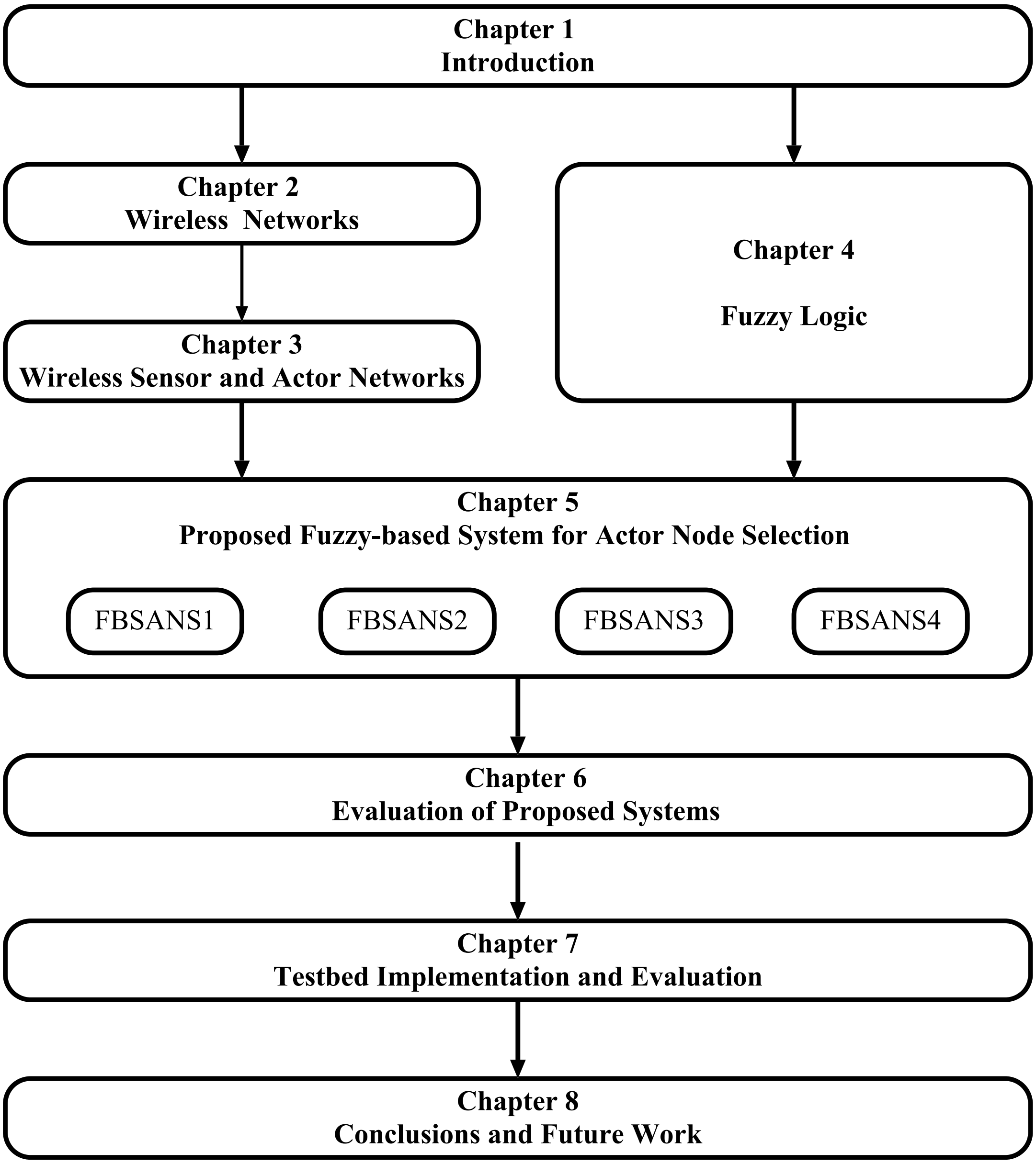


Figure 1.1: Thesis structure.

Chapter 2

Wireless Networks

2.1 Introduction

Wireless networks have evolved with great speed during the last decades and it seems like in the future this speed will keep going. A telecommunication network, in which no wires are used to create the interconnections, is referred to as Wireless Network. Compared with classical wired networks, wireless networks have mobility, flexibility and cost saving advantages.

In this chapter, we will describe some of basic concepts of wireless networks and some of their applications.

2.2 Ad-hoc Networks and MANETs

In Fig. 2.1 is shown the Ad-hoc network technology. The Ad-hoc networks can be fixed and mobile.

The Mobile Ad-hoc Networks (MANETs) are a continuing research area in the computing community. Along with the development of the next generation of wireless communication systems, there will be a need for the rapid deployment of independent mobile users. Some examples of possible uses include students using laptops to participate in an interactive lecture, business associates sharing information during a meeting and emergency disaster relief personnel coordinating efforts after a hurricane or earthquake. Such network scenarios cannot rely on centralized and organized connectivity, and can be conceived as applications of MANETs. A MANET is an autonomous collection of mobile users that communicate over rela-

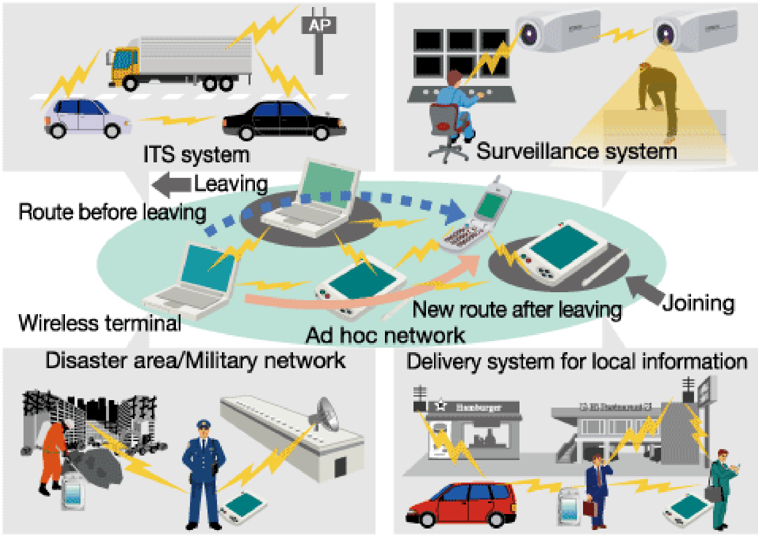


Figure 2.1: Ad-hoc network technology [11].

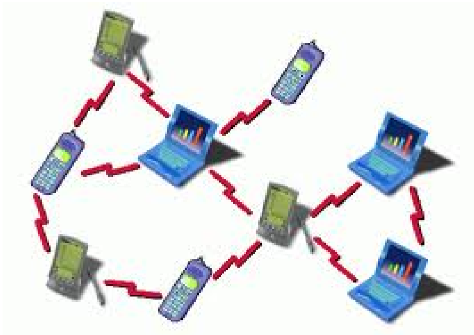


Figure 2.2: MANET [12].

tively bandwidth constrained wireless links. Because of the mobility of the nodes, the network topology may change rapidly and unpredictably. In Fig. 2.2 is shown a mobile Ad-hoc network. A mobile Ad-hoc network has following features:

- **Autonomous Terminal**
  In MANET [13], each mobile terminal is an autonomous node, which may function as both a host and a router. In other, since there is no background network words, besides the basic processing ability as a host, the mobile nodes can also perform switching functions as a router. So usually endpoints and switches are indistinguishable in MANET.

- **Distributed Operation**
  For the central control of the network operations, the control and management of the network is distributed among the terminals. The nodes involved in a MANET should collaborate amongst themselves and each node acts as a relay as needed, to implement functions e.g. security and routing.

- **Multihop Routing**
  Basic types of Ad-hoc routing algorithms can be single-hop and multihop, based on different link layer attributes and routing protocols. Single-hop MANET is simpler than multihop in terms of structure and implementation, with the cost of lesser functionality and applicability. When delivering data packets from a source to its destination out of the direct wireless transmission range, the packets should be forwarded via one or more intermediate nodes

- **Dynamic Network Topology**
  In these types of networks, the topology changes rapidly and unpredictably because of the nodes mobility. The connectivity among the terminals changes with time. MANET should adapt to the traffic and propagation conditions as well as the mobility patterns of the mobile network nodes. The mobile nodes in the network dynamically establish routing among themselves as they move about, forming their own network on the fly.

- **Light-weight Terminal**
  In most cases, the MANET nodes are mobile devices with less CPU processing capability, small memory size, and low power storage. Such devices need optimized algorithms and mechanisms that implement the computing and communicating functions.

MANET Characteristics

MANETs are new paradigm of networks, offering unrestricted mobility without any underlying infrastructure. Basically, MANETs are a collection of nodes communicating with each other by forming a multi-hop network. In the following we show the characteristics of a MANET:

- **Dynamic Topologies**
  Nodes are free to move arbitrarily. The network topology may change ran-

domly and have no restriction on their distance from other nodes. As a result of this random movement, the whole topology is changing in an unpredictable manner, which in turn gives rise to both directional as well as unidirectional links between the nodes.

- **Energy Constrained Operation**
  Almost all the nodes in an Ad-hoc network rely on batteries or other exhaustive means for their energy. The battery reduces due to extra work performed by the node in order to increase the lifetime of the network. Therefore, energy conservation is an important design optimization criterion.

- **Bandwidth Constraint**
  Wireless links have significantly lower capacity than infrastructures networks. Throughput of wireless communication is much less because of the effect of the multiple access, fading, noise, interference conditions. As a result of this, congestion becomes a obstacle in bandwidth utilization.

- **Limited Physical Security**
  MANETs are generally more vulnerable to physical security threats than wireless networks because the Ad-hoc network is a distributed system and all the security threats relevant to such a system are pretty much present, as a result, there is an increased possibility of intrusion, spoofing, masquerading, and denial-of-service type attacks.

The set of applications for MANETs is diverse, ranging from small, static networks that are constrained by power sources, to large-scale, mobile, highly dynamic networks. The design of network protocols for these networks is a complex issue. Regardless of the application, MANETs need efficient distributed algorithms to determine network organization, link scheduling, and routing. However, determining viable routing paths and delivering messages in a decentralized environment where network topology fluctuates is not a well-defined problem. While the shortest path (based on a given cost function) from a source to a destination in a static network is usually the optimal route, this idea is not easily extended to MANETs. Factors such as variable wireless link quality, propagation path loss, fading, multiuser interference, power expended, and topological changes, become relevant issues. The network should be able to adaptively alter the routing paths to alleviate any of these effects. Moreover, in a military environment, preservation of security, latency, reliability, intentional jamming, and recovery from failure are significant concerns. Military networks are designed to maintain a low probability of intercept and/or a low probability of detection. Hence, nodes prefer to radiate as little power as necessary and transmit as infrequently as possible, thus decreasing the probability of detection or interception. A lapse in any of these requirements may degrade the performance and dependability of the network.

MANET Challenges

- **Routing**
  Since the topology of the network is constantly changing, the issue of routing packets between any pair of nodes becomes a challenging task. Most protocols should be based on reactive routing instead of proactive. Multicast routing is another challenge because the multicast tree is no longer static due to the random movement of nodes within the network. Routes between nodes may potentially contain multiple hops, which is more complex than the single hop communication [14].

- **Security and Reliability**
  In addition to the common vulnerabilities of wireless connection, an Ad-hoc network has its particular security problems due to e.g. nasty neighbor relaying packets. The feature of distributed operation requires different schemes of authentication and key management. Further, wireless link characteristics introduce also reliability problems, because of the limited wireless transmission range, the broadcast nature of the wireless medium (e.g. hidden terminal problem), mobility-induced packet losses, and data transmission errors.

- **Quality of Service (QoS)**
  Providing different quality of service levels in a constantly changing environment will be a challenge. The inherent stochastic feature of communications quality in a MANET makes it difficult to offer fixed guarantees on the services offered to a device. An adaptive QoS must be implemented over the traditional resource reservation to support the multimedia services.

- **Internetworking**
  In addition to the communication within an Ad-hoc network, internetworking

between MANET and fixed networks (mainly IP based) is often expected in many cases. The coexistence of routing protocols in such a mobile device is a challenge for the harmonious mobility management [15], [16], [17].

- **Power Consumption and Conservation**
  For most of the light-weight mobile terminals, the communication related functions should be optimizedfor lean power consumption. Conservation of power and power-aware routing must be taken into consideration.

2.3 Wireless Sensor Networks

A Wireless Sensor Network (WSN) consists of a number of sensors spread across a geographical area (see Fig. 2.3). Each sensor has wireless communication capability and some level of intelligence for signal processing and networking of the data. Some examples include a group of soldier establishing communication for tactical communication or a measurement of the air pollution. Both, MANETs and sensor networks [18] can be further classified into two broad types: homogeneous and heterogeneous networks. In homogeneous networks, all nodes are identical in terms of battery energy and hardware complexity. While in a heterogeneous sensor network, two or more different types of nodes with different battery energy and functionality are used. The motivation is that the more complex hardware and the extra battery energy can be embedded in some nodes, thereby reducing the hardware cost of the rest of the network. Some examples of wireless sensor networks are the following.

- Military sensor networks to detect and gain as much information as possible about enemy movements, explosions, and other phenomena of interest.
- Sensor networks to detect and characterize Chemical, Biological, Radiological, Nuclear, and Explosive (CBRNE) attacks and material.
- Sensor networks to detect and monitor environmental changes in plains, forests, oceans, and so on.
- Wireless traffic sensor networks to monitor vehicle traffic on highways or in congested parts of a city.
- Wireless surveillance sensor networks for providing security in shopping malls, parking garages, and other facilities.

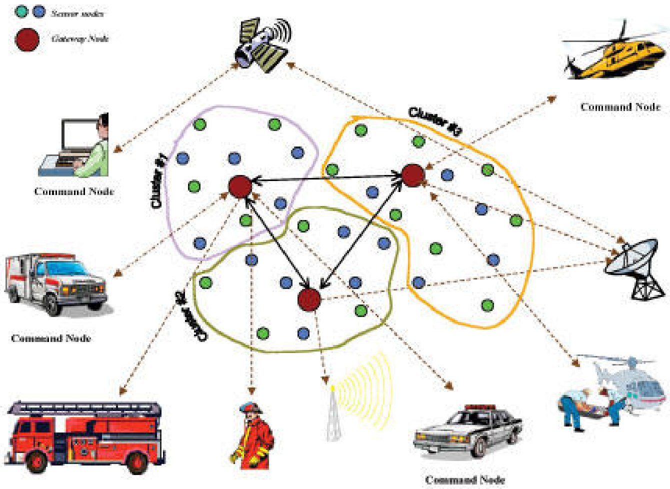


Figure 2.3: A wireless sensor network [19].

- Wireless parking lot sensor networks to determine which spots are occupied and which are free.

The above list suggests that WSNs offer certain capabilities and enhancements in operational efficiency in civilian applications as well as assist in the national effort to increase alertness to potential terrorist threats.

Two ways to classify WSNs are whether or not the nodes are individually addressable, and whether the data in the network is aggregated. The sensor nodes in a parking lot network should be individually addressable, so that one can determine the locations of all the free spaces. This application shows that it may be necessary to broadcast a message to all the nodes in the network. If one wants to determine the temperature in a corner of a room, then addressability may not be so important. Any node in the given region can respond. The ability of the sensor network to aggregate the data collected can greatly reduce the number of messages that need to be transmitted across the network.

The basic goals of a WSNs generally depend upon the application, but the following tasks are common to many networks.

- **Determine Value of Some parameters at a Given Location**
  In an environmental network, one might want to know the temperature, atmospheric pressure, amount of sunlight, and the relative humidity at a number of locations. This example shows that a given sensor node may be connected

to different types of sensors, each with a different sampling rate and range of allowed values.

- **Detect Occurrence of Events of Interest and Estimate Parameters of the Detected Event or Events**
  In the traffic sensor network, one would like to detect a vehicle moving through an intersection and estimate the speed and direction of the vehicle.

- **Classify a Detected Object**
  A vehicle in a traffic sensor network is a car, a mini-van, a light truck or a bus.

- **Track an Object**
  In a military sensor network, track an enemy tank as it moves through the geographic area covered by the network.

In these four tasks, an important requirement of the sensor network is that the required data be disseminated to the proper end users. In some cases, there are fairly strict time requirements on this communication. For example, the detection of an intruder in a surveillance network should be immediately communicated to the police so that action can be taken.

WSNs requirements include the following.

- **Large Number of Sensors**
  Aside from the deployment of sensors on the ocean surface or the use of mobile, unmanned, robotic sensors in military operations, most nodes in a smart sensor network are stationary. Networks of 10,000 or even 100,000 nodes are envisioned, so scalability is a major issue.

- **Low Energy Use**
  Since in many applications the sensor nodes will be placed in a remote area, service of a node may not be possible. In this case, the lifetime of a node may be determined by the battery life, thereby requiring the minimization of energy expenditure.

- **Network Self-organization**
  Given the large number of nodes and their potential placement in hostile locations, it is essential that the network be able to self-organize (manual configuration is not feasible). Moreover, nodes may fail (either from lack of energy or

from physical destruction) and new nodes may join the network. Therefore, the network must be able to periodically reconfigure itself so that it can continue to function. Individual nodes may become disconnected from the rest of the network, but a high degree of connectivity must be maintained.

- **Collaborative Signal Processing**
  Yet another factor that distinguishes these networks from MANETs is that the end goal is detection/estimation of some events of interest, and not just communications. To improve the performance of detection/estimation, it is often quite useful to fuse data from multiple sensors. This data fusion requires the transmission of data and control messages, and so it may put constraints on the network architecture.

- **Querying Ability**
  A user may want to query an individual node or a group of nodes for information collected in the region. Depending on the amount of data fusion performed, it may not be feasible to transmit a large amount of the data across the network. Instead, various local sink nodes will collect the data from a given area and create summary messages. A query may be directed to the sink node nearest to the desired location.

With the coming availability of low cost, short range radios along with advances in wireless networking, it is expected that wireless Ad-hoc sensor networks will become commonly deployed. In these networks, each node may be equipped with a variety of sensors, such as acoustic, seismic, infrared, still/motion video camera, etc. These nodes may be organized in clusters such that a locally occurring event can be detected by most of, if not all, the nodes in a cluster. Each node may have sufficient processing power to make a decision, and it will be able to broadcast this decision to the other nodes in the cluster. One node may act as the cluster master, and it may also contain a longer range radio using a protocol such as IEEE 802.11 or Bluetooth.

2.4 Wireless Mesh Networks

WMNs are a relative novel technology that is gaining significant attention. In contrast to traditional wireless networks, a WMN is dynamically self-organized and self-configured. In other words, the nodes in the mesh network automatically establish and maintain network connectivity. Additionally, all nodes have the capability to rely packets to other nodes on behalf of their neighbors, that is, every node of the network can act as a router. These features bring many advantages such as low up-front cost, easy network maintenance, robustness, and reliable service coverage. Moreover, the gateway functionality contained in some of the WMNs nodes enables the integration of this kind of networks with various existing technologies like Internet, cellular, IEEE 802.11, Wi-MAX, etc. Consequently, through an integrated wireless mesh network, the end-users can take advantage of multiple wireless networks [20]. WMNs are emerging as a possible solution for numerous applications. The most remarkable applications are the substitution of the wire line last mile broadband Internet service delivery, the backhaul of 3G and IEEE 802.11 'x' hot spots and transient networking.

2.4.1 Network Architecture

WMNs [21], [22], [23], [24] consist of mesh routers and mesh clients connected through wireless links. As mentioned before, both kind of nodes act as routers, forwarding packets on behalf of other nodes that may not be within direct wireless transmission range of their destinations. Mesh routers have minimal mobility (or no mobility at all) and form the backbone of WMNs. They are also the nodes that provide network access to mesh and conventional clients. Gateway and bridging functions also rely on this kind of nodes. Consequently, mesh routers are usually equipped with multiple interfaces.

On the other hand, mesh clients can be mobile and they only have one interface. Also, mesh clients usually suffer from power consumption constraints. The architecture of WMNs can be classified into three main groups based on the functionality of the nodes.

Infrastructure/Backbone Meshing

This type of infrastructure is only comprised of mesh routers, which form an infrastructure for clients that connect to them. The gateway functionality of the routers permits to integrate the wireless mesh network with clients employing existing technologies such as Ethernet or Wi-MAX among others. This architecture is shown in Fig. 2.4.

Client Meshing

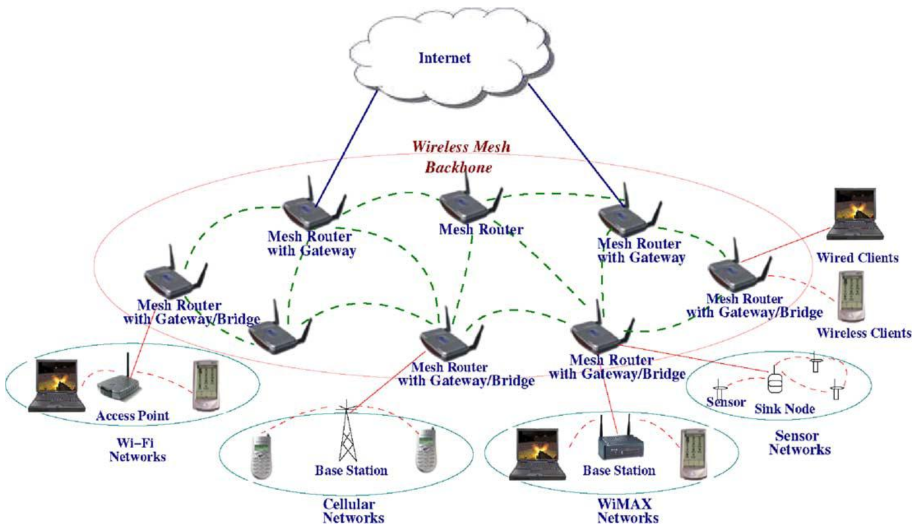


Figure 2.4: Infrastructure/Backbone meshing [25].

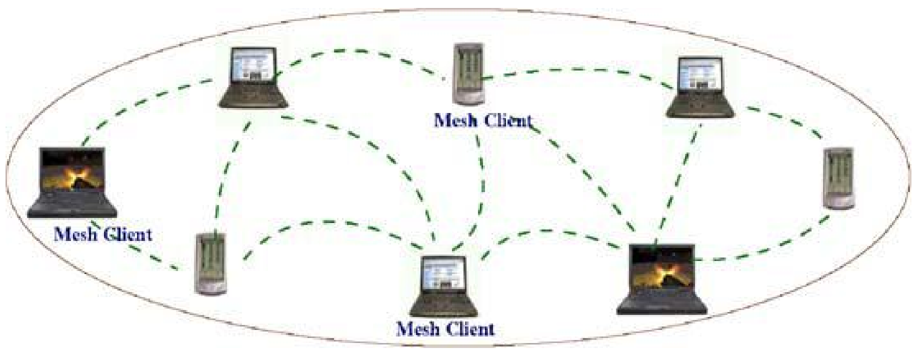


Figure 2.5: Client meshing [25].

Only mesh clients are contained in this type of architecture, as shown in Fig. 2.5. Client meshing provides peer-to-peer networks among client devices. This architecture is very similar to the Ad-hoc network architecture.

Hybrid Meshing

The combination of the backbone architecture with the client meshing results in the hybrid architecture. Mesh clients can access the network either through the mesh routers or directly meshing with other mesh clients. Furthermore, mesh routers can provide connectivity to networks with different technologies such as Wi-Fi, Wi-MAX and cellular networks (see Fig. 2.6).

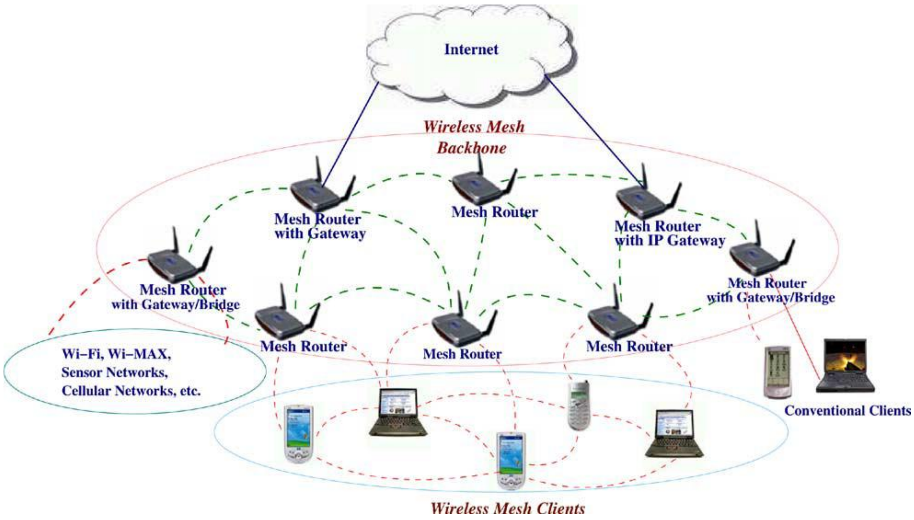


Figure 2.6: Hybrid meshing [25].

2.4.2 Advantages of Wireless Mesh Networks

The core advantages of a wireless mesh-based approach include the following.

- **Adaptive Backhaul Provisioning**
  One of the best features of a WMNs is the lack of the requirement to provide a wired backhaul connection to every node. Rather, user traffic is relayed over the air between nodes until it reaches its destination or a node with a connection to another network (like the Internet). Thus, one could deploy, for example, a Wi-Fi mesh to provide service over a large geographic area, but only very limited backhaul initially. As more users come online, and thus generate revenue, backhaul can be added as required in a very cost effective way.

- **Fault-tolerance**
  Meshes are very adaptable to failures in nodes or dropouts in radio coverage - traffic is simply re-routed dynamically. The self organizing functions run continuously, so when changes occur to connections and reception the mesh will automatically re-route around blockages in real time.

- **Bandwidth Scaling**
  Unlike most wireless networks, adding more nodes to a mesh increases overall network capacity and total available bandwidth.

- **Organization and Business Models**
  The decentralized nature of WMNs lends itself well to a decentralized ownership model wherein each participant in the network owns and maintains their own hardware, which can greatly simplify the financial and community aspects of the system.

- **Affordable**
  Each mesh node is inexpensive. As there are no central controllers needed the costs are linear. The fact that each mesh node runs both as a client and as a repeater potentially means saving on the number of radios needed and thus the total budget.

- **Ease and Simplicity**
  If you have a box that is pre-installed with wireless mesh software and uses standard wireless protocols such as 802.11b/g, the setup is extremely simple. Since routes are configured dynamically, it is often enough to simply drop the box into the network, and attach whatever antennas are required for it to reach one or more existing neighboring nodes (assuming that we can solve the issue of IP address allocation).

Chapter 3

Wireless Sensor and Actor Networks

3.1 WSAN Architectures

A WSAN is shown in Fig. 3.1. The main functionality of WSANs is to make actors perform appropriate actions in the environment, based on the data sensed from sensors and actors. When important data has to be transmitted (an event occurred), sensors may transmit their data back to the sink, which will control the actors' tasks from distance or transmit their data to actors, which can perform actions independently from the sink node. Here, the former scheme is called Semi-Automated Architecture and the latter one Fully-Automated Architecture, as seen in Figs. 3.2(a) and 3.2(b), respectively. Obviously, both architectures can be used in different applications. Fully-Automated Architecture, which is considered in this thesis, emerges the need to develop new sophisticated algorithms, in order to provide appropriate coordination between nodes of WSAN. On the other hand, it has advantages, such as *low latency*, *low energy consumption*, *long network lifetime* [5], *higher local position accuracy*, *higher reliability* and so on.

3.2 WSAN Challenges

The WSAN is shown in Fig. 3.1. Some of the key challenges in WSAN are related to the presence of actors and their functionalities.

Deployment and Positioning: WSAN are heterogeneous networks [26], where actors and sensors have different processing powers, mobility abilities and functionalities. Thus, at the moment of node deployment, algorithms must consider

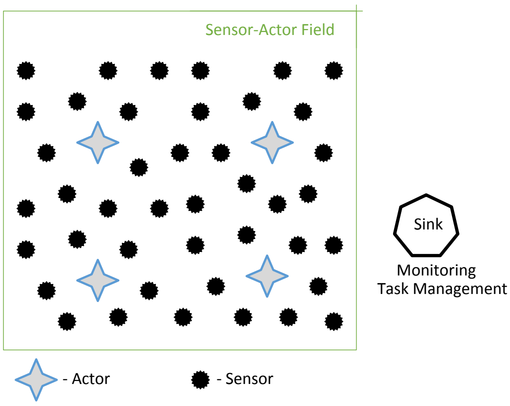
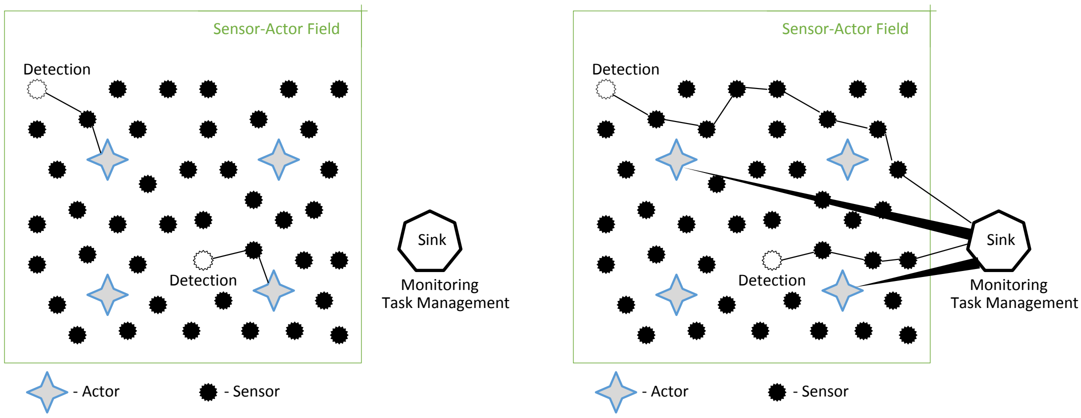


Figure 3.1: Wireless Sensor and Actor Network (WSAN).



(a) Fully-Automated

(b) Semi-Automated

Figure 3.2: WSAN Architectures

to optimize the number of sensors and actors and their initial positions based on applications [27, 28].

Architecture: The main functionality of WSANs is to make actors perform appropriate actions in the environment, based on the data sensed from sensors and actors [29, 30]. When important data has to be transmitted (an event occurred), sensors may transmit their data back to the sink, which will control the actors' tasks from distance or transmit their data to actors, which can perform actions independently from the sink node.

Real-Time: The purpose of using WSANs in most of the applications is mainly related to their ability to react independently to situations where human intervention is physically difficult or time-restricted [10, 31]. In other words, there are a lot of applications that have strict real-time requirements. In order to fulfill them, real-time limitations must be clearly defined for each application and system.

Coordination: Unlike WSN, where sensors coordinate with each-other to send data to the sink [32], in WSAN, sensor-actor coordination occurs as well, because all sensed data control actor's behavior. Also, actor-actor coordination is important in cases when actors collaborate on performing tasks together. In order to provide effective sensing and acting, a distributed local coordination mechanism is necessary among sensors and actors [30, 33].

Power Management: Similar to energy-constrained WSNs [34], in WSANs sensors have limited power supplies, which limits the network lifetime. Actors have more powerful power supplies but their functionalities are more sophisticated, so they spend more energy for complicated tasks. Thus, WSAN protocols should be designed with minimized energy consumption for both sensors and actors [10, 35].

Mobility: In WSANs, nodes, especially actors can be mobile [36]. For example, robots used in industrial monitoring sites or flying drones aver a disaster recovery area. Therefore, protocols developed for WSANs should support the mobility of nodes, [7, 37, 38], where dynamic topology changes, unstable routes and network isolations are present.

Self Healing: One of the main problems in mobile Self-Organizing Networks (SON) is the high probability of node isolations during network runtime. An actor failure may lead to partitioning the network and thus hinder the satisfaction of the application requirements. Many works have been done on connectivity restoration, by using actors ability to move without using much energy [7, 6]. Actors may also be specialized to carry extra energy supplies, in order to charge sensors or other actors in the network.

Scalability: Smart Cities are emerging fast and WSAN, with its practical functions of simultaneous sensing and acting, are a key technology. The heterogeneity is not limited and most of the systems will continue to grow together with cities. In order to keep the functionality of WSAN applicable, scalability should be considered when designing WSAN protocols and algorithms. Data replication, clustering and so on, can be used in order to support growing networks [28, 38].

3.3 Features of WSANs

However, due to the presence of actors, WSANs have some differences from wireless sensor networks (WSNs) as outlined below:

- While sensor nodes are small, inexpensive devices with limited sensing, computation and wireless communication capabilities, actors are usually resource-rich devices equipped with better processing capabilities, stronger transmission powers and longer battery life.

- In WSANs, depending on the application there may be a need to rapidly respond to sensor input. Moreover, to provide right actions, sensor data must still be valid at the time of acting. Therefore, the issue of real-time communication is very important in WSANs since actions are performed on the environment after sensing occurs.

- The number of sensor nodes deployed in studying a phenomenon may be in the order of hundreds or thousands. However, such a dense deployment is not necessary for actor nodes due to the different coverage requirements and physical interaction methods of acting task. Hence, in WSANs the number of actors is much lower than the number of sensors.

- In order to provide effective sensing and acting, a distributed local coordination mechanism is necessary among sensors and actors.

3.4 WSANs Applications

WSANs may consist of many different types of sensors such as seismic, low sampling rate magnetic, thermal, visual, infrared, acoustic and radar, which are able to monitor a wide variety of ambient conditions that include the following:

- temperature

- humidity

- vehicular movement

- lightning condition

- pressure
- soil makeup
- noise levels
- the presence or absence of certain kinds of objects
- mechanical stress levels on attached objects

Sensor nodes can be used for continuous sensing, event detection, event ID, location sensing and local control of actuators. The concept of micro-sensing and wireless connection of these nodes promise many new application areas. We categorize the applications into military, environment, health, home and other commercial areas. It is possible to expand this classification with more categories such as space exploration, chemical processing and disaster relief.

3.4.1 Military Applications

WSANs can be an integral part of military command, control, communications, computing, intelligence, surveillance, reconnaissance and targeting(C4ISRT) systems. The rapid deployment, self-organization and fault tolerance characteristics of sensor networks make them a very promising sensing technique for military C4ISRT. Since sensor networks are based on the dense deployment of disposable and low-cost sensor nodes, destruction of some nodes by hostile actions does not affect a military operation as much as the destruction of a traditional sensor, which makes sensor networks concept a better approach for battlefields. Some of the military applications of sensor networks are monitoring friendly forces, equipment and ammunition; battlefield surveillance; reconnaissance of opposing forces and terrain; targeting; battle damage assessment; and nuclear, biological and chemical (NBC) attack detection and reconnaissance.

Monitoring friendly forces, equipment and ammunition: Leaders and commanders can constantly monitor the status of friendly troops, the condition and the availability of the equipment and the ammunition in a battlefield by the use of sensor networks. Every troop, vehicle, equipment and critical ammunition can be attached with small sensors that report the status. These reports are gathered in sink nodes and sent to the troop leaders. The data can also be forwarded to the upper levels of the command hierarchy while being aggregated with the data from other units at each level.

Battlefield surveillance: Critical terrains, approach routes, paths and straits can be rapidly covered with sensor networks and closely watched for the activities of the opposing forces. As the operations evolve and new operational plans are prepared, new sensor networks can be deployed anytime for battlefield surveillance.

Reconnaissance of opposing forces and terrain: WSANs can be deployed in critical terrains, and some valuable, detailed, and timely intelligence about the opposing forces and terrain can be gathered within minutes before the opposing forces can intercept them.

Targeting: WSANs can be incorporated into guidance systems of the intelligent ammunition.

Battle damage assessment: Just before or after attacks, sensor networks can be deployed in the target area to gather the battle damage assessment data.

Nuclear, biological and chemical attack detection and reconnaissance: In chemical and biological warfare, being close to ground zero is important for timely and accurate detection of the agents. WSANs deployed in the friendly region and used as a chemical or biological warning system can provide the friendly forces with critical reaction time, which drops casualties drastically. We can also use sensor networks for detailed reconnaissance after an NBC attack is detected. For instance, we can make a nuclear reconnaissance without exposing a recce team to nuclear radiation.

3.4.2 Environmental Applications

Some environmental applications of sensor networks include tracking the movements of birds, small animals, and insects; monitoring environmental conditions that affect crops and livestock; irrigation; macro instruments for large-scale Earth monitoring and planetary exploration; chemical/biological detection; precision agriculture; biological, Earth, and environmental monitoring in marine, soil, and atmospheric contexts; forest fire detection; meteorological or geophysical research; flood detection; biocomplexity mapping of the environment; and pollution study.

Forest fire detection: Since sensor nodes may be strategically, randomly, and densely deployed in a forest, sensor nodes can relay the exact origin of the fire to the end users before the fire is spread uncontrollable. Millions of sensor nodes can be deployed and integrated using radio frequencies/ optical systems. Also, they may be equipped with effective power scavenging methods, such as solar cells, because the sensors may be left unattended for months and even years. The sensor nodes will collaborate with each other to perform distributed sensing and overcome obstacles, such as trees and rocks,that block wired sensors' line of sight.

Biocomplexity mapping of the environment: A biocomplexity mapping of the environment requires sophisticated approaches to integrate information across temporal and spatial scales. The advances of technology in the remote sensing and automated data collection have enabled higher spatial, spectral, and temporal resolution at a geometrically declining cost per unit area. Along with these advances, the sensor nodes also have the ability to connect with the Internet, which allows remote users to control, monitor and observe the biocomplexity of the environment. Although satellite and airborne sensors are useful in observing large biodiversity, e.g., spatial complexity of dominant plant species, they are not fine grain enough to observe small size biodiversity, which makes up most of the biodiversity in an ecosystem. As a result, there is a need for ground level deployment of wireless sensor nodes to observe the biocomplexity. One example of biocomplexity mapping of the environment is done at the James Reserve in Southern California. Three monitoring grids with each having 25-100 sensor nodes will be implemented for fixed view multimedia and environmental sensor data loggers.

Flood detection: An example of a flood detection is the ALERT system deployed in the US. Several types of sensors deployed in the ALERT system are rainfall, water level and weather sensors. These sensors supply information to the centralized database system in a pre-defined way. Research projects, such as the COUGAR Device Database Project at Cornell University and the DataSpace project at Rutgers, are investigating distributed approaches in interacting with sensor nodes in the sensor field to provide snapshot and long-running queries.

Precision Agriculture : Some of the benefits is the ability to monitor the pesticides level in the drinking water, the level of soil erosion, and the level of air pollution in real time.

3.4.3 Health Applications

Some of the health applications for sensor networks are providing interfaces for the disabled; integrated patient monitoring; diagnostics; drug administration in hospitals; monitoring the movements and internal processes of insects or other small animals; telemonitoring of human physiological data; and tracking and monitoring doctors and patients inside a hospital.

Telemonitoring of human physiological data: The physiological data collected by the sensor networks can be stored for a long period of time, and can be used for medical exploration. The installed sensor networks can also monitor and detect elderly people's behavior, e.g., a fall. These small sensor nodes allow the subject a greater freedom of movement and allow doctors to identify pre-defined symptoms earlier. Also, they facilitate a higher quality of life for the subjects compared to the treatment centers. A "Health Smart Home" is designed in the Faculty of Medicine in Grenoble - France to validate the feasibility of such system.

Tracking and monitoring doctors and patients inside a hospital: Each patient has small and light weight sensor nodes attached to them. Each sensor node has its specific task. For example, one sensor node may be detecting the heart rate while another is detecting the blood pressure. Doctors may also carry a sensor node, which allows other doctors to locate them within the hospital.

Drug administration in hospitals: If sensor nodes can be attached to medications, the chance of getting and prescribing the wrong medication to patients can be minimized. Because, patients will have sensor nodes that identify their allergies and required medications. Computerized systems as described in have shown that they can help minimize adverse drug events.

3.4.4 Home Applications

Home automation: As technology advances, smart sensor nodes and actuators can be buried in appliances, such as vacuum cleaners, micro-wave ovens, refrigerators, and VCRs. These sensor nodes inside the domestic devices caninteract with each other and with the external network via the Internet or Satellite. They allow end users to manage home devices locally and remotely more easily.

Smart environment: The design of smart environment can have two different perspectives, i.e., human-centered and technology-centered. For human-centered, a smart environment has to adapt to the needs of the end users in terms of input/output capabilities. For technology-centered, new hardware technologies, networking solutions, and middleware services have to be developed. A scenario of how sensor nodes can be used to create a smart environment. The sensor nodes can be embedded into furniture and appliances, and they can communicate with each other and the room server. The room server can also communicate with other room servers to learn about the services they offered, e.g., printing, scanning, and faxing. These room servers and sensor nodes can be integrated with existing embedded devices to become self-organizing, self-regulated, and adaptive systems based on control theory models. Another example of smart environment is the "Residential Laboratory" at Georgia Institute of Technology. The computing and sensing in this environment has to be reliable, persistent, and transparent.

3.4.5 Other Commercial Applications

Some of the commercial applications are monitoring material fatigue; building virtual keyboards; managing inventory; monitoring product quality; constructing smart office spaces; environmental control in office buildings; robot control and guidance in automatic manufacturing environments; interactive toys; interactive museums; factory process control and automation; monitoring disaster area; smart structures with sensor nodes embedded inside; machine diagnosis; transportation; factory instrumentation; local control of actuators; detecting and monitoring car thefts; vehicle tracking and detection; and instrumentation of semiconductor processing chambers, rotating machinery, wind tunnels, and anechoic chambers.

Environmental control in office buildings: The air conditioning and heat of most buildings are centrally controlled. Therefore, the temperature inside a room can vary by few degrees; one side might be warmer than the other because there is only one control in the room and the air flow from the central system is not evenly distributed. A distributed wireless sensor network system can be installed to control the air flow and temperature in different parts of the room. It is estimated that such distributed technology can reduce energy consumption by two quadrillion British Thermal Units (BTUs) in the US, which amounts to saving of 55 dollar billion per year and reducing 35 million metric tons of carbon emissions.

Interactive museums: In the future, children will be able to interact with objects in museums to learn more about them. These objects will be able to respond to their touch and speech. Also, children can participate in real time cause-and-effect experiments, which can teach them about science and environment. In addition, the wireless sensor networks can provide paging and localization inside the museum. An example of such museums is the San Francisco Exploratorium that features a combination of data measurements and cause-and-effect experiments.

Detecting and monitoring car thefts: Sensor nodes are being deployed to detect and identify threats within a geographic region and report these threats to remote end users by the Internet for analysis.

Managing inventory control: Each item in a warehouse may have a sensor node attached. The end users can find out the exact location of the item and tally the number of items in the same category. If the end users want to insert new inventories, all the users need to do is to attach the appropriate sensor nodes to the inventories. The end users can track and locate where the inventories are at all times.

Vehicle tracking and detection: There are two approaches as described in to track and detect the vehicle: first, the line of bearing of the vehicles determined locally within the clusters and then it is forwarded to the base station, and second, the raw data collected by the sensor nodes are forwarded to the base station to determine the location of the vehicle.

Chapter 4

Fuzzy Logic

4.1 Introduction

For a long time, classical logic has been felt too limited as a framework for modeling all facets of human reasoning. So far, probability has been the only uncertainty with which mathematics has worked, but recently the uniqueness of probability theory as a model for capturing uncertainty and vagueness has been questioned. The uncertainty of probability generally relates to the occurrence of phenomena, as symbolized by the concept of randomness. Randomness and fuzziness differ in nature from probability. That is, they are different aspects of uncertainty. The uncertainty lies in the meaning of the words, and since it is an essential characteristic of the words, it always follows them around to some extend.

Many attempts have been made, especially in this century, for augmenting the representational capabilities of logic, or for proposing non-additive models of uncertainty. One of the most radical and fruitful of these attempts was initiated by Prof. Lotfi Zadeh in 1965 with publication of his paper "Fuzzy Sets" [39, 40, 41]. Fuzzy set theory has became accepted in the literature as a tool for dealing with certain forms of imprecision that frequently occur in decision making environments, but for which probability calculus is inadequate. Fuzzy theory use linguistic variables to describe the control parameters. By using relatively simple linguistic expressions is possible to describe and grasp very complex problems. A very important property of the linguistic variables is the capability of describing imprecise parameters.

This chapter is devoted to fuzzy set theory. We will introduce the meaning of FL and the essentials of FL. Next, we will give the basics of fuzzy set theory.

Finally, we will illustrate the Fuzzy Control (FC) principles by treating the linguistic variables, FC rules, fuzzification, control knowledge base, conflict resolution and decision making, and the defuzzification methods, which are the theoretical need in the design of the FL-based proposed systems.

4.2 Meaning of FL

When discussing FL, there is a semantic issue which requires clarification. The term "fuzzy logic" is currently used in two different sense. In a narrow sense, FL is a logical system that aims at a formalization of approximate reasoning. As such, it is rooted in multivalued logic, but its agenda is quite different from that of traditional multivalued logical systems. In this connection, what should be noted is that many of concepts which account for the effectiveness of FL as a logic of approximate reasoning are not a part of traditional multivalued logical systems. Among these are the concept of a linguistic variable, canonical form, fuzzy if-then rules, fuzzy quantifiers, and such modes of reasoning as interpolative reasoning, syllogistic reasoning and dispositional reasoning.

In a broad sense, FL is almost synonymous with fuzzy set theory. Fuzzy set theory, as its name suggests, is basically a theory of classes with unsharp boundaries. Fuzzy set theory is much broader than FL in its narrow sense and contains the latter as one of its branches [42, 43, 44]. Among the other branches of fuzzy set theory are e.g., fuzzy arithmetic, fuzzy mathematical programming, fuzzy topology, fuzzy graph theory, and fuzzy data analysis. What is important to recognize is that any crisp theory can be fuzzified by generalizing the concept of a set within that theory to the concept of a fuzzy set. Indeed, it is very likely that eventually most theories will be fuzzified in this way. The impetus for the transition from crisp theory to a fuzzy one derives from the fact that both are generality of a theory and its applicability to real-wold problems are substantially enhanced by replacing the concept of a set with that of a fuzzy set. Today, the growing tendency is to use the term "fuzzy logic" in its broad sense. In part, this reflects the fact that fuzzy set theory sounds less euphonious than FL.

4.3 Essentials of FL

FL is the logic underlying modes of reasoning which are approximate rather then exact. The importance of FL derives from the fact that most modes of human reasoning and especially common sense reasoning are approximate in nature.

The essential characteristics of FL relate to the following.

- In FL, exact reasoning is viewed as a limiting case of approximate reasoning.
- In FL everything is a matter of degree.
- Any logic system can be fuzzified.
- In FL, knowledge is interpreted as a collection of elastic or, equivalently, fuzzy constraints on a collection of variables.
- Inference is viewed as a process of propagation of elastic constrains.

FL is different from other traditional logical systems in some details. The principal differences are mentioned as follows.

- **Truth**
  In bivalent logical systems, truth can have only two values : true or false. In multivalued systems, the truth value of a proposition may be an element of a) a finite set; b) an interval such as [0, 1]; or c) a boolean algebra. In FL, the truth value of a proposition may be a fuzzy subset of any partially ordered set but usually it is assumed to be a fuzzy subset of the interval [0, 1] or more simple a point in this interval. The so-called linguistic truth values expressed as *true*, *very true*, *not quite true*, etc., are interpreted as labels of fuzzy subsets of the unit interval.
- **Predicates**
  In bivalent systems, the predicates are crisp. In FL, the predicates are fuzzy, e.g., *tall*, *old*, *much longer than*. It should be noted that most of the predicates in a natural language are fuzzy rather than crisp.
- **Predicate modifiers**
  In classical systems, the only widely used predicate modifier is the negation *not*. In FL, there is a variety of predicate modifiers which act as hedges, e.g.,

very, *more or less*, *quite*, *rather*, *extremely*. Such predicate modifiers play an essential role in the generation of the values of linguistic variables, e.g., *very young*, *not very young*, *more or less young*.

- **Quantifiers**
  In classical logical systems there are just two quantifiers : *universal* and *existential*. FL admits in addition, a wide variety of fuzzy quantifiers exemplified by *few*, *several*, *most*, *almost*, *always*, *about five*, etc. In FL, a fuzzy quantifier is interpreted as a fuzzy number or fuzzy proportion.

- **Probabilities**
  In classical logical systems, probability is numerical or interval-valued. In FL, one has the additional option of employing linguistic or, more generally, fuzzy probabilities exemplified by *likely*, *unlikely*, *very likely*, *around 0.8*, etc. Such probabilities may be interpreted as fuzzy numbers which may be manipulated through the use of fuzzy arithmetic.

- **Possibilities**
  In contrast to classical logic, the concept of possibility in FL is graded rather than bivalent. Furthermore, as in the case of probabilities, possibilities may be treated as linguistic variables with values such as *possible*, *quite possible*, *almost impossible*, etc. Such values may be interpreted as labels of fuzzy subsets in the real line.

It is important to observe that in every instance FL adds to the options which are available in classical logical systems. In this sense, FL may be viewed as an extension of such systems rather than a system of reasoning which is in conflict with the classical systems [41, 45, 46].

4.4 Basics of Fuzzy Set Theory

The concept of a fuzzy set deals with the representation of classes whose boundaries are not determined. It uses a characteristic function, taking values usually in the interval [0, 1]. The fuzzy sets are used for representing linguistical labels. This can be viewed as expressing an uncertainty about the clear-cut meaning of the label. But important point is that the valuation set is supposed to be common to the various linguistic labels that are involved in the given problem.

The fuzzy set theory uses the membership function to encode a preference among the possible interpretations of the corresponding label. A fuzzy set can be defined by examplification, ranking elements according to their typicality with respect to the concept underlying the fuzzy set [47, 48, 49]. The prototypical element receives the greater membership grade. Fuzzy set naturally appears in non-strict specification. It may be soft constraints or flexible requirements for which slight violations can be tolerated (e.g., the dead line is today, but tomorrow is still acceptable although less good), or elastic classes of objects, approximate descriptions of types of situation to which a given procedure can be applied, or even procedures with fuzzy stated instructions. In each case fuzzy sets preserve a gradual and smooth transition from one category into another and avoid abrupt discontinuities that would be caused by the assignment of precise boundaries for the considered subsets. The specification thus becomes more robust and adaptive. In this case, fuzzy sets provide a tool for bridging the gap between the perceived continuity of the world and human discrete cognitive representation. In particular, fuzzy sets help with interfacing numerical data and symbolic labels.

4.4.1 Quantification of Ambiguity

Most natural languages contain ambiguity and multiplicity of meaning. The objects of adjectives, especially, are not clearly specific, and are ambiguous in terms of breath of meaning. If we say “tall person”, we can’t clearly determine who is tall or who is not tall. The ambiguity of “old person” comes from the adjective “old”. Words are usually qualitative, but ones like “tall” and “old” are perceived in connection with amounts of height or age. If we leave out abstract adjectives like “ambiguous”, “vague” and “uncertain”, adjectives that involve amounts are common. In engineering, especially, the adjectives that describe the states and conditions of various things are almost always connected to amounts in this way.

Let’s take a look at the ambiguity of the meanings of “tall” and “old” in terms of expression of amount. With a range of height of 140 cm to 200 cm, the degree to which heigh x[cm] can be called “tall” is μ, that is, we make height x correspond to degree μ ($0 \leq \mu \leq 1$). If the horizontal axis is x and the vertical axis is μ, the

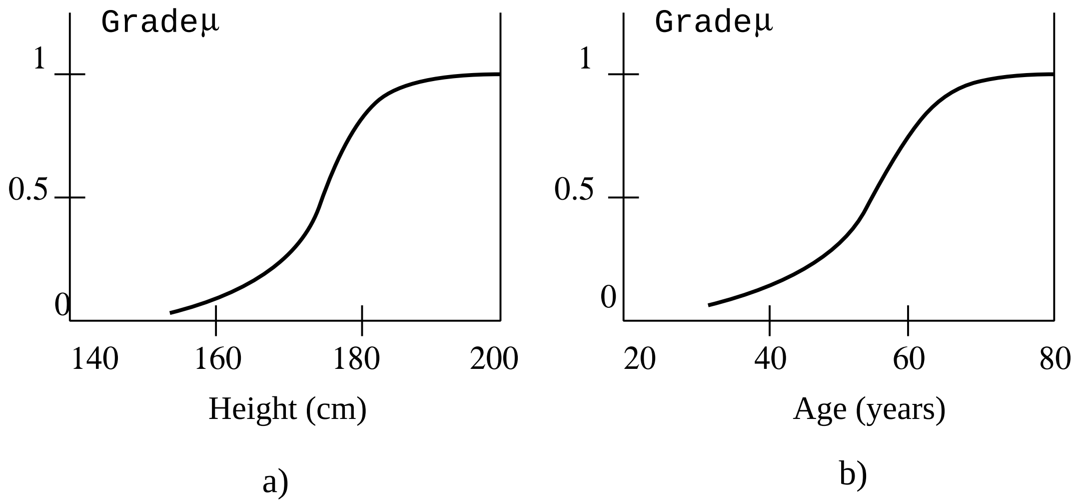


Figure 4.1: a) Grade of "tall", b) Grade of "old".

graph would be drawn as in Fig. 4.1(a). This graph expresses the ambiguity of "tall" in terms of quantity. In the same way the ambiguity of "old" is expressed in Fig. 4.1(b). The amount in the horizontal axis is the age in years, and the vertical axis shows the degree to which a person can be labeled "old". The horizontal axis is the quantification of the word, the expression of height or age in one dimensional space, and the vertical axis is the quantification of the degree of ambiguity. This kind of representation of a word is called *quantification of meaning*. The meaning of the word is quantified over a specific range; for height this range is 140 cm to 200 cm, and for age it is 20 to 80 years.

4.4.2 Fuzzy Set Definitions

A fuzzy set is a class with fuzzy boundaries, that is a class in which the transition from membership to non-membership is gradual rather than abrupt. Fuzzy set theory works with quantification of the meanings of words in graphs within the framework of set theory. It is an attempt to express the adjectives meaning by means of the concept of sets. This is because set theory is a very basic concept and has connection with all fields of contemporary mathematics. In following are some of the essential notations for the introduction of the fuzzy set theory:

- X whole set (the universe of discourse);
- E subset of X;
- $\oslash$ empty set;
- $\{0, 1\}$ the set of zero and 1;
- $[0, 1]$ the real number interval from zero to 1;
- χ_E characteristic function of set E;
- $a \wedge b$ the min of a and b;
- $a \vee b$ the max of a and b.

A fuzzy set is an extension of a crisp set. Crisp sets only allow full membership or no membership at all, whereas fuzzy sets allow partial membership. In other words, an element may partially belong to a set. In a crisp set, the membership or non-membership of an element x in set E, where E is a crisp subset of X, is described by the following characteristic function:

$$\chi_E = \begin{cases} 1; & x \in E \\ 0; & x \;\; not \in E. \end{cases} \tag{4.1}$$

This corresponds to the membership function of E. The grade is two-valued; if x is included in E it is 1; if not is zero.

On the other hand, a fuzzy set is a class with fuzzy boundaries. An abstract representation of a fuzzy subset of set X would look something like Fig. 4.2. The rectangular frame represents set X, the dotted circle represents the subset of X that we denote by A. Fuzzy set theory defines the degree to which element x of the set X is included in this subset. The function that gives the degree to which it is included is called the membership function. A more precise definition of a fuzzy set may be stated as follows:

Definition 1

Let X=$\{x\}$ be the universe of discourse (i.e. a collection of objects), denoted generically by x; then a fuzzy subset of X, A, is a set of ordered pairs $(x, \mu_A(x))$, x

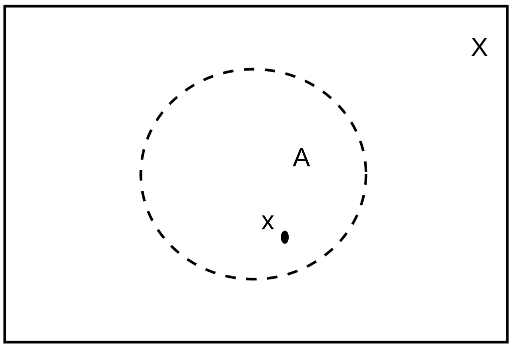


Figure 4.2: Fuzzy subset A.

ϵ X, where $\mu_A(x)$ is the grade of membership of x in A, and $\mu_A : X \rightarrow [0, 1]$ is the membership function.

Since a fuzzy set is always defined as a subset of a general set X, the "sub" is frequently abbreviated, and is just called a fuzzy set. From the definition we see that the function over the interval $[0, 1]$ has a one-to-one correspondence with the fuzzy set. This function is a quantification of the ambiguity of area A. In fact, this function has the same characteristics as the graphs in Fig. 4.1(a,b). Fig. 4.1(a) can be thought of as a representation of the membership functions of the "group of heights that can be thought of as tall" fuzzy set within the set of heights of 140 cm to 200 cm. Fig. 4.1(b) can be viewed as the membership function of the fuzzy set which is "the group of ages that can be considered old" in the range from 20 to 80 years. However, there are an infinite number of fuzzy sets and any form of membership functions is possible, so fuzzy sets do not always have to correspond to words.

If we think about the membership function of the fuzzy set not only for "tall", but also for "about average" and "short", we come up with something which will look like Fig. 4.3. As can been seen from this figure, there are two basic things that control fuzzy sets. The first is the horizontal axis, that is, the whole set X. X is called the support set of the fuzzy set, or simple support. The second is the membership function. Anyone would probably think of the membership function of "about average" as rising in the middle, but the grade of about 150 cm or 170 cm would probably vary subjectively with the person doing the thinking. In this way, fuzzy sets can be seen as being subjective, as opposed to standard sets, which are objective.

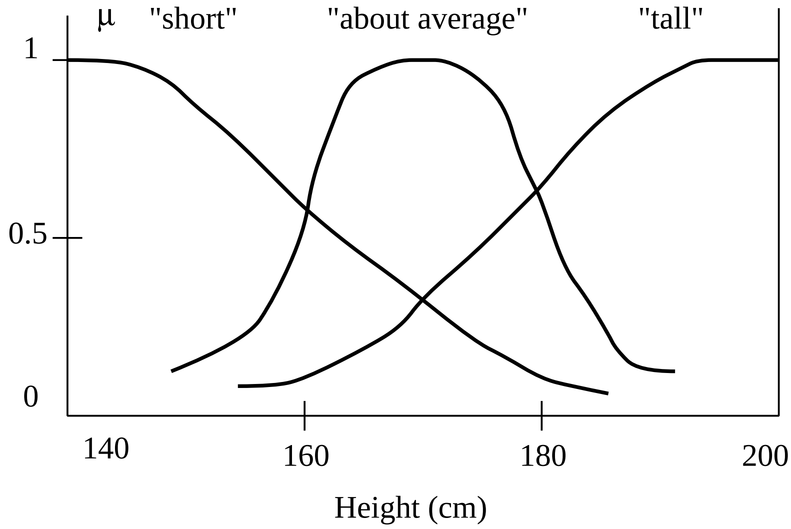


Figure 4.3: Membership functions for “short”, “about average”, “tall”.

In the following we give some definitions for operation with fuzzy sets.

Definition 2

Equality. If A and B are fuzzy subsets of X, then A and B are equal, written as A=B, if and only if:

$$\mu_A(x) = \mu_B(x), \forall x \in X.$$

Definition 3

Containment. If A and B are fuzzy subsets of X, then A is subset of B, written as $A \subseteq B$, if and only if:

$$\mu_A(x) \leq \mu_B(x), \forall x \in X.$$

Definition 4

Complementation. The complement of a fuzzy subset A of X denoted by $\bar{A}$, is defined as follows:

$$\mu_{\bar{A}}(x) = 1 - \mu_A(x), \forall x \in X.$$

Definition 5

Union. The union of two fuzzy subsets, A and B of X, denoted by $A \cup B$, is defined by:

$$\mu_{A \cup B}(x) = max(\mu_A(x), \mu_B(x)), \forall x \in X.$$

Definition 6

Intersection. The intersection of two fuzzy subsets A and B of X, denoted by $A \cap B$, is defined by:

$$\mu_{A \cap B}(x) = min(\mu_A(x), \mu_B(x)),\ \forall x \in X.$$

Definition 7

Concentration. The concentration of a fuzzy subset A of X, denoted by $\mu_{CON(A)}(x)$, is defined by:

$$\mu_{CON(A)}(x) = \mu_A^2(x),\ \forall x \in X.$$

Definition 8

Dilution. The dilution of a fuzzy subset A of X, denoted by $\mu_{DIL(A)}(x)$, is defined by:

$$\mu_{DIL(A)}(x) = \sqrt{\mu_A(x)},\ \forall x \in X.$$

Definition 9

Fuzzy relations. Let $X = \{(x)\}$ and $Y = \{(y)\}$ be two arbitrary domains of discourse. A fuzzy relation R from X to Y is a fuzzy subset of the Cartesian product $X \times Y = \{(x, y)\}$, characterized by membership function $\mu_R : X \times Y \to [0, 1]$ which associates with each pair (x, y) its grade of membership $\mu_R(x, y)$ in R.

Definition 10

Fuzzy composition. Let R be a fuzzy relation in $X \times Y$ and S a fuzzy relation in $Y \times Z$. The composition of R and S, $R \circ S$, is a fuzzy relation in $X \times Z$ as defined below:

$$R \circ S \longleftrightarrow \mu_{R \circ S}(x, z) = \vee_y \{(\mu_R(x, y) \wedge \mu_S(y, z)\}, \tag{4.2}$$

where $\vee = max$, $\wedge = min$. This composition uses max and min operations, so it is called max-min composition.

4.5 FC

The ability of fuzzy sets and possibility theory to model gradual properties or soft constraints whose satisfaction is matter of degree, as well as information pervaded with imprecision and uncertainty, makes them useful in a great variety of applications.

The most popular area of application is FC, since the appearance, especially in Japan, of industrial applications in domestic appliances, process control, and automotive systems, among many other fields. In the FC systems, expert knowledge is encoded in the form of fuzzy rules, which describe recommended actions for different classes of situations represented by fuzzy sets. An interpolation mechanism provided by the FC methodology is then at work. The current situation encountered by the system partially resembles two or more prototypical situations for which recommended control actions are known, and a control action that is intermediary between these recommended ones is computed on the basis of the resemblance degrees.

A FC unit can do the same work as a Proportional-integral-derivative (PID) controller, since it implicitly defines a numerical function tying the control variables and the observed control variables together. The difference between classical and FC methods lies in the way this control law is found. In the context of classical automatic control, especially optimal control theory, the control law is calculated using a mathematical model of process, whereas the FL approach, consistent with artificial intelligence, suggests that the control law be built starting from the expertise of a human operator. In applications of PID controllers, the philosophy is close to FL controllers, since the tuning of the PID parameters is usually done in an ad hoc way. However, only linear control laws can be attained with a PID, while the fuzzy controller may capture non-liner laws, which may explain the success of the fuzzy controllers over PID controllers. In fact, any kind of control law can be modelled by the FC methodology, provided that this law is expressible in terms of "if ... then ..." rules, just like in the case of expert systems. However, FL diverges from the standard expert system approach by providing an interpolation mechanism from several rules. In the contents of complex processes, it may turn out to be more practical to get knowledge from an expert operator than to calculate an optimal control, due to modeling costs or because a model is out of reach.

4.5.1 Linguistic Variables

A concept that plays a central role in the application of FL is that of a linguistic variable. Considering the membership functions in Fig. 4.3. The linguistic variable is "height" whose linguistic values are *short, about average, tall* with *tall* defined by the membership function such as shown in Fig. 4.1(a). Clearly, a numerical value such as 170 is simpler then the function *tall*. But *tall* represents a choice of one out of three possible values whereas 170 is a choice of one out of, say, 200 values. The point of this example is that the use of linguistic variables may be viewed as a form of data compression. It is suggestive to refer to this form of data compression as granulation [50, 51, 52].

The same effect can be achieved by conventional quantization, but in the case of quantization, the values are intervals, whereas in the case of granulation the values are overlapping fuzzy sets. The advantages of granulation over quantization are as follows:

- it is more general;
- it mimics the way in which humans interpret linguistic values;
- the transition from one linguistic value to a contiguous linguistic value is gradual rather than abrupt, resulting in continuity and robustness.

4.5.2 FC Rules

FC describes the algorithm for process control as a fuzzy relation between information about the conditions of the process to be controlled, x and y, and the output for the process z. The control algorithm is given in "if-then" expression, such as:

If x is small and y is big, then z is medium;
If x is big and y is medium, then z is big.

These rules are called *FC rules*. The "if" clause of the rules is called the antecedent and the "then" clause is called consequent. In general, variables x and y are called the input and z the output. "Small" and "big" are fuzzy values for x and y, and they are expressed by fuzzy sets.

Fuzzy controllers are constructed of groups of these FC rules, and when an actual input is given, the output is calculated by means of fuzzy inference.

4.5.3 Coding the Inputs: Fuzzification

In the coding the values from sensors, one transforms the values of the sensor measurement in terms of the linguistic labels in the precondition of the rules.

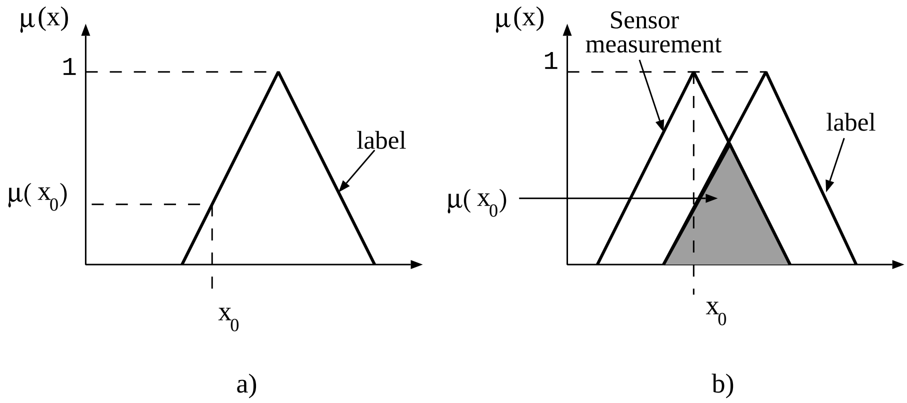


Figure 4.4: Fuzzification step. a) Crisp sensor reading, b) Fuzzy sensor reading.

If the sensor reading has a crisp value, than the fuzzification stage requires matching the sensor measurement against the membership function of the linguistic variable as is shown in Fig. 4.4(a). If the sensor reading contains noise, it may be modeled by using a triangular membership function where the vertex of the triangle refers to the mean value of the data set of sensor measurement and the base refers to a function of the standard deviation. Then in this case, fuzzification refers to finding out the intersection of the label's membership function and the distribution for the sensed data as shown in Fig. 4.4(b). However, the most widely used fuzzification method is the former case when the sensor reading is crisp.

4.5.4 Control Knowledge Base

There are two main tasks in designing the control knowledge base. First, a set of linguistic variables must be selected which describe the values of the main control parameters of the process. Both the input and output parameters must be linguistically defined in this stage using proper term sets. The selection of the level of granularity of a term set for an input variable or an output variable plays an important role in the smoothness of control. Second, a control knowledge base must be developed which uses the above linguistic description of the input and output parameters. Four methods [41, 53, 54] have been suggested for doing this:

- expert's experience and knowledge;
- modeling the operator's control action;

- modeling a process;
- self organization.

Among the above methods, the first one is the most widely used. In the modeling of the human expert operator's knowledge, fuzzy rules of the form "If Error is small and Change-in-error is small then the Force is small" have been used in several studies [55, 56, 57, 58]. This method is effective when expert human operators can express the heuristics or the knowledge that they use in controlling a process in terms of rules of the above form.

The second method directly models the control actions of the operator. Instead of interviewing the operator, the types of control actions taken by the operators are modelled.

The third method deals with fuzzy modeling of a process where an approximate model of the plant is confirmed by using implications which describe the possible states of the system. In this method a model is developed and a fuzzy controller is constructed to control the fuzzy model, making this approach similar to the traditional approach taken in control theory. Hence, structure identification and parameter identification processes are needed.

The fourth method refers to the research of Procyk and Mamdani [44]. The main idea in this method is the development of rules which can be adjusted over time to improve the controllers performance. This method is very similar to the use of neural networks in designing the knowledge base of a fuzzy logic controller.

4.5.5 Conflict Resolution and Decision Making

More than one FC rule can be fired at one time, because of the partial matching attribute of FC rules and the fact that the preconditions of the rules do overlap. The methodology which is used in deciding what control action should be taken as the result of the firing of several rules can be referred to as the process of "conflict resolution".

The following example, using two rules, illustrate this process. Assume that we have the following:

$$\begin{aligned}\text{Rule 1}&: \text{IF } X \text{ is } A_1 \text{ and } Y \text{ is } B_1 \text{ THEN } Z \text{ is } C_1;\\ \text{Rule 2}&: \text{IF } X \text{ is } A_2 \text{ and } Y \text{ is } B_2 \text{ THEN } Z \text{ is } C_2.\end{aligned}$$

Now, if we have x_0 and y_0 as the sensor readings for fuzzy variables X and Y, then their truth values are represented by membership functions $\mu_{A_1}(x_0)$ and $\mu_{B_1}(y_0)$ for Rule 1, and $\mu_{A_2}(x_0)$ and $\mu_{B_2}(y_2)$ for Rule 2. The *strength* for Rule 1 can be calculated by:

$$\alpha_1 = \mu_{A_1}(x_0) \wedge \mu_{B_1}(y_0). \tag{4.3}$$

Similarly for Rule 2:

$$\alpha_2 = \mu_{A_2}(x_0) \wedge \mu_{B_2}(y_0). \tag{4.4}$$

The control output of rule 1 is calculated by applying the matching strength of its precondition on its conclusion:

$$\mu_{C_1'}(\omega) = \alpha_1 \wedge \mu_{C_1}(\omega) \tag{4.5}$$

and for Rule 2:

$$\mu_{C_2'}(\omega) = \alpha_2 \wedge \mu_{C_2}(\omega) \tag{4.6}$$

where ω ranges over the values that the rule conclusion can take. This means that as a result of reading sensor values x_0 and y_0, Rule 1 is recommending a control action with $\mu_{C_1'}(\omega)$ as its membership function and Rule 2 is recommending a control action with $\mu_{C_2'}(\omega)$ as its membership function. The conflict-resolution process then produces:

$$\mu_C(\omega) = \mu_{C_1'}(\omega) \vee \mu_{C_2'}(\omega) = [\alpha_1 \wedge \mu_{C_1}(\omega)] \vee [\alpha_2 \wedge \mu_{C_2}(\omega)] \tag{4.7}$$

where $\mu_C(\omega)$ is a pointwise membership function for the combined conclusion of Rule 1 and Rule 2. The result of the last operation is a membership function and has to be translated (defuzzified) to a single value appropriate for control. The inference process with different fuzzy variable membership functions is shown in Fig. 4.5.

4.5.6 Defuzzification Methods

The defuzzification operation produces a nonFC action that best represent the membership function of an inferred FC action. Several defuzification methods have been suggested in literature. Among them, four methods which have been applied most often are described in following.

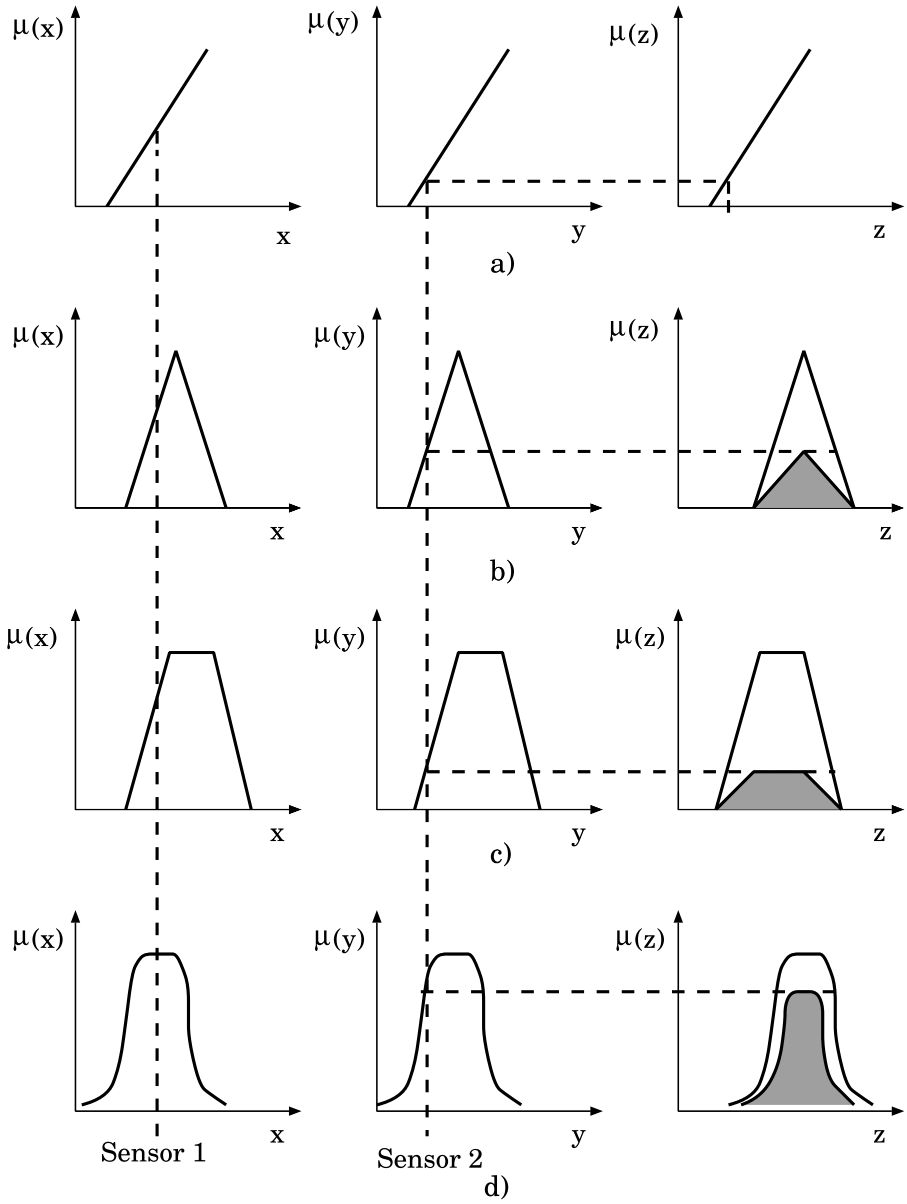


Figure 4.5: Inference process with different fuzzy variable membership functions: a) monotonic, b) triangular, c) trapezoidal, d) bell shape.

- **Tsukamoto's Defuzzification Method**
  If monotonic membership functions are used, then a crisp control action can be calculated by:

$$Z^* = \frac{\sum_{i=1}^{n} \omega_i x_i}{\sum_{i=1}^{n} \omega_i} \tag{4.8}$$

where n is the number of rules with firing strength (ω_i) greater then 0 and x_i is the amount of control action recommended by rule i.

- **The Center Of Area (COA) Method**
  Assuming that a control action with a pointwise membership function μ_C has been produced. The COA method calculates the center of gravity of the distribution for the control action. Assuming a discrete universe of discourse, we have:
$$Z^* = \frac{\sum_{j=1}^{q} z_j \mu_C(z_j)}{\sum_{j=1}^{q} \mu_C(z_j)} \tag{4.9}$$
  where q is the number of quantization levels of the output, z_j is the amount of control output at the quantization level j and $\mu_C(z_j)$ represents its membership function value in C.

- **The Mean Of Maximum(MOM) Method**
  The MOM method generates a crisp control action by averaging the support values which their membership values reach the maximum. For a discrete universe of discourse, this is calculated by:
$$Z^* = \sum_{j=1}^{l} \frac{z_j}{l} \tag{4.10}$$
  where l is the number of quantized z values which reach their maximum memberships.

- **Defuzzification when Output of Rules are Function of Their Inputs**
  FC rules may be written as a function of their inputs. For example,
$$\text{Rule } i: \text{ If } X \text{ is } A_i \text{ and } Y \text{ is } B_i \text{ then } Z \text{ is } f_i(X,Y);$$
  assuming that α_i is the firing strength of the rule i, then:
$$Z^* = \frac{\sum_{i=1}^{n} \alpha_i f_i(x_i, y_i)}{\sum_{j=1}^{n} \alpha_i}. \tag{4.11}$$

Chapter 5

Proposed Fuzzy-based Systems for Actor Node Selection in WSANs

In this chapter, we present four of the proposed fuzzy-based systems.

5.1 Problem Description

After data has been sensed from sensors, it is collected to the sink for semi-automated architecture or spread to the actors for fully-automated architecture. Then a task is assigned to actors. In general, one or more actors take responsibility and perform appropriate actions. Different actors may be chosen for acting, depending on their characteristics and conditions. For example, if an intervention is required in the 4^{th} floor of a building, a flying robot can go there faster and easier. While, if a kid is inside a room in fire, it is better to send a small robot. In this way, it will have more flexibility in moving in a dangerous place. The issue here is which of the actors will be selected to respond to critical data collected from the field (actor selection).

If WSAN uses semi-automated architecture, the sinks are used to collect data and control the actors. They may be supplied with detailed information about actors characteristics (size, ability etc.) and they may also collect actor's conditions during network run-time. If fully-automated architecture is being used, the collected data is processed only by actors, so they first have to decide whether they have the proper ability and right conditions to perform. We define this as the level of willingness or actor selection decision. Soon after that, actors coordinate with each-other, to

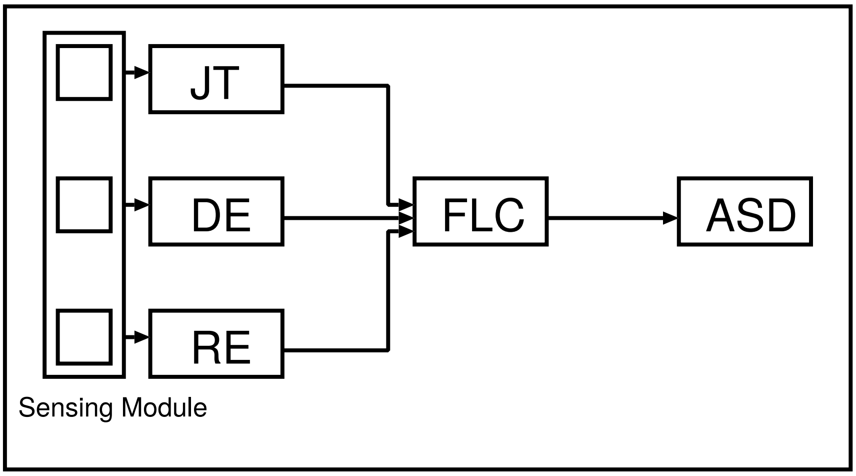


Figure 5.1: Structure of implemented FBSANS1.

decide more complicated procedures like acting multiple actors, or choosing the most appropriate one from several candidates.

In this work, we propose four fuzzy-based system in order to select an actor node for a required task.

5.2 System Parameters

Based on WSAN characteristics and challenges, we consider the following parameters for implementation of our proposed system.

Job Type (JT): A sensed event may be triggered by various causes, such as when water level passed a certain height of the dam. Similarly, for solving a problem, actors need to perform actions of different types. Actions may be classified regarding time duration, complexity, working force required etc., and then assign a priority to them, which will guide actors to make their decisions. In our system JT is defined by different levels of difficulty. The hardest the task, the more likely an actor is to be selected.

Distance to Event (DE): The number of actors in a WSAN is smaller than the number of sensors. Thus, when an actor is called for action near an event, the distance from the actor to the event is different for different actors and events. Depending on three distance levels, our system takes decisions on the availability of the actor node.

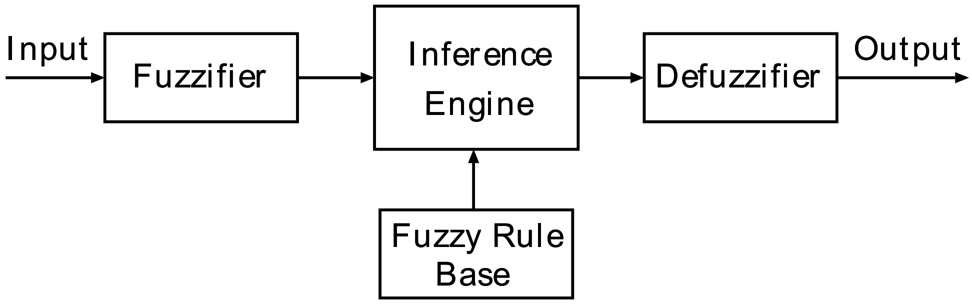


Figure 5.2: FLC structure.

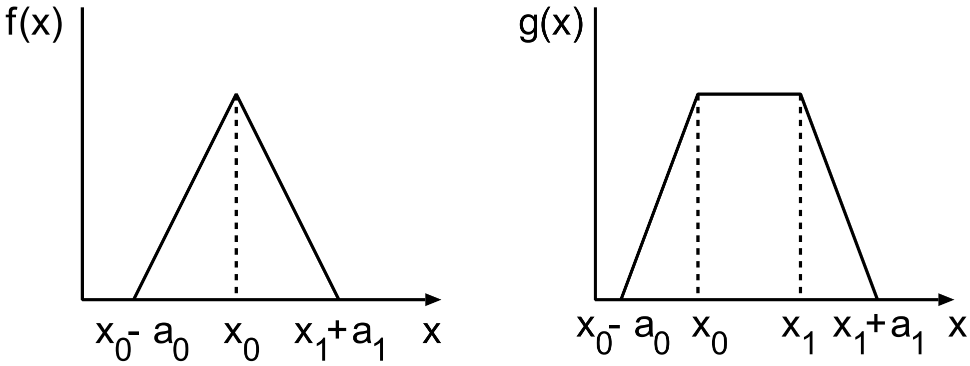


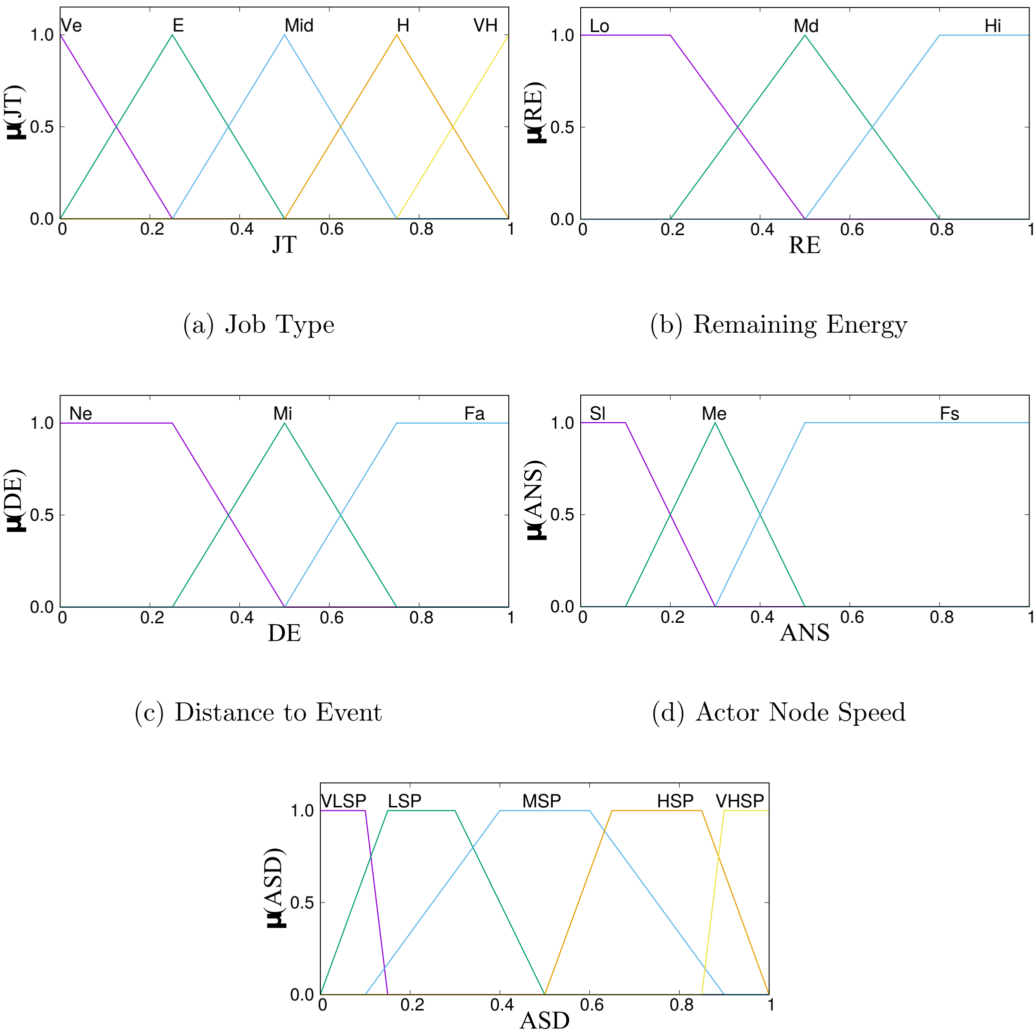
Figure 5.3: Triangular and trapezoidal membership functions.

Remaining Energy (RE): As actors are active in the monitored field, they perform tasks and exchange data in different ways from each other. Consequently, also based on their characteristics, some actors may have a lot of power remaining and other may have very little, when an event occurs. We consider three levels of RE for actor selection.

Actor Node Speed (ANS): It is obvious that in a heterogeneous WSAN, actors are of different types and may operate in different environments. So, in order to judge the mobility degree of an actor, the system uses the speed of an actor.

Density of Actor (DOA): The number of actor nodes can be different in various areas. When in an area we have spare actors, the probability to select an actor node is very high, otherwise if it is dense it has a low probability to be selected for carrying out the task.

Congestion Situation (CS): The actor nodes can be in different congestion situations. When an actor node is congested is not selected for a required task, otherwise if it is not congested is selected with a high probability for carrying out the task.



(a) Job Type

(b) Remaining Energy

(c) Distance to Event

(d) Actor Node Speed

(e) Actor Selection Decision

Figure 5.4: Fuzzy membership functions.

Actor Selection Decision (ASD): Our system is able to decide the willingness of an actor to be assigned a certain task at a certain time. The actors respond in five different levels, which can be interpreted as:

- Very Low Selection Possibility (VLSP)- It is not worth assigning the task to this actor.
- Low Selection Possibility (LSP)- There might be other actors which can do the job better.

- Middle Selection Possibility (MSP) - The Actor is ready to be assigned a task, but is not the “chosen” one.
- High Selection Possibility (HSP) - The actor takes responsibility of completing the task.
- Very High Selection Possibility (VHSP) - Actor has almost all required information and potential and takes full responsibility.

In this paper we have used these parameters with different abbreviations, as follows:

- Job Type as (JT)
- Distance to Event as (DE) or (DAJP)
- Remaining Energy as (RE) or (REA)

5.3 Systems Implementation

Fuzzy sets and fuzzy logic have been developed to manage vagueness and uncertainty in a reasoning process of an intelligent system such as a knowledge based system, an expert system or a logic control system[59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70]. In this work, we use fuzzy logic to implement proposed systems. We call the systems Fuzzy-Based Systems for Actor Node Selection (FBSANS).

The structure of the proposed Fuzzy-Based System for Actor Selection 1 (FBSANS1) is shown in Fig. 5.1. It consists of one Fuzzy Logic Controller (FLC), which is the main part of our system and its basic elements are shown in Fig. 5.2. They are the fuzzifier, inference engine, Fuzzy Rule Base (FRB) and defuzzifier.

As shown in Fig. 5.3, we use triangular and trapezoidal membership functions for FLC, because they are suitable for real-time operation [71]. The x_0 in $f(x)$ is the center of triangular function, $x_0(x_1)$ in $g(x)$ is the left (right) edge of trapezoidal function, and $a_0(a_1)$ is the left (right) width of the triangular or trapezoidal function. We explain in details the design of FLC in following.

5.3.1 Description of FBSANS1

We use three input parameters for FLC of FBSANS1:

- Job Type (JT);
- Remaining Energy (RE);
- Distance to Event (DE);

The term sets for each input linguistic parameter are defined respectively as shown below.

$$
\begin{aligned}
T(JT) &= \{VeryEasy(Ve), Easy(E), Medium(Mid), \\
&\quad Hard(H), VeryHard(VH)\} \\
T(DE) &= \{Near(Ne), Middle(Mi), Far(Fa)\} \\
T(RE) &= \{Low(Lo), Medium(Md), High(Hi)\}
\end{aligned}
$$

The output linguistic parameter is the Actor Selection Decision (ASD). We define the term set of ASD as:

$$
\begin{aligned}
&\{Very\ Low\ Selection\ Possibility\ (VLSP), \\
&Low\ Selection\ Possibility\ (LSP), \\
&Middle\ Selection\ Possibility\ (MSP), \\
&High\ Selection\ Possibility\ (HSP), \\
&Very\ High\ Selection\ Possibility\ (VHSP)\}.
\end{aligned}
$$

The membership functions are shown in Fig. 5.4 and the FRB of FBSANS1 is shown in Table 5.1. The FRB forms a fuzzy set of dimensions $|\mu(JT)| \times |\mu(RE)| \times |\mu(DE)|$, where $|\mu(x)|$ is the number of terms on $\mu(x)$. The FRB of FBSANS1 has 45 rules. The control rules have the form: IF "conditions" THEN "control action".

5.3.2 Description of FBSANS2

We consider four input parameters for FLC of FBSANS2:

- JT;
- RE;
- DE;
- ANS.

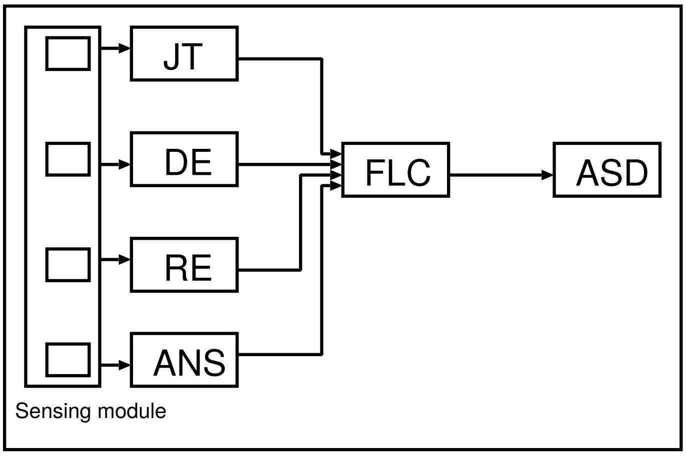


Figure 5.5: Structure of implemented FBSANS2.

We added ANS input parameter to FBSANS2 in order to consider the mobility of actor node. The structure of FBSANS2 is shown in Fig. 5.5.

The term sets for each input linguistic parameter are defined respectively as shown below.

$$
\begin{aligned}
T(JT) &= \{VeryEasy(Ve), Easy(E), Medium(Mid),\\
&\quad Hard(H), VeryHard(VH)\}\\
T(DE) &= \{Near(Ne), Middle(Mi), Far(Fa)\}\\
T(RE) &= \{Low(Lo), Medium(Md), High(Hi)\}\\
T(ANS) &= \{Slow(Sl), Medium(Me), Fast(Fs)\}
\end{aligned}
$$

The output linguistic parameter is the Actor Selection Decision (ASD). We define the term set of ASD as:

$$
\begin{aligned}
\{&Very\ Low\ Selection\ Possibility\ (VLSP),\\
&Low\ Selection\ Possibility\ (LSP),\\
&Middle\ Selection\ Possibility\ (MSP),\\
&High\ Selection\ Possibility\ (HSP),\\
&Very\ High\ Selection\ Possibility\ (VHSP)\}.
\end{aligned}
$$

The membership functions are shown in Fig. 5.4 and the FRB of FBSANS2 is shown in Table 5.2.

Table 5.1: FRB of FBSANS1.

Rule	JT	RE	DE	ASD
1	Ve	Lo	Ne	MSP
2	E	Lo	Ne	MSP
3	Mid	Lo	Ne	HSP
4	H	Lo	Ne	HSP
5	VH	Lo	Ne	VHSP
6	Ve	Md	Ne	HSP
7	E	Md	Ne	HSP
8	Mid	Md	Ne	VHSP
9	H	Md	Ne	VHSP
10	VH	Md	Ne	VHSP
11	Ve	Hi	Ne	VHSP
12	E	Hi	Ne	VHSP
13	Mid	Hi	Ne	VHSP
14	H	Hi	Ne	VHSP
15	VH	Hi	Ne	VHSP
16	Ve	Lo	Mi	LSP
17	E	Lo	Mi	MSP
18	Mid	Lo	Mi	MSP
19	H	Lo	Mi	MSP
20	VH	Lo	Mi	HSP
21	Ve	Md	Mi	MSP
22	E	Md	Mi	MSP
23	Mid	Md	Mi	HSP
24	H	Md	Mi	VHSP
25	VH	Md	Mi	VHSP
26	Ve	Hi	Mi	HSP
27	E	Hi	Mi	VHSP
28	Mid	Hi	Mi	VHSP
29	H	Hi	Mi	VHSP
30	VH	Hi	Mi	VHSP
31	Ve	Lo	Fa	VLSP
32	E	Lo	Fa	VLSP
33	Mid	Lo	Fa	LSP
34	H	Lo	Fa	MSP
35	VH	Lo	Fa	MSP
36	Ve	Md	Fa	LSP
37	E	Md	Fa	MSP
38	Mid	Md	Fa	MSP
39	H	Md	Fa	HSP
40	VH	Md	Fa	HSP
41	Ve	Hi	Fa	MSP
42	E	Hi	Fa	HSP
43	Mid	Hi	Fa	HSP
44	H	Hi	Fa	VHSP
45	VH	Hi	Fa	VHSP

Table 5.2: FRB of FBSANS2.

Rule	JT	RE	DE	ANS	ASD	Rule	JT	RE	DE	ANS	ASD	Rule	JT	RE	DE	ANS	ASD
1	Ve	Lo	Ne	Sl	MSP	46	Ve	Lo	Ne	Me	LSP	91	Ve	Lo	Ne	Fs	VLSP
2	E	Lo	Ne	Sl	MSP	47	E	Lo	Ne	Me	MSP	92	E	Lo	Ne	Fs	LSP
3	Mid	Lo	Ne	Sl	HSP	48	Mid	Lo	Ne	Me	HSP	93	Mid	Lo	Ne	Fs	MSP
4	H	Lo	Ne	Sl	VHSP	49	H	Lo	Ne	Me	VHSP	94	H	Lo	Ne	Fs	HSP
5	VH	Lo	Ne	Sl	VHSP	50	VH	Lo	Ne	Me	VHSP	95	VH	Lo	Ne	Fs	HSP
6	Ve	Md	Ne	Sl	HSP	51	Ve	Md	Ne	Me	MSP	96	Ve	Md	Ne	Fs	MSP
7	E	Md	Ne	Sl	HSP	52	E	Md	Ne	Me	HSP	97	E	Md	Ne	Fs	MSP
8	Mid	Md	Ne	Sl	VHSP	53	Mid	Md	Ne	Me	VHSP	98	Mid	Md	Ne	Fs	HSP
9	H	Md	Ne	Sl	VHSP	54	H	Md	Ne	Me	VHSP	99	H	Md	Ne	Fs	VHSP
10	VH	Md	Ne	Sl	VHSP	55	VH	Md	Ne	Me	VHSP	100	VH	Md	Ne	Fs	VHSP
11	Ve	Hi	Ne	Sl	VHSP	56	Ve	Hi	Ne	Me	HSP	101	Ve	Hi	Ne	Fs	HSP
12	E	Hi	Ne	Sl	VHSP	57	E	Hi	Ne	Me	VHSP	102	E	Hi	Ne	Fs	HSP
13	Mid	Hi	Ne	Sl	VHSP	58	Mid	Hi	Ne	Me	VHSP	103	Mid	Hi	Ne	Fs	VHSP
14	H	Hi	Ne	Sl	VHSP	59	H	Hi	Ne	Me	VHSP	104	H	Hi	Ne	Fs	VHSP
15	VH	Hi	Ne	Sl	VHSP	60	VH	Hi	Ne	Me	VHSP	105	VH	Hi	Ne	Fs	VHSP
16	Ve	Lo	Mi	Sl	LSP	61	Ve	Lo	Mi	Me	VLSP	106	Ve	Lo	Mi	Fs	VLSP
17	E	Lo	Mi	Sl	LSP	62	E	Lo	Mi	Me	LSP	107	E	Lo	Mi	Fs	VLSP
18	Mid	Lo	Mi	Sl	MSP	63	Mid	Lo	Mi	Me	MSP	108	Mid	Lo	Mi	Fs	LSP
19	H	Lo	Mi	Sl	HSP	64	H	Lo	Mi	Me	HSP	109	H	Lo	Mi	Fs	MSP
20	VH	Lo	Mi	Sl	VHSP	65	VH	Lo	Mi	Me	HSP	110	VH	Lo	Mi	Fs	HSP
21	Ve	Md	Mi	Sl	MSP	66	Ve	Md	Mi	Me	LSP	111	Ve	Md	Mi	Fs	LSP
22	E	Md	Mi	Sl	MSP	67	E	Md	Mi	Me	MSP	112	E	Md	Mi	Fs	LSP
23	Mid	Md	Mi	Sl	HSP	68	Mid	Md	Mi	Me	HSP	113	Mid	Md	Mi	Fs	MSP
24	H	Md	Mi	Sl	VHSP	69	H	Md	Mi	Me	VHSP	114	H	Md	Mi	Fs	HSP
25	VH	Md	Mi	Sl	VHSP	70	VH	Md	Mi	Me	VHSP	115	VH	Md	Mi	Fs	VHSP
26	Ve	Hi	Mi	Sl	HSP	71	Ve	Hi	Mi	Me	MSP	116	Ve	Hi	Mi	Fs	MSP
27	E	Hi	Mi	Sl	HSP	72	E	Hi	Mi	Me	HSP	117	E	Hi	Mi	Fs	MSP
28	Mid	Hi	Mi	Sl	VHSP	73	Mid	Hi	Mi	Me	VHSP	118	Mid	Hi	Mi	Fs	HSP
29	H	Hi	Mi	Sl	VHSP	74	H	Hi	Mi	Me	VHSP	119	H	Hi	Mi	Fs	VHSP
30	VH	Hi	Mi	Sl	VHSP	75	VH	Hi	Mi	Me	VHSP	120	VH	Hi	Mi	Fs	VHSP
31	Ve	Lo	Fa	Sl	LSP	76	Ve	Lo	Fa	Me	VLSP	121	Ve	Lo	Fa	Fs	VLSP
32	E	Lo	Fa	Sl	LSP	77	E	Lo	Fa	Me	LSP	122	E	Lo	Fa	Fs	VLSP
33	Mid	Lo	Fa	Sl	MSP	78	Mid	Lo	Fa	Me	LSP	123	Mid	Lo	Fa	Fs	VLSP
34	H	Lo	Fa	Sl	MSP	79	H	Lo	Fa	Me	MSP	124	H	Lo	Fa	Fs	LSP
35	VH	Lo	Fa	Sl	HSP	80	VH	Lo	Fa	Me	MSP	125	VH	Lo	Fa	Fs	MSP
36	Ve	Md	Fa	Sl	MSP	81	Ve	Md	Fa	Me	LSP	126	Ve	Md	Fa	Fs	VLSP
37	E	Md	Fa	Sl	MSP	82	E	Md	Fa	Me	MSP	127	E	Md	Fa	Fs	LSP
38	Mid	Md	Fa	Sl	HSP	83	Mid	Md	Fa	Me	MSP	128	Mid	Md	Fa	Fs	MSP
39	H	Md	Fa	Sl	HSP	84	H	Md	Fa	Me	HSP	129	H	Md	Fa	Fs	MSP
40	VH	Md	Fa	Sl	VHSP	85	VH	Md	Fa	Me	HSP	130	VH	Md	Fa	Fs	HSP
41	Ve	Hi	Fa	Sl	HSP	86	Ve	Hi	Fa	Me	MSP	131	Ve	Hi	Fa	Fs	LSP
42	E	Hi	Fa	Sl	HSP	87	E	Hi	Fa	Me	HSP	132	E	Hi	Fa	Fs	MSP
43	Mid	Hi	Fa	Sl	HSP	88	Mid	Hi	Fa	Me	HSP	133	Mid	Hi	Fa	Fs	HSP
44	H	Hi	Fa	Sl	VHSP	89	H	Hi	Fa	Me	VHSP	134	H	Hi	Fa	Fs	HSP
45	VH	Hi	Fa	Sl	VHSP	90	VH	Hi	Fa	Me	VHSP	135	VH	Hi	Fa	Fs	VHSP

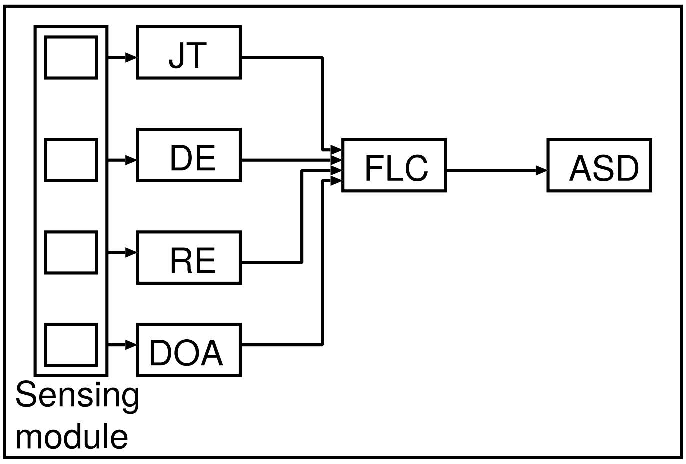


Figure 5.6: Structure of implemented FBSANS3.

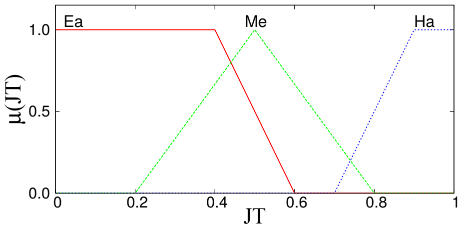
5.3.3 Description of FBSANS3

For FBSANS3 we use four input parameters:

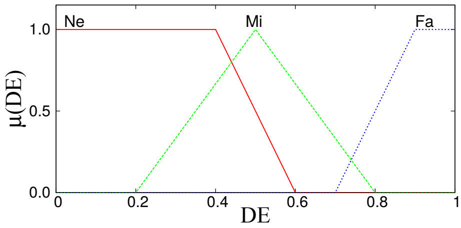
- Job Type (JT);
- Distance to Event (DE);
- Remaining Energy (RE);
- Density of Actor Nodes (DOA).

The term sets for each input linguistic parameter are defined respectively as shown below.

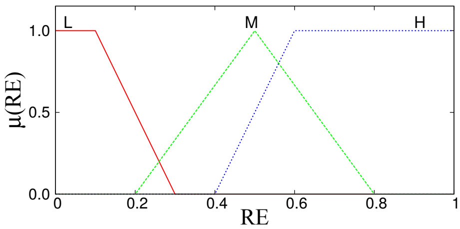
$$\begin{aligned}
T(JT) &= \{Easy(Ea), Medium(Me), Hard(Ha)\} \\
T(DE) &= \{Near(Ne), Middle(Mi), Far(Fa)\} \\
T(RE) &= \{Low(L), Middle(M), High(H)\} \\
T(DOA) &= \{Spare(Sp), Normal(Nrm), Dense(Dn)\}
\end{aligned}$$



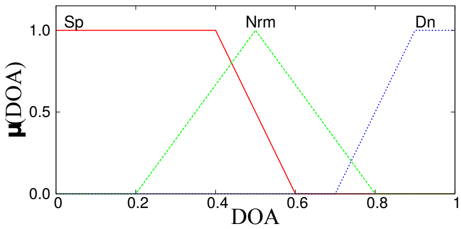
(a) Job Type



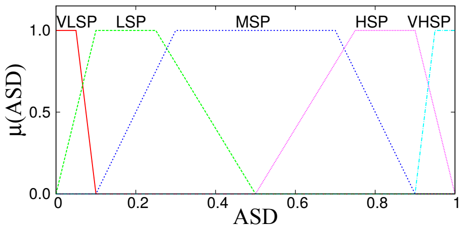
(b) Distance to Event



(c) Remaining Energy



(d) Density of Actor Nodes



(e) Actor Selection Decision

Figure 5.7: Fuzzy membership functions of FBSANS3.

The membership functions for input parameters of FLC are defined as:

$$
\begin{aligned}
\mu_{Ea}(JT) &= g(JT; Ea_0, Ea_1, Ea_{w0}, Ea_{w1}) \\
\mu_{Me}(JT) &= f(JT; Me_0, Me_{w0}, Me_{w1}) \\
\mu_{Ha}(JT) &= g(JT; Ha_0, Ha_1, Ha_{w0}, Ha_{w1}) \\
\mu_{Ne}(DE) &= g(DE; Ne_0, Ne_1, Ne_{w0}, Ne_{w1}) \\
\mu_{Mi}(DE) &= f(DE; Mi_0, Mi_{w0}, Mi_{w1}) \\
\mu_{Fa}(DE) &= g(DE; Fa_0, Fa_1, Fa_{w0}, Fa_{w1}) \\
\mu_{L}(RE) &= g(RE; L_0, L_1, L_{w0}, L_{w1}) \\
\mu_{M}(RE) &= f(RE; M_0, M_{w0}, M_{w1}) \\
\mu_{H}(RE) &= g(RE; H_0, H_1, H_{w0}, H_{w1}) \\
\mu_{Sp}(DOA) &= g(DOA; Sp_0, Sp_1, Sp_{w0}, Sp_{w1}) \\
\mu_{Nrm}(DOA) &= f(DOA; Nrm_0, Nrm_{w0}, Nrm_{w1}) \\
\mu_{Dn}(DOA) &= g(DOA; Dn_0, Dn_1, Dn_{w0}, Dn_{w1})
\end{aligned}
$$

Table 5.3: FRB of FBSANS3.

No.	JT	DE	RE	DOA	ASD	No.	JT	DE	RE	DOA	ASD
1	Ea	Ne	L	Dn	VLSP	41	Me	Mi	M	Nrm	MSP
2	Ea	Ne	L	Nrm	LSP	42	Me	Mi	M	Sp	MSP
3	Ea	Ne	L	Sp	LSP	43	Me	Mi	H	Dn	HSP
4	Ea	Ne	M	Dn	LSP	44	Me	Mi	H	Nrm	HSP
5	Ea	Ne	M	Nrm	MSP	45	Me	Mi	H	Sp	HSP
6	Ea	Ne	M	Sp	MSP	46	Me	Fa	L	Dn	VLSP
7	Ea	Ne	H	Dn	MSP	47	Me	Fa	L	Nrm	VLSP
8	Ea	Ne	H	Nrm	HSP	48	Me	Fa	L	Sp	LSP
9	Ea	Ne	H	Sp	HSP	49	Me	Fa	M	Dn	LSP
10	Ea	Mi	L	Dn	VLSP	50	Me	Fa	M	Nrm	LSP
11	Ea	Mi	L	Nrm	VLSP	51	Me	Fa	M	Sp	MSP
12	Ea	Mi	L	Sp	LSP	52	Me	Fa	H	Dn	MSP
13	Ea	Mi	M	Dn	LSP	53	Me	Fa	H	Nrm	MSP
14	Ea	Mi	M	Nrm	LSP	54	Me	Fa	H	Sp	HSP
15	Ea	Mi	M	Sp	MSP	55	Ha	Ne	L	Dn	MSP
16	Ea	Mi	H	Dn	MSP	56	Ha	Ne	L	Nrm	MSP
17	Ea	Mi	H	Nrm	MSP	57	Ha	Ne	L	Sp	MSP
18	Ea	Mi	H	Sp	HSP	58	Ha	Ne	M	Dn	HSP
19	Ea	Fa	L	Dn	VLSP	59	Ha	Ne	M	Nrm	HSP
20	Ea	Fa	L	Nrm	VLSP	60	Ha	Ne	M	Sp	HSP
21	Ea	Fa	L	Sp	VLSP	61	Ha	Ne	H	Dn	VHSP
22	Ea	Fa	M	Dn	VLSP	62	Ha	Ne	H	Nrm	VHSP
23	Ea	Fa	M	Nrm	LSP	63	Ha	Ne	H	Sp	VHSP
24	Ea	Fa	M	Sp	LSP	64	Ha	Mi	L	Dn	LSP
25	Ea	Fa	H	Dn	LSP	65	Ha	Mi	L	Nrm	MSP
26	Ea	Fa	H	Nrm	MSP	66	Ha	Mi	L	Sp	MSP
27	Ea	Fa	H	Sp	MSP	67	Ha	Mi	M	Dn	MSP
28	Me	Ne	L	Dn	LSP	68	Ha	Mi	M	Nrm	HSP
29	Me	Ne	L	Nrm	LSP	69	Ha	Mi	M	Sp	HSP
30	Me	Ne	L	Sp	MSP	70	Ha	Mi	H	Dn	HSP
31	Me	Ne	M	Dn	MSP	71	Ha	Mi	H	Nrm	VHSP
32	Me	Ne	M	Nrm	MSP	72	Ha	Mi	H	Sp	VHSP
33	Me	Ne	M	Sp	HSP	73	Ha	Fa	L	Dn	LSP
34	Me	Ne	H	Dn	HSP	74	Ha	Fa	L	Nrm	LSP
35	Me	Ne	H	Nrm	HSP	75	Ha	Fa	L	Sp	LSP
36	Me	Ne	H	Sp	VHSP	76	Ha	Fa	M	Dn	MSP
37	Me	Mi	L	Dn	LSP	77	Ha	Fa	M	Nrm	MSP
38	Me	Mi	L	Nrm	LSP	78	Ha	Fa	M	Sp	MSP
39	Me	Mi	L	Sp	LSP	79	Ha	Fa	H	Dn	HSP
40	Me	Mi	M	Dn	MSP	80	Ha	Fa	H	Nrm	HSP
						81	Ha	Fa	H	Sp	HSP

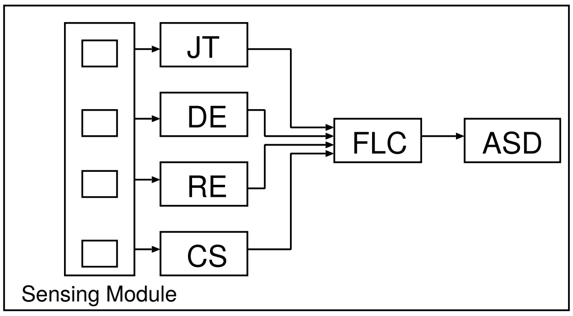


Figure 5.8: Proposed system model.

The small letters *w0* and *w1* mean left width and right width, respectively.

The output linguistic parameter is the Actor Selection Decision (ASD). We define the term set of ASD as:

$$\begin{aligned}
&\{Very\ Low\ Selection\ Possibility\ (VLSP),\\
&Low\ Selection\ Possibility\ (LSP),\\
&Middle\ Selection\ Possibility\ (MSP),\\
&High\ Selection\ Possibility\ (HSP),\\
&Very\ High\ Selection\ Possibility\ (VHSP)\}.
\end{aligned}$$

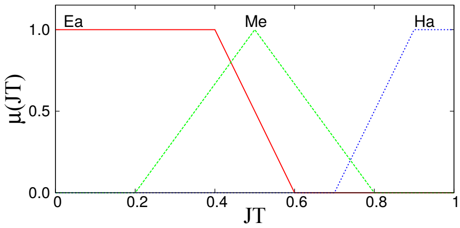
The membership functions for the output parameter *ASD* are defined as:

$$\begin{aligned}
\mu_{VLSP}(ASD) &= g(ASD; VLSP_0, VLSP_1, VLSP_{w0}, VLSP_{w1})\\
\mu_{LSP}(ASD) &= g(ASD; LSP_0, LSP_1, LSP_{w0}, LSP_{w1})\\
\mu_{MSP}(ASD) &= g(ASD; MSP_0, MSP_1, MSP_{w0}, MSP_{w1})\\
\mu_{HSP}(ASD) &= g(ASD; HSP_0, HSP_1, HSP_{w0}, HSP_{w1})\\
\mu_{VHSP}(ASD) &= g(ASD; VHSP_0, VHSP_1, VHSP_{w0}, VHSP_{w1}).
\end{aligned}$$

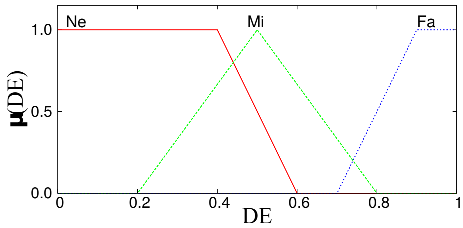
The membership functions are shown in Fig. 5.7 and the Fuzzy Rule Base (FRB) for FBSANS3 are shown in Table 5.3.

5.3.4 Description of FBSANS4

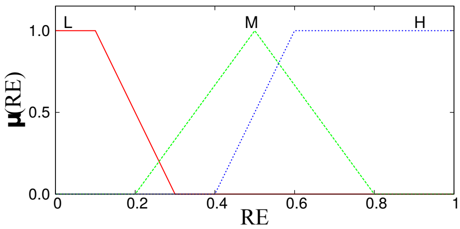
For FBSANS4, we add the actor Congestion Situation (CS) parameter, so FBSANS4 has four input parameters.



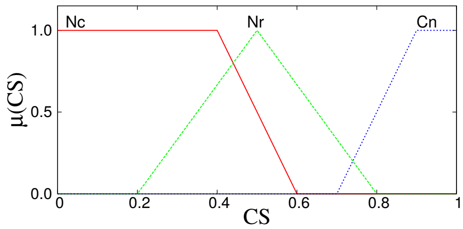
(a) Job Type



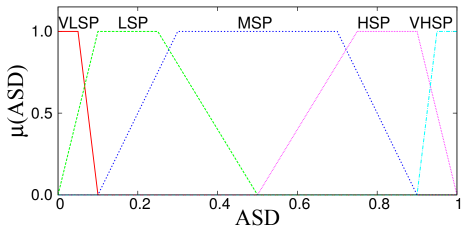
(b) Distance to Event



(c) Remaining Energy



(d) Congestion Situation



(e) Actor Selection Decision

Figure 5.9: Fuzzy membership functions for FBSANS4.

The term sets for each input linguistic parameter are defined as follows.

$$
\begin{aligned}
T(JT) &= \{Easy(Ea), Medium(Me), Hard(Ha)\} \\
T(DE) &= \{Near(Ne), Middle(Mi), Far(Fa)\} \\
T(RE) &= \{Low(L), Middle(M), High(H)\} \\
T(CS) &= \{NotCongested(Nc), Normal(Nr), Congested(Cn)\}
\end{aligned}
$$

The membership functions for input parameters are defined as follows.

$$\begin{aligned}
\mu_{Ea}(JT) &= g(JT; Ea_0, Ea_1, Ea_{w0}, Ea_{w1}) \\
\mu_{Me}(JT) &= f(JT; Me_0, Me_{w0}, Me_{w1}) \\
\mu_{Ha}(JT) &= g(JT; Ha_0, Ha_1, Ha_{w0}, Ha_{w1}) \\
\mu_{Ne}(DE) &= g(DE; Ne_0, Ne_1, Ne_{w0}, Ne_{w1}) \\
\mu_{Mi}(DE) &= f(DE; Mi_0, Mi_{w0}, Mi_{w1}) \\
\mu_{Fa}(DE) &= g(DE; Fa_0, Fa_1, Fa_{w0}, Fa_{w1}) \\
\mu_{L}(RE) &= g(RE; L_0, L_1, L_{w0}, L_{w1}) \\
\mu_{M}(RE) &= f(RE; M_0, M_{w0}, M_{w1}) \\
\mu_{H}(RE) &= g(RE; H_0, H_1, H_{w0}, H_{w1}) \\
\mu_{Nc}(CS) &= g(CS; Nc_0, Nc_1, Nc_{w0}, Nc_{w1}) \\
\mu_{Nr}(CS) &= f(CS; Nr_0, Nr_{w0}, Nr_{w1}) \\
\mu_{Cn}(CS) &= g(CS; Cn_0, Cn_1, Cn_{w0}, Cn_{w1})
\end{aligned}$$

The small letters *w0* and *w1* mean left width and right width, respectively. The membership functions for the output parameter ASD are defined as:

$$\begin{aligned}
\mu_{VLSP}(ASD) &= g(ASD; VLSP_0, VLSP_1, VLSP_{w0}, VLSP_{w1}) \\
\mu_{LSP}(ASD) &= g(ASD; LSP_0, LSP_1, LSP_{w0}, LSP_{w1}) \\
\mu_{MSP}(ASD) &= g(ASD; MSP_0, MSP_1, MSP_{w0}, MSP_{w1}) \\
\mu_{HSP}(ASD) &= g(ASD; HSP_0, HSP_1, HSP_{w0}, HSP_{w1}) \\
\mu_{VHSP}(ASD) &= g(ASD; VHSP_0, VHSP_1, VHSP_{w0}, VHSP_{w1}).
\end{aligned}$$

We define the term set of ASD as:

$$\begin{aligned}
&\{Very\ Low\ Selection\ Possibility\ (VLSP), \\
&Low\ Selection\ Possibility\ (LSP), \\
&Middle\ Selection\ Possibility\ (MSP), \\
&High\ Selection\ Possibility\ (HSP), \\
&Very\ High\ Selection\ Possibility\ (VHSP)\}.
\end{aligned}$$

The membership functions are shown in Fig. 5.9 and the Fuzzy Rule Base (FRB) is shown in Table 5.4. The FRB forms a fuzzy set of dimensions $|T(JT)| \times |T(DE)| \times |T(RE)| \times |T(CS)|$, where $|T(x)|$ is the number of terms on $T(x)$. The FRB has 81 rules. The control rules have the form: IF "conditions" THEN "control action".

Table 5.4: FRB of FBSANS4.

No.	JT	DE	RE	CS	ASD	No.	JT	DE	RE	CS	ASD
1	Ea	Ne	L	Nc	VLSP	41	Me	Mi	M	Nr	MSP
2	Ea	Ne	L	Nr	LSP	42	Me	Mi	M	Cn	MSP
3	Ea	Ne	L	Cn	LSP	43	Me	Mi	H	Nc	HSP
4	Ea	Ne	M	Nc	LSP	44	Me	Mi	H	Nr	HSP
5	Ea	Ne	M	Nr	MSP	45	Me	Mi	H	Cn	HSP
6	Ea	Ne	M	Cn	MSP	46	Me	Fa	L	Nc	VLSP
7	Ea	Ne	H	Nc	MSP	47	Me	Fa	L	Nr	VLSP
8	Ea	Ne	H	Nr	HSP	48	Me	Fa	L	Cn	LSP
9	Ea	Ne	H	Cn	HSP	49	Me	Fa	M	Nc	LSP
10	Ea	Mi	L	Nc	VLSP	50	Me	Fa	M	Nr	LSP
11	Ea	Mi	L	Nr	VLSP	51	Me	Fa	M	Cn	MSP
12	Ea	Mi	L	Cn	LSP	52	Me	Fa	H	Nc	MSP
13	Ea	Mi	M	Nc	LSP	53	Me	Fa	H	Nr	MSP
14	Ea	Mi	M	Nr	LSP	54	Me	Fa	H	Cn	HSP
15	Ea	Mi	M	Cn	MSP	55	Ha	Ne	L	Nc	MSP
16	Ea	Mi	H	Nc	MSP	56	Ha	Ne	L	Nr	MSP
17	Ea	Mi	H	Nr	MSP	57	Ha	Ne	L	Cn	MSP
18	Ea	Mi	H	Cn	HSP	58	Ha	Ne	M	Nc	HSP
19	Ea	Fa	L	Nc	VLSP	59	Ha	Ne	M	Nr	HSP
20	Ea	Fa	L	Nr	VLSP	60	Ha	Ne	M	Cn	HSP
21	Ea	Fa	L	Cn	VLSP	61	Ha	Ne	H	Nc	VHSP
22	Ea	Fa	M	Nc	VLSP	62	Ha	Ne	H	Nr	VHSP
23	Ea	Fa	M	Nr	LSP	63	Ha	Ne	H	Cn	VHSP
24	Ea	Fa	M	Cn	LSP	64	Ha	Mi	L	Nc	LSP
25	Ea	Fa	H	Nc	LSP	65	Ha	Mi	L	Nr	MSP
26	Ea	Fa	H	Nr	MSP	66	Ha	Mi	L	Cn	MSP
27	Ea	Fa	H	Cn	MSP	67	Ha	Mi	M	Nc	MSP
28	Me	Ne	L	Nc	LSP	68	Ha	Mi	M	Nr	HSP
29	Me	Ne	L	Nr	LSP	69	Ha	Mi	M	Cn	HSP
30	Me	Ne	L	Cn	MSP	70	Ha	Mi	H	Nc	HSP
31	Me	Ne	M	Nc	MSP	71	Ha	Mi	H	Nr	VHSP
32	Me	Ne	M	Nr	MSP	72	Ha	Mi	H	Cn	VHSP
33	Me	Ne	M	Cn	HSP	73	Ha	Fa	L	Nc	LSP
34	Me	Ne	H	Nc	HSP	74	Ha	Fa	L	Nr	LSP
35	Me	Ne	H	Nr	HSP	75	Ha	Fa	L	Cn	LSP
36	Me	Ne	H	Cn	VHSP	76	Ha	Fa	M	Nc	MSP
37	Me	Mi	L	Nc	LSP	77	Ha	Fa	M	Nr	MSP
38	Me	Mi	L	Nr	LSP	78	Ha	Fa	M	Cn	MSP
39	Me	Mi	L	Cn	LSP	79	Ha	Fa	H	Nc	HSP
40	Me	Mi	M	Nc	MSP	80	Ha	Fa	H	Nr	HSP
						81	Ha	Fa	H	Cn	HSP

Chapter 6

Evaluation of Proposed Systems

In this chapter, we evaluate the proposed system by computer simulations. The simulations are carried out in a Linux Ubuntu OS computer with these specifications: RAM (8GB), CPU Intel Core i5 (3.2 GHz $\times$ 4) and SSD (650 GB). For simulation, we used our implemented FuzzyC system [72, 73]. The FuzzyC is a simulation system written in C language and equipped with Fuzzy library.

6.1 Simulation Results for FBSANS1

We present the simulation results of FBSANS1 in Fig. 6.1. In Fig. 6.1(a), we display how the output parameter ASD is affected by JT value, for different values of RE and DE=0.1. Then, we increase the value of DE and repeat the simulations.

From simulation results of FBSANS1, we can observe that when the difficulty level of the job (JT) increases, ASD also increases. For different values of RE, the value of ASD differs in a way that actors with low battery are not involved in many task assignment. Thus, for lower values of RE, ASD decreases. In this way the network lifetime is increased. From Fig. 6.1(a) to Fig. 6.1(e), the DE increases and ASD decreases. In this case, our system instructs actors that are near the event to be more active in task assignment, while for actors that are further away and need more time and energy to reach the event place not to be active. By doing this the response to emergency situations is improved and the energy management is better.

Comparing Fig. 6.1(b) with Fig. 6.1(a) for JT=0.5, RE=0.5 and DE=0.25 the ASD decreases 4%. Than, comparing Fig. 6.1(c) with Fig. 6.1(a) for JT=0.5, RE=0.5 and DE=0.5 the ASD is decreased 6%. Comparing Fig. 6.1(d) with Fig. 6.1(a) for JT=0.5, RE=0.5 and DE=0.75, ASD is decreased 26%. At last, comparing Fig. 6.1(e) with Fig. 6.1(a) for JT=0.5, RE=0.5 and DE=0.90, ASD is decreased 32%.

6.2 Simulation Results for FBSANS2

We present the simulation results of FBSANS2 in Fig. 6.2, Fig. 6.3 and Fig. 6.4.

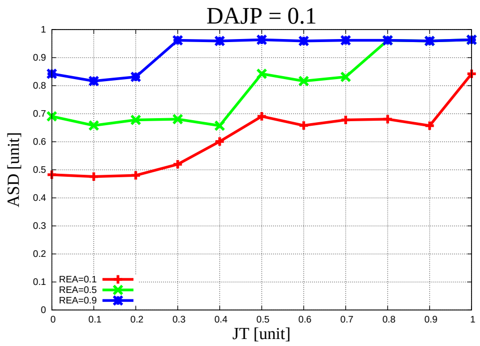
From simulation results of FBSANS2, as in general, we notice that as JT becomes difficult the ASD becomes higher because actors are programmed for different jobs, the same as FBSANS1. The DE defines the distance of the actor from the job place, so when DE is small, the ASD is higher. The actors closest to the job place use less energy to reach the job position. We also notice that for each value of DE, when the ANS increases the network topology is more dynamic. In this condition, the actor may lose connectivity and changes its condition (such as distance from job place) in a while, so it will be not reachable any more. However, when the actor is moving with higher speed, the response can be faster for emergency situations.

In Fig. 6.2 are shown the results for DE=0.1. We can see that in Fig. 6.2(a) for JT=0.2 when DE=0.1-ANS=0.1 and RE=0.5 the ASD is 0.78. Comparing Fig. 6.2(b) with Fig. 6.2(a) we can see that for JT=0.2 when DE=0.1-ANS=0.3 and RE=0.5 the ASD is decreased 8%. Also comparing Fig. 6.2(c) with Fig. 6.2(a) for JT=0.2 when DE=0.1-ANS=0.5 and RE=0.5 the ASD is decreased 28%.

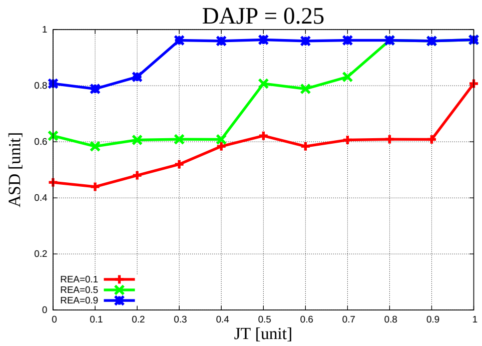
In Fig. 6.3 are shown the results for DE=0.5. Comparing Fig. 6.3(b) with Fig. 6.3(a) for JT=0.2 when DE=0.5-ANS=0.3 and RE=0.5 the ASD is decreased 3%. Comparing Fig.6.3(c) with Fig. 6.3(a) for JT=0.2 when DE=0.5-ANS=0.5 and RE=0.5 the ASD is decreased 17%.

In Fig. 6.4 are shown the results for DE=0.9. Comparing Fig. 6.4(b) with Fig. 6.4(a) for JT=0.2 when DE=0.9-ANS=0.3 and RE=0.5 the ASD is decreased 2%. Comparing Fig. 6.4(c) with Fig. 6.4(a) for JT=0.2 when DE=0.9-ANS=0.5 and RE=0.5 the ASD is decreased 18%.

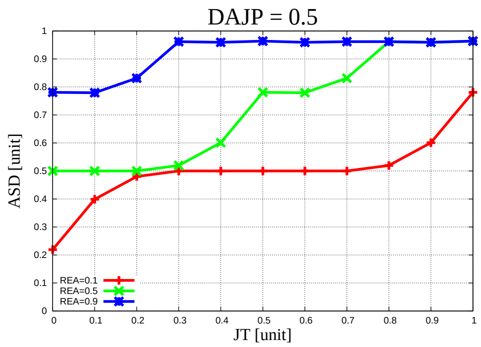
Comparing complexity of FBSANS1 and FBSANS2, the FBSANS2 is more complex than FBSANS1. However, it also considers mobility of actor nodes. Thus, the FBSANS2 is more flexible system than FBSANS1.



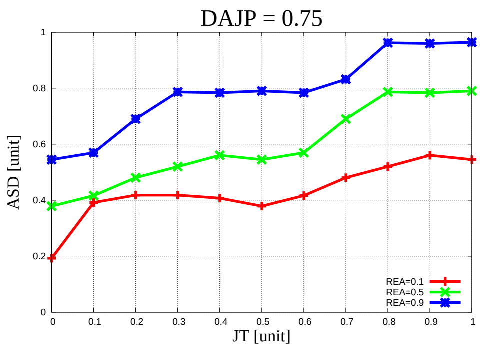
(a) DE=0.10



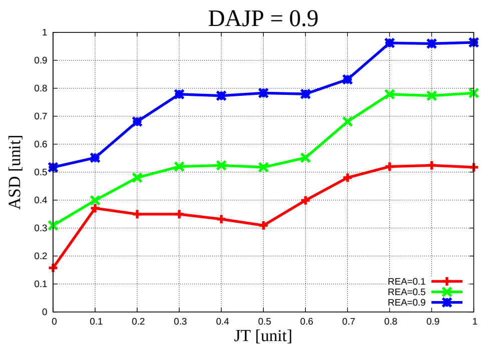
(b) DE=0.25



(c) DE=0.50



(d) DE=0.75



(e) DE=0.90

Figure 6.1: Simulation results of FBSANS1 for DE.

6.3 Simulation Results for FBSANS3

We present the simulation results in Fig. 6.5, Fig. 6.6 and Fig. 6.7. From simulation results, we found that as JT becomes difficult the ASD becomes higher because actors are programmed for different jobs. As shown in Fig. 6.5, when RE is higher, the probability to select the present node as actor node is higher. When DE parameter is increased, the ASD value is decreased.

In Fig. 6.5 are shown the results for DE=0.1. We see that in Fig. 6.5(a) for JT=0.7 when DE=0.1-DOA=0.1 and RE=0.5 the ASD is 0.96. Comparing Fig. 6.5(b) with Fig. 6.5(a) we can see that for JT=0.7 the ASD is decreased 18%. Also comparing Fig. 6.5(c) with Fig. 6.5(a) the ASD for JT=0.7 is decreased 43%.

In Fig. 6.6 are shown the simulation results for DE=0.5. Comparing Fig. 6.6(b) with Fig. 6.6(a), for JT=0.7 when DE=0.5-DOA=0.5 and RE=0.5, ASD is decreased 22%. Comparing Fig. 6.6(c) with Fig. 6.6(a), for JT=0.7, DE=0.5-DOA=0.9 and RE=0.5, ASD is decreased 28%.

In Fig. 6.7 are shown the results for DE=0.9. Comparing Fig. 6.7(b) with Fig. 6.7(a), for JT=0.7, DE=0.9-DOA=0.5 and RE=0.5, ASD is decreased 2%. Also comparing Fig. 6.7(c) with Fig. 6.7(a), for JT=0.7, DE=0.9-DOA=0.5 and RE=0.5, ASD is decreased 27%.

Comparing Fig. 6.6(c) with Fig. 6.5(c) and Fig. 6.7(c) with Fig. 6.5(c), for JT=0.7, DOA=0.9 and RE=0.5, the ASD is decreased 5% and 27%, respectively.

6.4 Simulation Results for FBSANS4

In this section are shown the simulation results of the fourth simulation system.

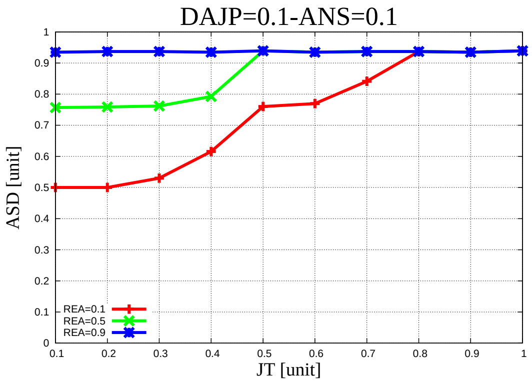
We present the simulation results in Fig. 6.8, Fig. 6.9 and Fig. 6.10. From simulation results, we found that as JT becomes difficult the ASD becomes higher because actors are programmed for different jobs. As shown in Fig. 6.5, when RE is higher, the probability to select the present node as actor node is higher.

In Fig. 6.8 are shown the results for DE=0.1. We see that in Fig. 6.8(a) for JT=0.7 when DE=0.1-CS=0.1 and RE=0.5 the ASD is 0.95. Comparing Fig. 6.8(b) with Fig. 6.8(a) we can see that for JT=0.7 the ASD is decreased 17%. Also comparing Fig. 6.5(c) with Fig. 6.5(a) the ASD for JT=0.7, DE=0.1-CS=0.5 and RE=0.5 is decreased 40%.

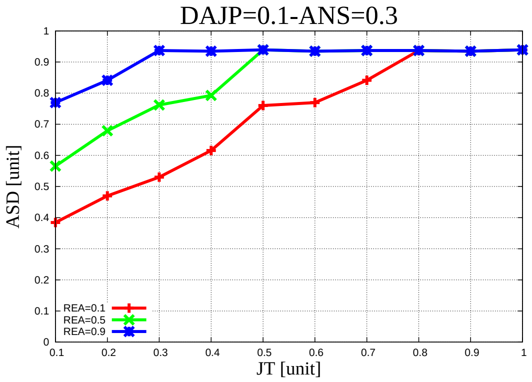
In Fig. 6.9 are shown the simulation results for DE=0.5. Comparing Fig. 6.9(b) with Fig. 6.9(a), for JT=0.7 when DE=0.5-CS=0.5 and RE=0.5, ASD is decreased 20%. Comparing Fig. 6.9(c) with Fig. 6.9(a), for JT=0.7, DE=0.5-CS=0.9 and RE=0.5, ASD is decreased 28%.

In Fig. 6.10 are shown the results for DE=0.9. Comparing Fig. 6.10(b) with Fig. 6.10(a), for JT=0.7, DE=0.9-CS=0.5 and RE=0.5, ASD is decreased 6%. Also comparing Fig. 6.10(c) with Fig. 6.10(a), for JT=0.7, DE=0.9-CS=0.5 and RE=0.5, ASD is decreased 28%.

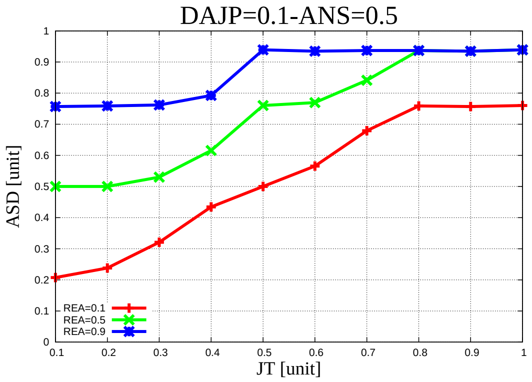
Comparing Fig. 6.9(c) with Fig. 6.8(c) and Fig. 6.10(c) with Fig. 6.8(c), for JT=0.7, CS=0.9 and RE=0.5, the ASD is decreased 5% and 32%, respectively.



(a) ANS=0.1

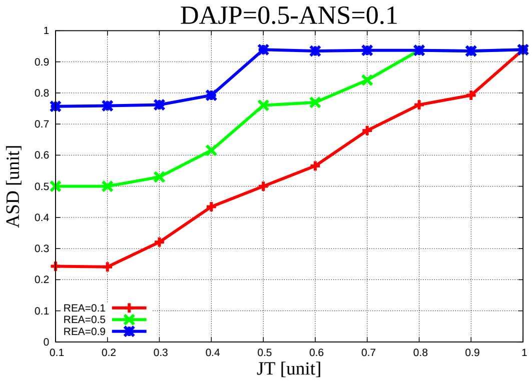


(b) ANS=0.3

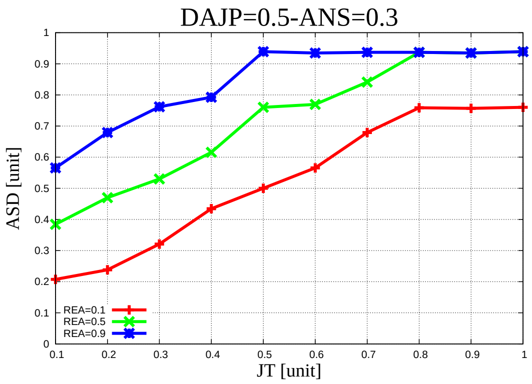


(c) ANS=0.5

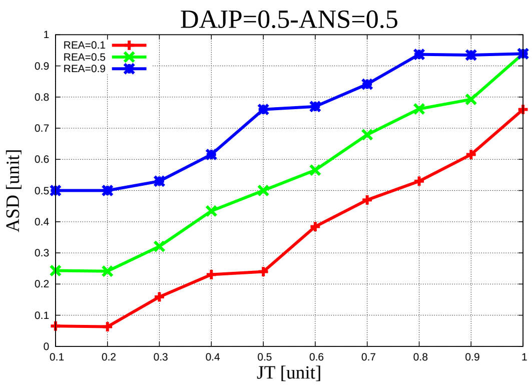
Figure 6.2: Simulation results of FBSANS1 for $DE = 0.1$.



(a) ANS=0.1

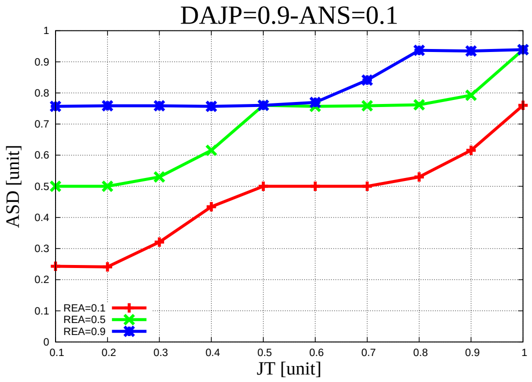


(b) ANS=0.3

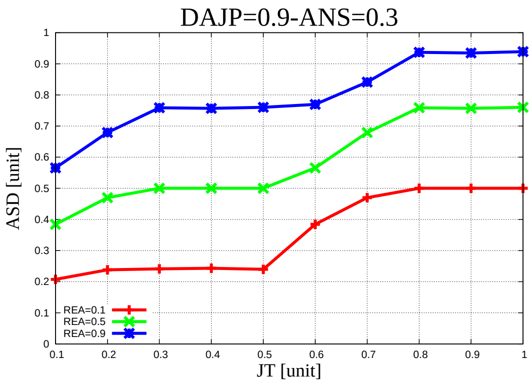


(c) ANS=0.5

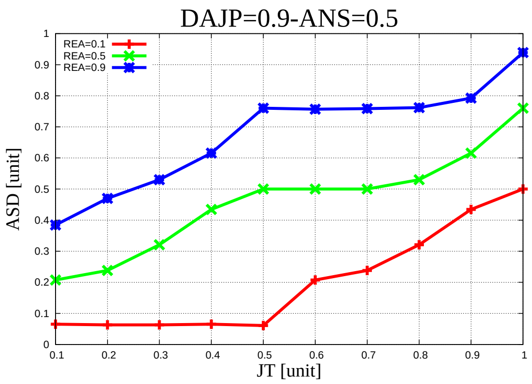
Figure 6.3: Simulation results of FBSANS2 for $DE = 0.5$.



(a) ANS=0.1

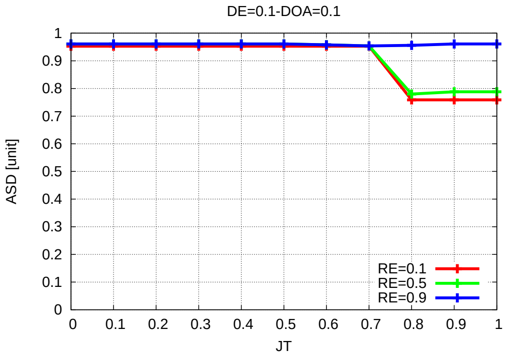


(b) ANS=0.3

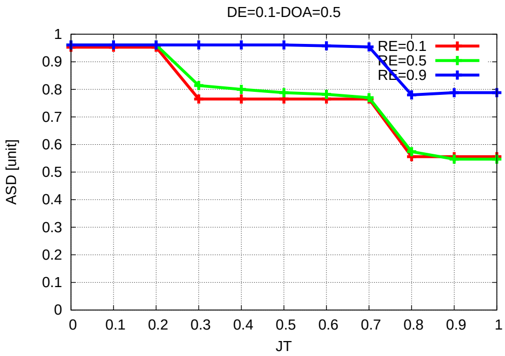


(c) ANS=0.5

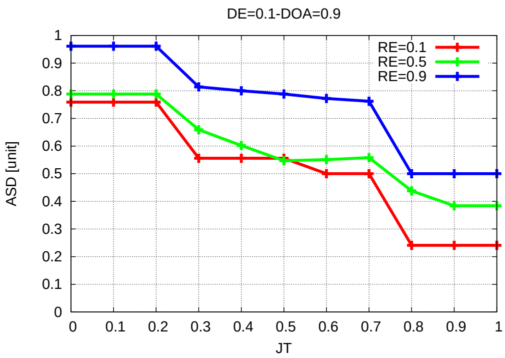
Figure 6.4: Simulation results of FBSANS2 for $DE = 0.9$.



(a) DOA=0.1

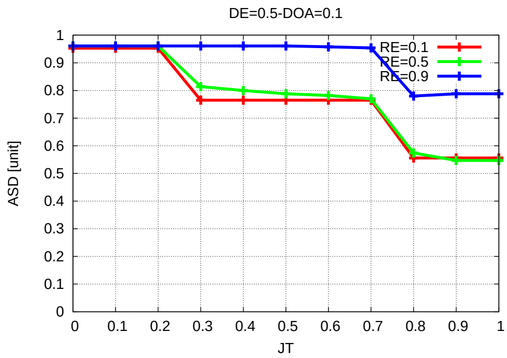


(b) DOA=0.5

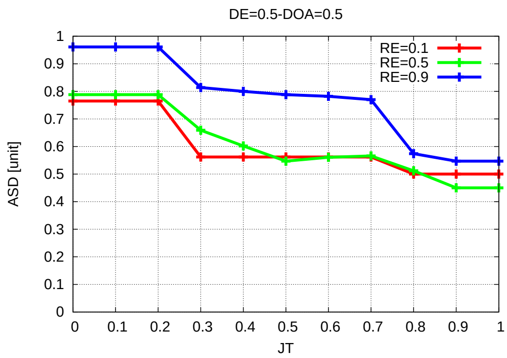


(c) DOA=0.9

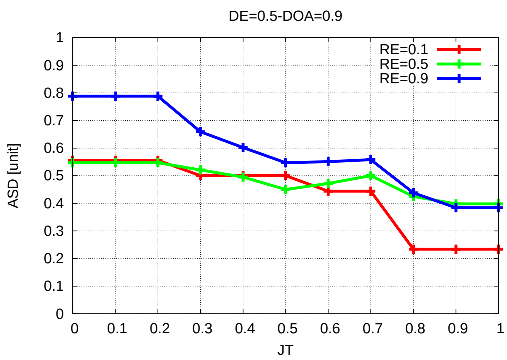
Figure 6.5: Simulation results of FBSANS3 for $DE = 0.1$.



(a) DOA=0.1

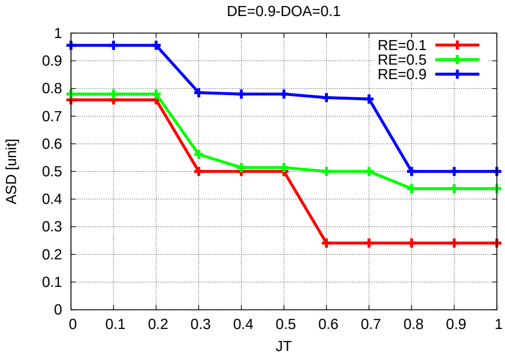


(b) DOA=0.5

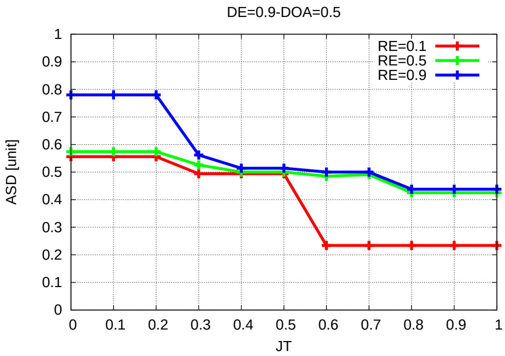


(c) DOA=0.9

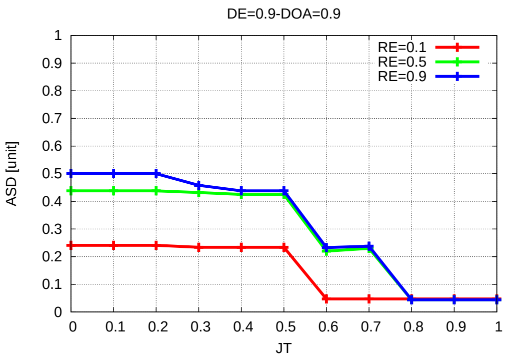
Figure 6.6: Simulation results of FBSANS3 for $DE = 0.5$.



(a) DOA=0.1

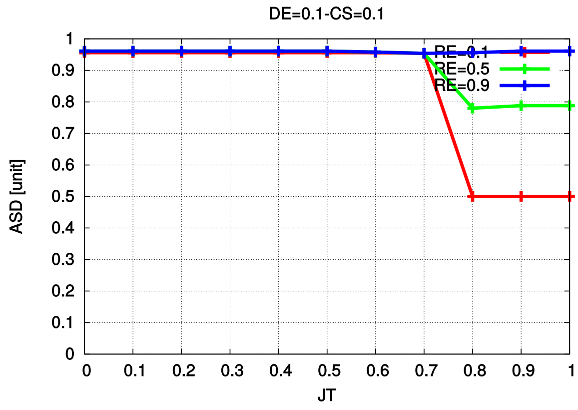


(b) DOA=0.5

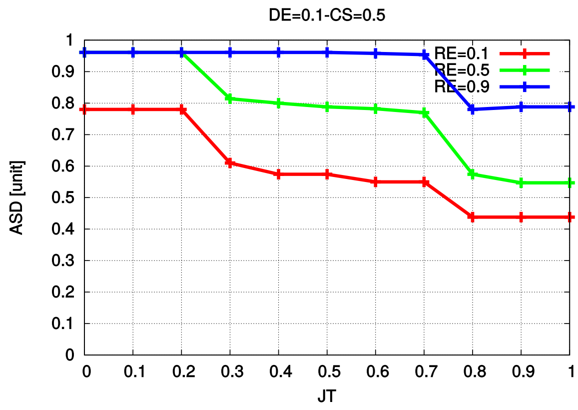


(c) DOA=0.9

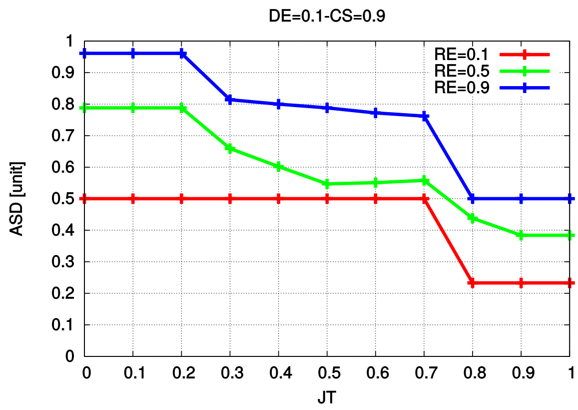
Figure 6.7: Simulation results of FBSANS3 for $DE = 0.9$.



(a) CS=0.1

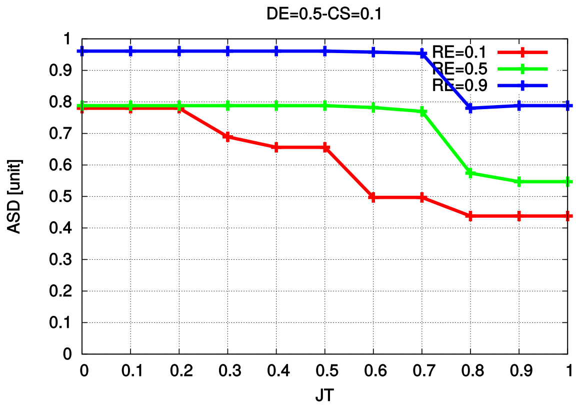


(b) CS=0.5

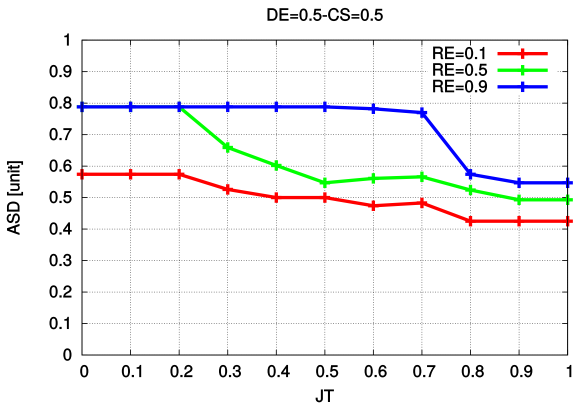


(c) CS=0.9

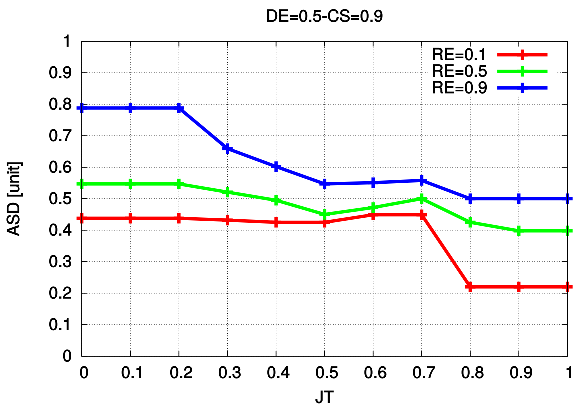
Figure 6.8: Simulation results of FBSANS4 for $DE = 0.1$.



(a) CS=0.1

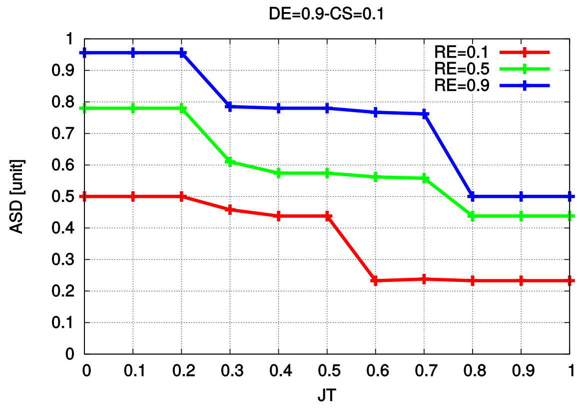


(b) CS=0.5

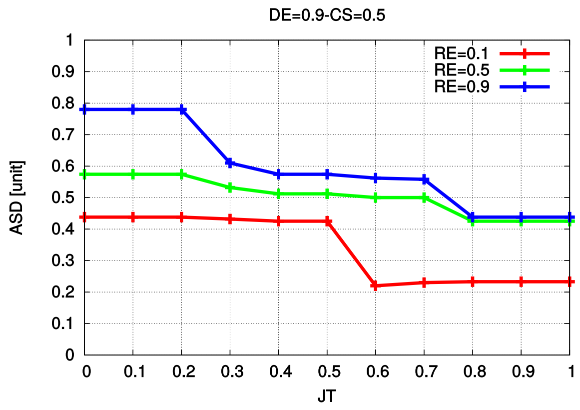


(c) CS=0.9

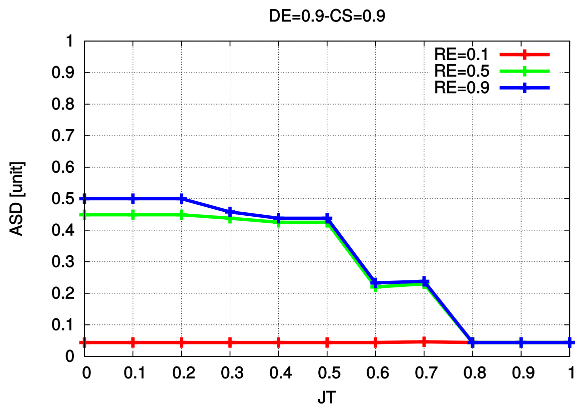
Figure 6.9: Simulation results of FBSANS4 for $DE = 0.5$.



(a) CS=0.1



(b) CS=0.5



(c) CS=0.9

Figure 6.10: Simulation results of FBSANS4 for $DE = 0.9$.

Chapter 7

Testbed Implementation

7.1 Testbed Settings

In this chapter is presented the testbed implementation and performance evaluation results.

Our testbed is composed of sensors and two Roombas (Model 630) acting as actors (see Fig. 7.1). The iRobot Corporation [74] provides Roomba Open Interface (ROI) specifications. In case of Roomba, the ROI connector is the gateway to reversible Roomba hacking. All devices can be plugged into the ROI. Our testbed use Bluetooth module to connect the ROI. The Bluetooth module is from BlueSMiRF (WRL-12582) [75].

All sensors run Linux Raspbian with kernel 2.6 [76]. All experiments have been performed in indoor environment, within our departmental floor of size roughly 20m. The actors are in radio range of each other.

The image processing part of the system runs on Apple Mac Pro equipped with OpenCV 2.4.11. The OpenCV is an open source computer vision and machine learning software library [77]. Monitoring system is composed of sensors and infrared camera. These devices are connected to Sink node.

7.2 Testbed Parameters

Based on WSAN characteristics and challenges, we consider the following parameters for implementation of our testbed.

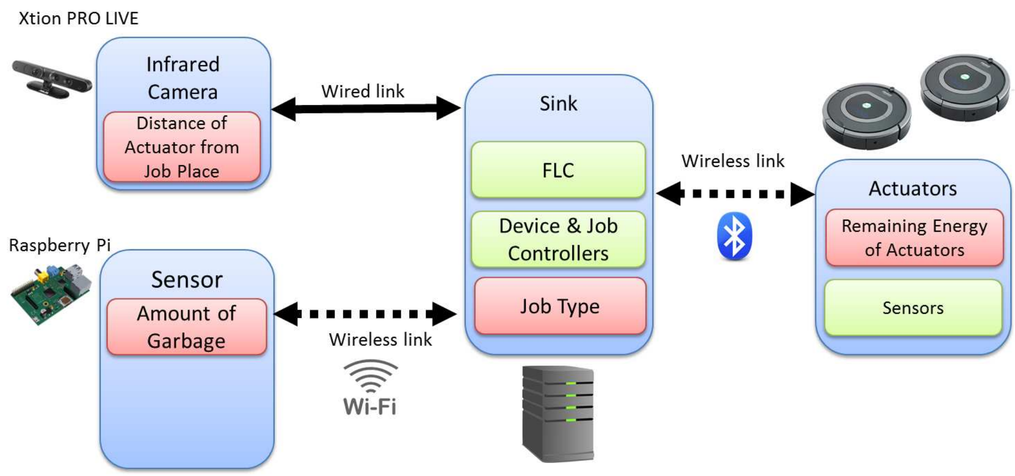


Figure 7.1: Testbed overview.

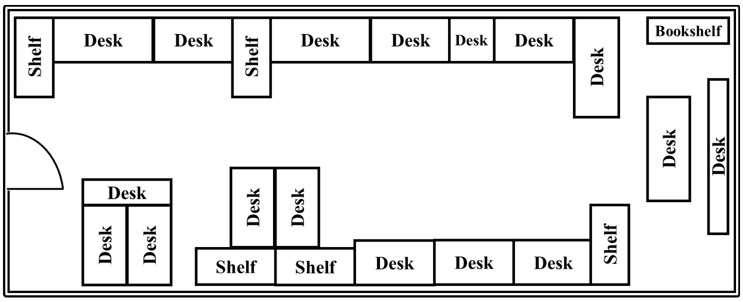
Job Type (JT): A sensed event may be triggered by various causes, such as when water level passed a certain height of the dam. Similarly, for solving a problem, actors need to perform actions of different types. Actions may be classified regarding time duration, complexity, working force required etc., and then assign a priority to them, which will guide actors to make their decisions. In our system JT is defined by three levels of difficulty. The hardest the task, the more likely an actor is to be selected.

Remaining Energy (RE): As actors are active in the monitored field (see Fig. 7.2), they perform tasks and exchange data in different ways from each other. Consequently, also based on their characteristics, some actors may have a lot of power remaining and other may have very little, when an event occurs. We consider three levels of RE for actor selection.

Distance to Event (DE): The number of actors in a WASN is smaller than the number of sensors in our testbed. Thus, when an actor is called for action near an event, the distance from the actor to the event is different for different actors and events. Depending on three distance levels, our system takes decisions on the availability of the actor node. Our testbed uses laser range scanner to measure the distance from actors to events.

Amount of Garbage (AG): As sensors are active in the monitored field, they find dirt and debris at constant intervals. In order to implement these functions we use laser range scanner. Actuator also provides the dirt and debris detections using

(a) Snapshot



(b) Logical floor layout

Figure 7.2: Monitored field.

optical and acoustic sensors by Dirt Detect technology [78]. We consider four levels of AG for actor selection.

Actuator Selection Decision (ASD): Our system is able to decide the willingness of an actor to be assigned and carry out a certain task. The actors respond in five different levels, which can be interpreted as:

- Not Select: It is not worth assigning the task to all actors.
- Select #1: The actor #1 takes responsibility of completing the task.

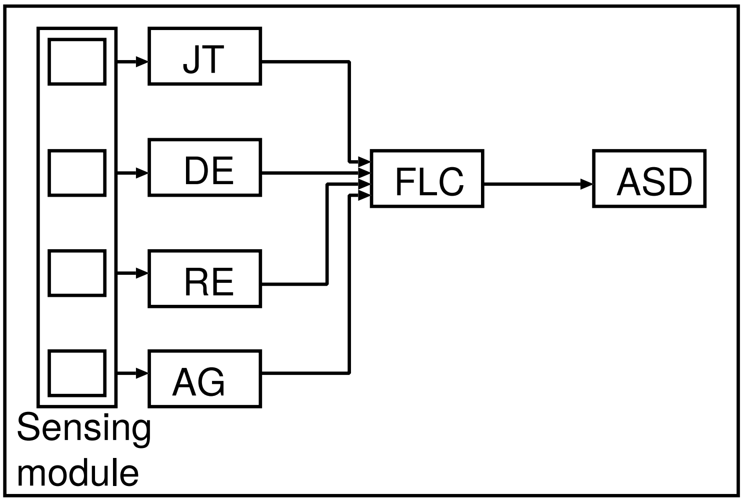


Figure 7.3: Proposed fuzzy-based testbed model.

- Select #2: Another actor (actor #2) takes responsibility of completing the task.
- Select All #1: Both actors, #1 and #2, have required information and potential to take moderate responsibility.
- Select All #2: Both actors, #1 and #2, have almost all required information and potential to take full responsibility.

7.3 Fuzzy-based Testbed

Fuzzy sets and fuzzy logic [79] have been developed to manage vagueness and uncertainty in a reasoning process of an intelligent system such as a knowledge based system, an expert system or a logic control system. In this paper, we use fuzzy logic system called FuzzyC [80] to implement the proposed fuzzy-based testbed.

The structure of the proposed system is shown in Fig. 7.3. We use JT, RE, DE and AG input parameters for FLC. The term sets for each input linguistic parameter are defined respectively as shown in Table 7.1.

The output linguistic parameter is the Actuator Selection Decision (ASD). The membership functions are shown in Fig. 7.4 and the Fuzzy Rule Base (FRB) is shown in Table 7.2. The FRB forms a fuzzy set of dimensions $|T(JT)| \times |T(RE)| \times$

Table 7.1: Parameters and their term sets for FLC.

Parameters	Term Sets
Job Type (JT)	Easy (Es), Normal (Nm), Hard (Hd)
Remaining Energy (RE)	Low (L), Medium (M), High (H)
Distance to Event (DE)	Near (Ne), Middle (Mi), Far (Fa)
Amount of Garbage (AG)	Non (No), Little (Li), Medium (Mdm), Many (Ma)
Actor Selection Decision (ASD)	Not Select (NS), Select #1 (S1), Select #2 (S2), Select All #1 (SA1), Select All #2 (SA2)

$|T(DE)| \times |T(AG)|$where $|T(x)|$ is the number of terms on $T(x)$. The FRB has 108 rules. The control rules have the form: IF "conditions" THEN "control action".

7.4 Evaluation Results

We present the evaluation results for different job types from Fig. 7.5 to Fig. 7.7. The horizontal axis shows the DE input parameter. The vertical axis shows the ASD output parameter.

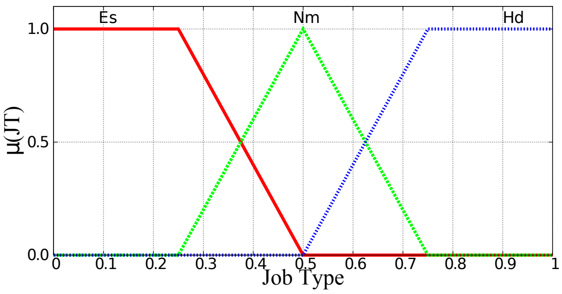
In Fig. 7.5 are shown the results for easy job type. We can observe that ASD increases with the increase of RE for all cases. When DE is small, the difference of ASDs are small. When DE is more than 0.5 units, ASD increases linearly and reaches the saturation value.

The results for normal job type are shown in Fig. 7.6. When DE and AG are high, the results of ASD is high. In this condition, the actors take full responsibility. Also when RE is 0.9, ASD reaches 0.9 units. The actors use energy to reach the event position. Therefore, if the actor changes its condition often, it will lose a lot of energy. On the other hand, when ASD is 0.1, our testbed does not consider the task assignment to actors.

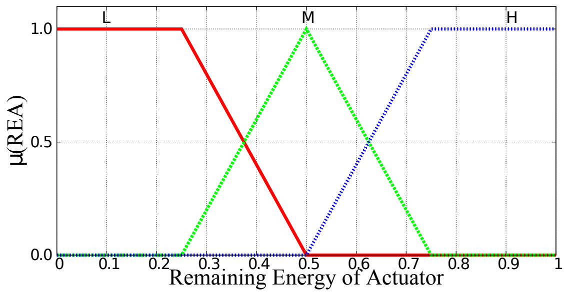
The results for hard job type are shown in Fig. 7.7. The results of ASD for hard job are higher than other job types. From these results, we notice that as

Table 7.2: FRB of proposed fuzzy-based testbed.

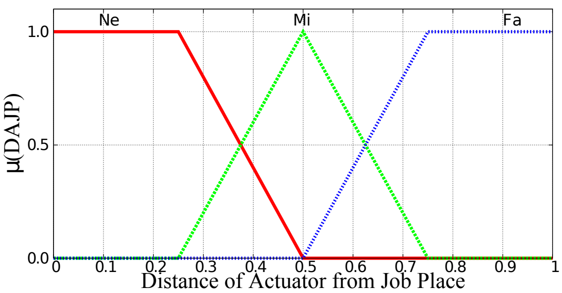
Rule	JT	RE	DE	AG	ASD	Rule	JT	RE	DE	AG	ASD	Rule	JT	RE	DE	AG	ASD
1	Es	L	Ne	No	NS	37	Nm	L	Ne	No	NS	73	Hd	L	Ne	No	NS
2	Es	L	Ne	Li	NS	38	Nm	L	Ne	Li	NS	74	Hd	L	Ne	Li	NS
3	Es	L	Ne	Mdm	NS	39	Nm	L	Ne	Mdm	NS	75	Hd	L	Ne	Mdm	NS
4	Es	L	Ne	Ma	NS	40	Nm	L	Ne	Ma	NS	76	Hd	L	Ne	Ma	S1
5	Es	L	Mi	No	NS	41	Nm	L	Mi	No	NS	77	Hd	L	Mi	No	NS
6	Es	L	Mi	Li	NS	42	Nm	L	Mi	Li	NS	78	Hd	L	Mi	Li	NS
7	Es	L	Mi	Mdm	NS	43	Nm	L	Mi	Mdm	NS	79	Hd	L	Mi	Mdm	S1
8	Es	L	Mi	Ma	NS	44	Nm	L	Mi	Ma	S1	80	Hd	L	Mi	Ma	S1
9	Es	L	Fa	No	NS	45	Nm	L	Fa	No	NS	81	Hd	L	Fa	No	S1
10	Es	L	Fa	Li	NS	46	Nm	L	Fa	Li	S1	82	Hd	L	Fa	Li	S1
11	Es	L	Fa	Mdm	S1	47	Nm	L	Fa	Mdm	S1	83	Hd	L	Fa	Mdm	S1
12	Es	L	Fa	Ma	S1	48	Nm	L	Fa	Ma	S1	84	Hd	L	Fa	Ma	S1
13	Es	M	Ne	No	S1	49	Nm	M	Ne	No	S1	85	Hd	M	Ne	No	S1
14	Es	M	Ne	Li	S1	50	Nm	M	Ne	Li	S1	86	Hd	M	Ne	Li	S2
15	Es	M	Ne	Mdm	S1	51	Nm	M	Ne	Mdm	S2	87	Hd	M	Ne	Mdm	S2
16	Es	M	Ne	Ma	S2	52	Nm	M	Ne	Ma	S2	88	Hd	M	Ne	Ma	SA1
17	Es	M	Mi	No	S1	53	Nm	M	Mi	No	S1	89	Hd	M	Mi	No	S2
18	Es	M	Mi	Li	S1	54	Nm	M	Mi	Li	S2	90	Hd	M	Mi	Li	S2
19	Es	M	Mi	Mdm	S2	55	Nm	M	Mi	Mdm	S2	91	Hd	M	Mi	Mdm	SA1
20	Es	M	Mi	Ma	S2	56	Nm	M	Mi	Ma	SA1	92	Hd	M	Mi	Ma	SA2
21	Es	M	Fa	No	S2	57	Nm	M	Fa	No	S2	93	Hd	M	Fa	No	SA1
22	Es	M	Fa	Li	S2	58	Nm	M	Fa	Li	SA1	94	Hd	M	Fa	Li	SA1
23	Es	M	Fa	Mdm	SA1	59	Nm	M	Fa	Mdm	SA1	95	Hd	M	Fa	Mdm	SA2
24	Es	M	Fa	Ma	SA1	60	Nm	M	Fa	Ma	SA2	96	Hd	M	Fa	Ma	SA2
25	Es	H	Ne	No	S1	61	Nm	H	Ne	No	S2	97	Hd	H	Ne	No	S2
26	Es	H	Ne	Li	S2	62	Nm	H	Ne	Li	S2	98	Hd	H	Ne	Li	SA1
27	Es	H	Ne	Mdm	S2	63	Nm	H	Ne	Mdm	SA1	99	Hd	H	Ne	Mdm	SA2
28	Es	H	Ne	Ma	SA1	64	Nm	H	Ne	Ma	SA2	100	Hd	H	Ne	Ma	SA2
29	Es	H	Mi	No	S2	65	Nm	H	Mi	No	S2	101	Hd	H	Mi	No	SA1
30	Es	H	Mi	Li	S2	66	Nm	H	Mi	Li	SA1	102	Hd	H	Mi	Li	SA2
31	Es	H	Mi	Mdm	SA1	67	Nm	H	Mi	Mdm	SA2	103	Hd	H	Mi	Mdm	SA2
32	Es	H	Mi	Ma	SA2	68	Nm	H	Mi	Ma	SA2	104	Hd	H	Mi	Ma	SA2
33	Es	H	Fa	No	SA1	69	Nm	H	Fa	No	SA1	105	Hd	H	Fa	No	SA2
34	Es	H	Fa	Li	SA1	70	Nm	H	Fa	Li	SA2	106	Hd	H	Fa	Li	SA2
35	Es	H	Fa	Mdm	SA2	71	Nm	H	Fa	Mdm	SA2	107	Hd	H	Fa	Mdm	SA2
36	Es	H	Fa	Ma	SA2	72	Nm	H	Fa	Ma	SA2	108	Hd	H	Fa	Ma	SA2



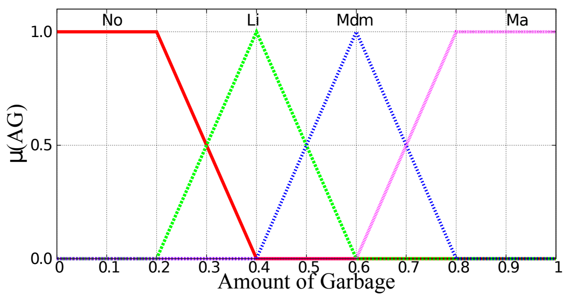
(a) JT



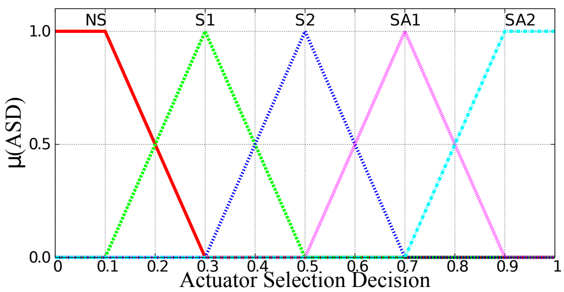
(b) RE



(c) DE



(d) AG



(e) ASD

Figure 7.4: Membership Functions

Table 7.3: Experimental results by Infrared Sensor.

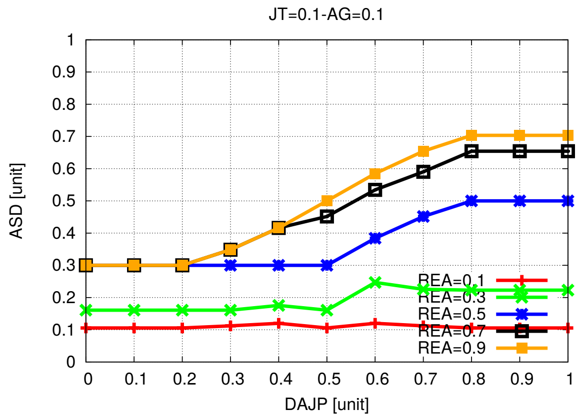
D [m]	1.0, 2.0, 3.0, 4.0, 5.0
Exp [m]	1.034, 2.005, 3.010, 3.948, 4.983
D [m]	6.0, 7.0, 8.0, 9.0
Exp [m]	5.933, 7.030, 8.019, 9.084

JT becomes difficult the ASD becomes higher because actors are programmed for difficult jobs, the response can be faster for emergency situations.

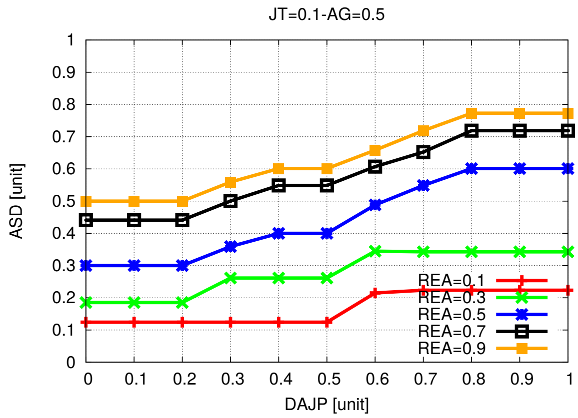
For object tracking, object recognition and 3D reconstruction, it is basic to extract feature points [81, 82]. Also, when calculating the relationship between two still pictures for tracking a moving object, it is needed to connect each other feature points [83]. In order to find good feature points of accuracy, it is necessary to select the good feature points, corner and intersection compared with around them [84]. In this work, we use QPToolkit to extract the position measurement based on ARToolkit [85].

We present the evaluation results for detecting the actors in the monitored fields in Fig. 7.8. We can observe that our testbed detect two actors even if fake label is in monitored field.

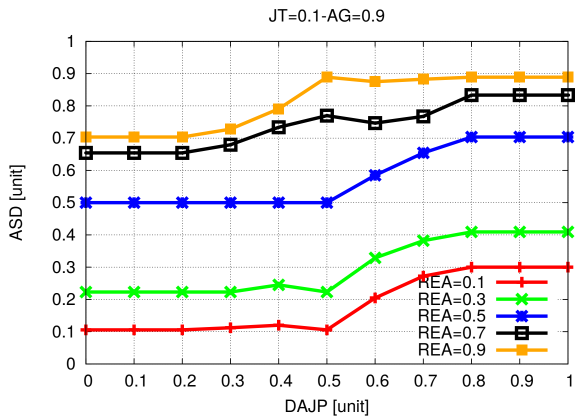
In order to evaluate the accuracy of distance, we carried out measurement by infrared camera. In Table 7.3, we show the experimental results from 1 to 9 m. The difference between experimental results and real distance is about 35 mm in average. In Fig. 7.9, we show the snapshot of our testbed for object tracking. The red circle show the object detected (color tracking) and the distance from infrared camera. Our fuzzy-based model can use the above values to select the actor in order to have short latency, low energy consumption and proper task assignment.



(a) JT=0.1, AG=0.1

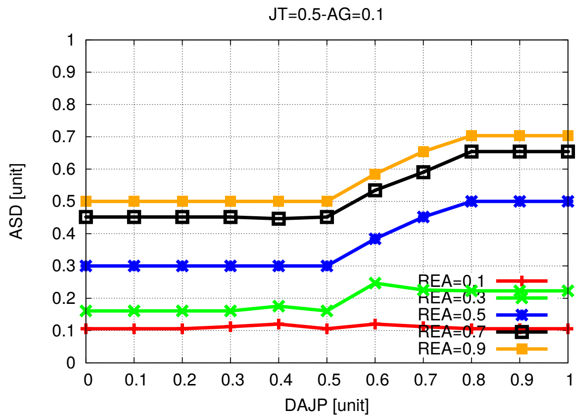


(b) JT=0.1, AG=0.5

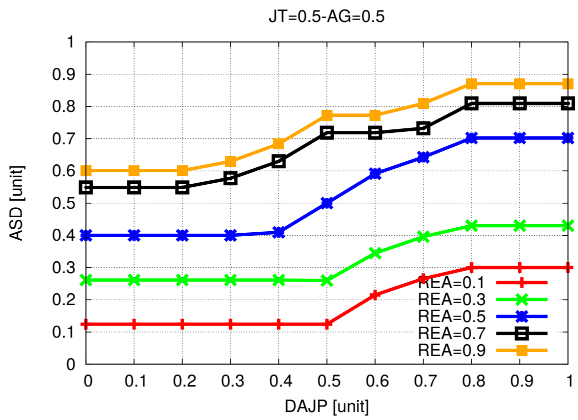


(c) JT=0.1, AG=0.9

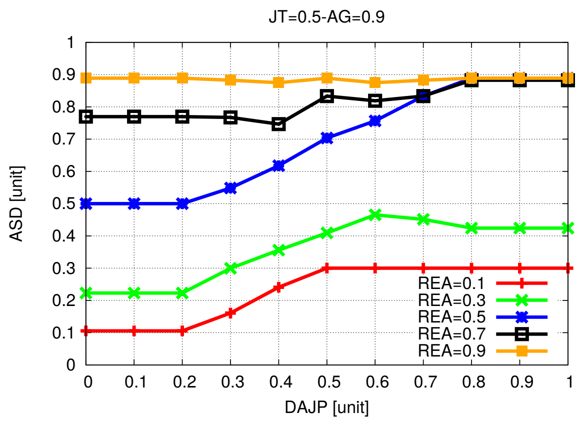
Figure 7.5: Evaluation results (JT=0.1).



(a) JT=0.5, AG=0.1

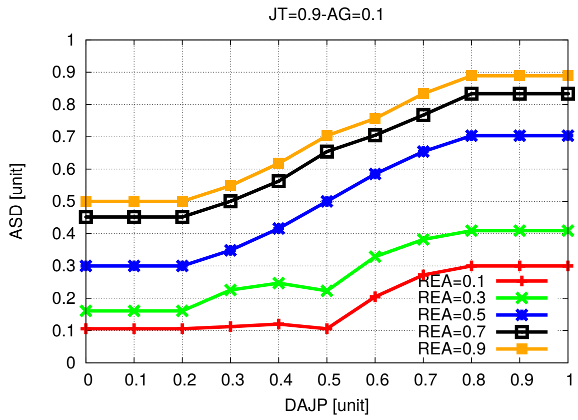


(b) JT=0.5, AG=0.5

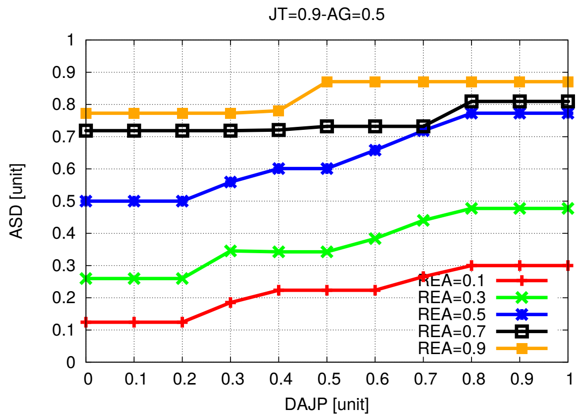


(c) JT=0.5, AG=0.9

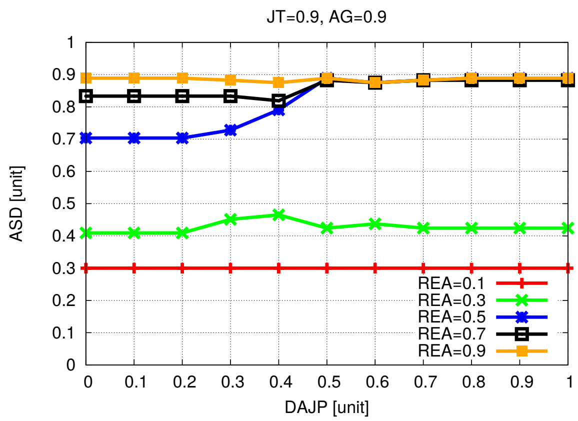
Figure 7.6: Evaluation results (JT=0.5).



(a) JT=0.9, AG=0.1

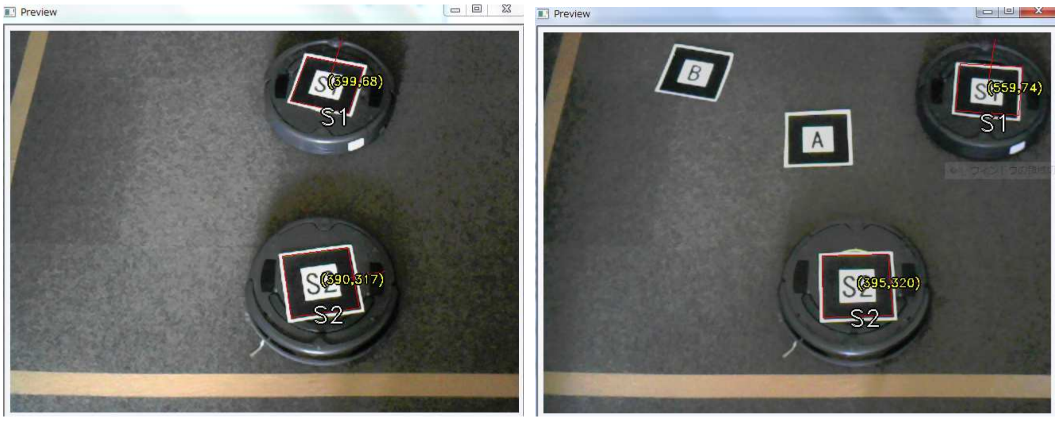


(b) JT=0.9, AG=0.5



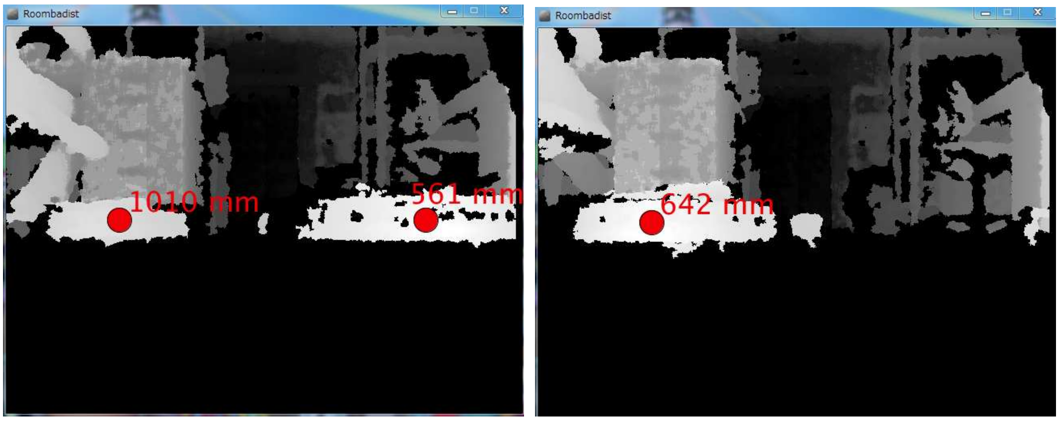
(c) JT=0.9, AG=0.9

Figure 7.7: Evaluation results (JT=0.9).



(a) Sample 1 (b) Sample 2

Figure 7.8: Detection of actors.



(a) Sample 1 (b) Sample 2

Figure 7.9: Monitoring distance for actors.

Chapter 8

Concluding Remarks

8.1 Conclusions and Future Work

In this thesis, we proposed and implemented two fuzzy-based systems that decide whether the actor will be selected for the required job or not based on data supplied by sensors and actual actor condition in WSANs considering or not the actor mobility. The thesis is organized as follows.

In Chapter 1, we presented an introduction to the thesis and its content. We introduced the background, the purpose and the outline of this thesis.

Chapter 2 presented an overview of Wireless Networks. It described the characteristics, requirements and the basic goals of two most used categories of Ad-hoc networks.

Chapter 3 provided an introduction in wireless sensor and actor networks. It described the architecture of WSANs, peculiarities and challenges and their main applications.

Chapter 4 presented fuzzy logic. It discussed the meaning and basics of Fuzzy Set Theory (FST) and the Fuzzy Control (FC) principles such as linguistic variables, FC rules, fuzzification and defuzification methods.

Chapter 5 introduced our proposed fuzzy-based systems. We explained in details their design and implementation.

In Chapter 6, were shown the simulation results of our proposed systems.

In Chapter 7, we showed the implementation of a testbed for WSANs and its application in a real scenario.

The main challenges for WSANs have to do with node coordination, energy management and mobility. A WSAN can be implemented as semi-automated architecture (which is similar to WSN) and fully-automated architecture (which is the real challenge of embedded WSANs). In this work, we proposed and implemented four fuzzy-based simulation systems for WSAN. The systems select the actor node in order to have short delays, low energy consumption and proper task assignment. From the simulation results of FBSANS1, we conclude as follows.

- When the difficulty level of the job (JT) increases, ASD also increases.
- For different values of RE, the value of ASD differs in a way that actors with low battery are not involved in many task assignment. Thus, for lower values of RE, ASD decreases. In this way the network lifetime is increased.
- When the DE increases and ASD decreases, our system instructs actors that are near the event to be more active in task assignment, while for actors that are further away and need more time and energy to reach the event place not to be active. By doing this the response to emergency situations is improved and the energy management is better.

From the simulation results of FBSANS2, we conclude as follows.

- As JT becomes difficult the ASD becomes higher because actors are programmed for different jobs.
- The DE defines the distance of the actor from the job place, so when DE is small, the ASD is higher. The actors closest to the job place use less energy to reach the job position.
- For each value of DE, when the ANS increases the network topology is more dynamic. In this condition, the actor may lose connectivity and changes its condition (such as distance from job place) in a while, so it will be not reachable any more. But, the actor is moving with higher speed, the response can be faster for emergency situations.

From simulation results, we found that the response of implemented systems to emergency situations is improved and the energy management is better. Comparing complexity of FBSANS1 and FBSANS2, the FBSANS2 is more complex than

FBSANS1. However, it also considers mobility of actor nodes. Thus, the FBSANS2 is more flexible system than FBSANS1.

From the simulation results of FBSANS3, we conclude as follows.

- When JT and RE increases also ASD increases. But, when DE and DOA increases the ASD decreases, because the longer the distance from the event, the lower are the chances for the actor to be selected.
- By increasing DE value from 0.1 to 0.5 and 0.9, for JT=0.7, DOA=0.9 and RE=0.5, the ASD is decreased 5% and 27%, respectively.

From the simulation results of FBSANS4, we conclude as follows.

- ASD decreases when DE and CS increases.
- By increasing the value of CS from 0.1 to 0.5, for JT=0.7 when DE=0.5-CS=0.5 and RE=0.5, the ASD is decreased 20%.
- By increasing the value of CS from 0.1 to 0.9, for JT=0.7, DE=0.5-CS=0.9 and RE=0.5, the ASD is decreased 28%.
- Comparing the 0.5 and 0.9 value with 0.1 value of CS parameter, for JT=0.7, CS=0.9 and RE=0.5, the ASD is decreased 5% and 32%, respectively.

Based on the experimental results of the Testbed, we conclude as follows.

- ASD increases with the increase of JT and RE for all cases. When DE is small, the difference of ASDs are small.
- We evaluated the performance of proposed fuzzy-based testbed for object tracking in a monitored field. Our testbed detects two actors even if fake label is in monitored field.
- The difference between experimental results and real distance is about 35 mm in average.

In the future work, we will consider also other parameters for actor selection and make extensive simulations to evaluate the proposed system. We also will improve the testbed and make experiments for different scenarios.

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