# MISSION AWARE ENERGY SAVING STRATEGIES FOR ARMY GROUND VEHICLES

by

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# CHAPTER 1 INTRODUCTION

## 1.1 Introduction

Technology is advancing in transportation, manufacturing, entertainment, security, and communication areas. However, the energy required to operate them is slowly diminishing. This threatens national security as well as human lives on earth. Since the technology is affordable, its usage is widespread globally. As usage grows, the demand for energy increases rapidly. Therefore, saving energy or minimizing its consumption is very important.

Natural fuel such as crude oil stores energy that can be extracted to perform many activities on earth. Therefore, fuel energy is a basic necessity for the modern world. On the contrary, the quadrupled automotive vehicle usage has increased consumption of fuel energy in terms of petrol and diesel has peaked. Ground vehicles are used for either commercial (or passenger) or military applications. Army, commercial, and passenger ground vehicles are almost identical in engine, transmission, and electrical generator characteristics. However, the Army ground vehicles seem to embed numerous electronic systems namely, large radio communications, computers, weapons, mine detecting, and surveillance systems. These systems demand more electrical energy (load) during military missions than the systems used in the normal operations of a commercial or passenger vehicle. Fig. 1 and Fig. 2 show an example of a commercial passenger vehicle and an Army ground vehicle with its systems, respectively. Current and future electrical demands can exceed energy generation and storage capabilities of an Army ground vehicle [1] [2]. The increased electrical energy consumption requirements of the vehicle increase fuel consumption. Refueling is a major concern on battle fields. According to a defense science board report [3] [4], a department of defense has spent nearly $13.6 billion on petroleum fuel, and 3.8 billion kWh of electricity, which is 78% of the total energy consumption by the federal government. Therefore, saving energy in Army ground vehicles is very important.

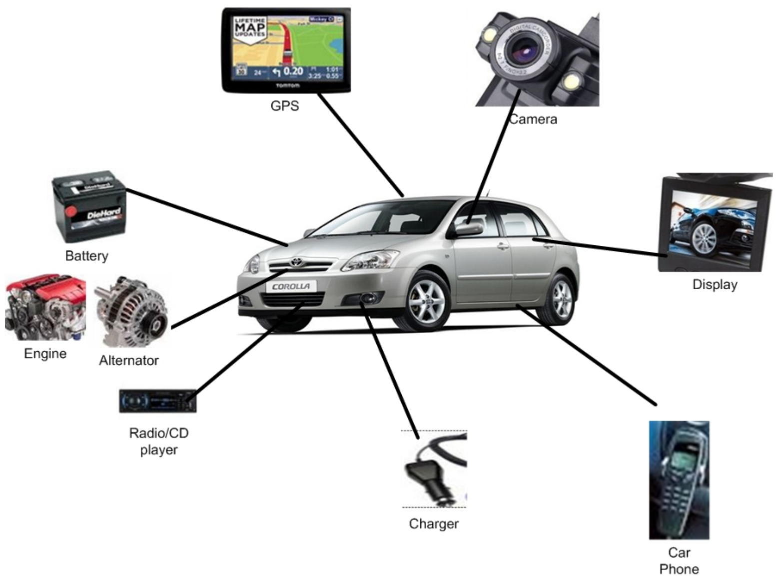


Fig. 1. Passenger vehicle: example electrical systems.

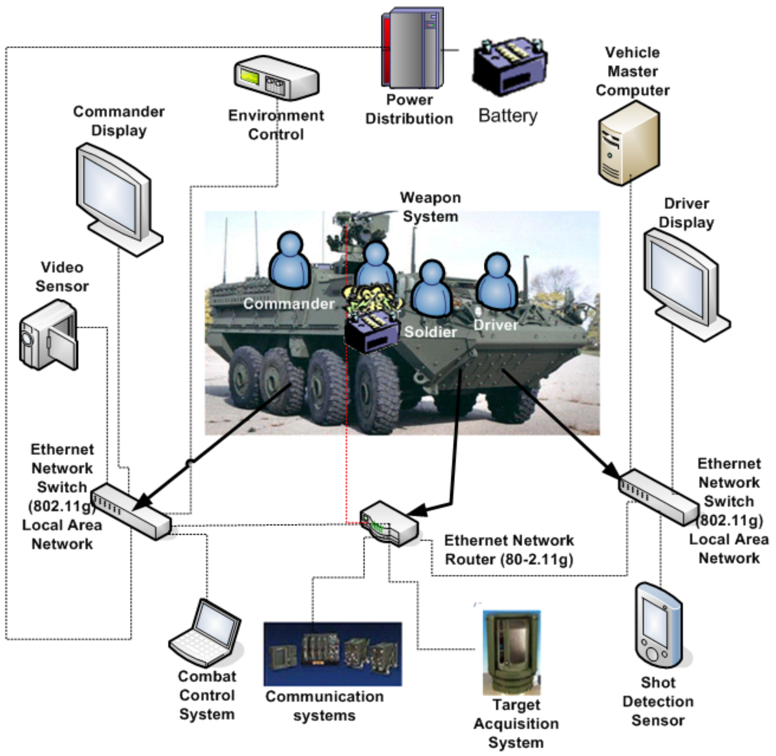


Fig. 2. Army vehicle: example electrical systems

Fig. 3 shows the electrical energy demand of ground automotive vehicles for a family of vehicles namely, passenger vehicles, commercial vehicles (e.g., buses, trucks), and Army vehicles. The Army ground vehicles seem to have more electrical energy demand than other vehicles. The voltage requirements vary between different the families of vehicles. The range is between 12 and 28 volts. Fig. 4 shows the corresponding horsepower demands on the engine to meet the electrical needs of the vehicle. Many different architectures are available to allow engines to generate electricity in a vehicle. However, the range information in the figures assumes that an alternator is used to generate electricity and a pulley is used to transfer mechanical energy from the engine to the alternator.

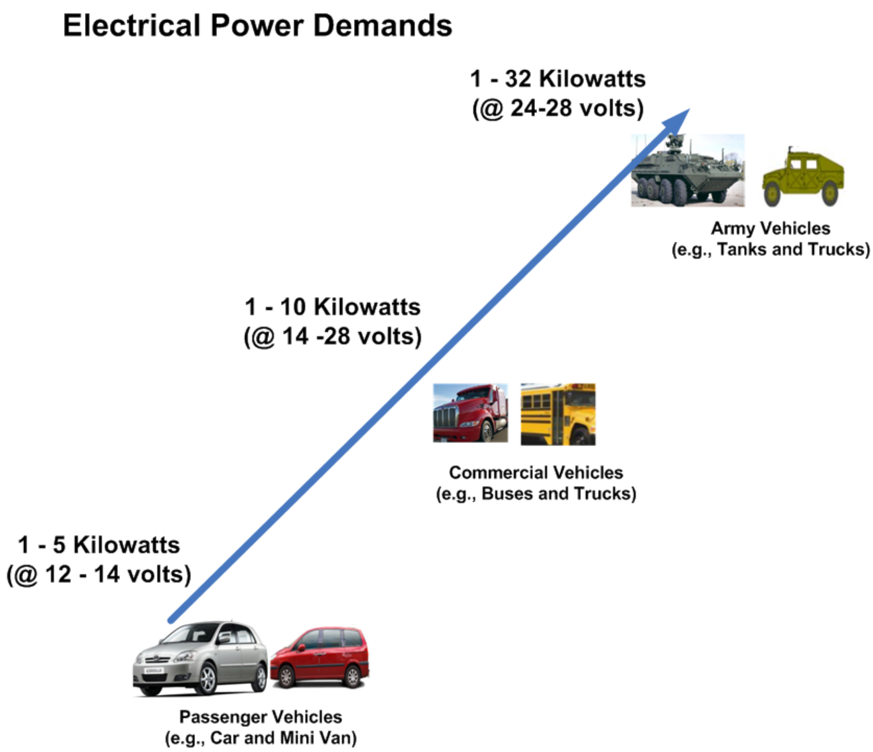


Fig. 3. Electrical energy demands range

The main objective of this dissertation research is to develop strategies to save energy while meeting the electrical needs of conventional Army ground vehicles during stationary surveillance missions. The strategies should be aware of mission requirements, provide appro-

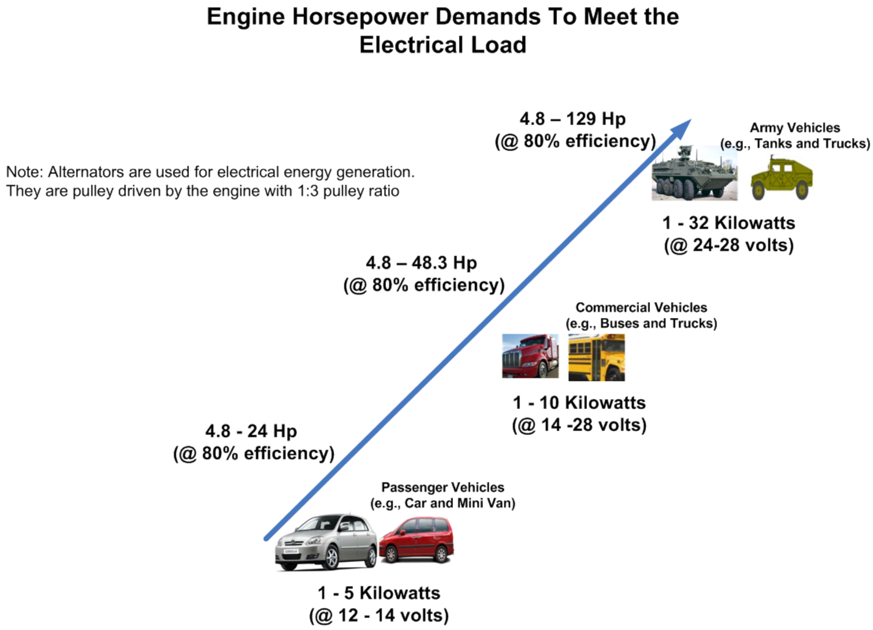


Fig. 4. Engine horsepower demands range

priate energy saving approaches and also meet the electrical demands of the vehicle. Section 1.2 through Section 1.5 describes the background for the proposed dissertation research and Section 1.7 discusses the problem statement.

## 1.2 Army Ground Vehicles

Army is one of the military divisions specialized in land warfare. In a given war mission, the war zone is very hostile, the terrain is unknown and the soldiers have to perform several critical complex activities to defeat enemy forces. To carry out a mission, the Army uses many types of ground vehicles namely, combat, tactical, medical, reconnaissance, fire support, and ammunition carrying vehicles. The Army ground vehicles have multiple electronic devices, weapons, and computing resources to aid in a mission. Normally, the ground vehicles carry soldiers to the battle field and also allow them to conduct specific operations to meet the mission requirements. Fig. 5 shows an example of an Army ground vehicle along with its electronic systems.

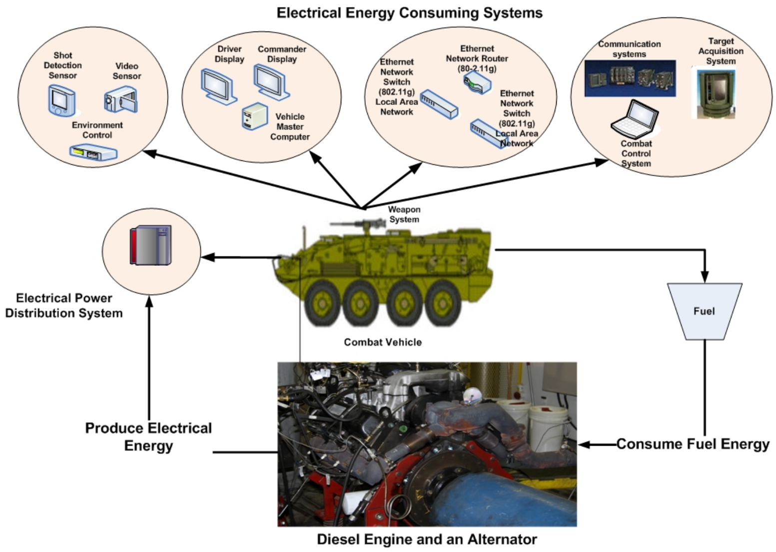


Fig. 5. Army ground combat vehicle example.

A typical Army ground vehicle uses a diesel engine, a drivetrain, an automatic transmission, a belt-driven alternator, batteries, and electrical systems. During stationary operations of a vehicle, an engine is either on and is in neutral gear or it is completely turned off. If the engine is off, the batteries within the vehicle have to supply power to the systems. If the engine is on, it consumes fuel and drives an alternator to generate electricity that powers the systems. Unnecessary battery discharges and in-efficient operation of the engine increases the energy consumption of the vehicle.

## 1.3 Mission Awareness

The Army performs several battle and surveillance missions to protect people and defend countries against enemies. Most of the time, the Army uses ground vehicles to conduct mission activities. An example mission scenario can be viewed as two soldiers performing operations in an Army ground vehicle using computer workstations, surveillance systems, video cameras, radio communication systems, a weapon, and a vehicle master computer. Fig. 6 shows an example of the activities conducted during a sample mission scenario.

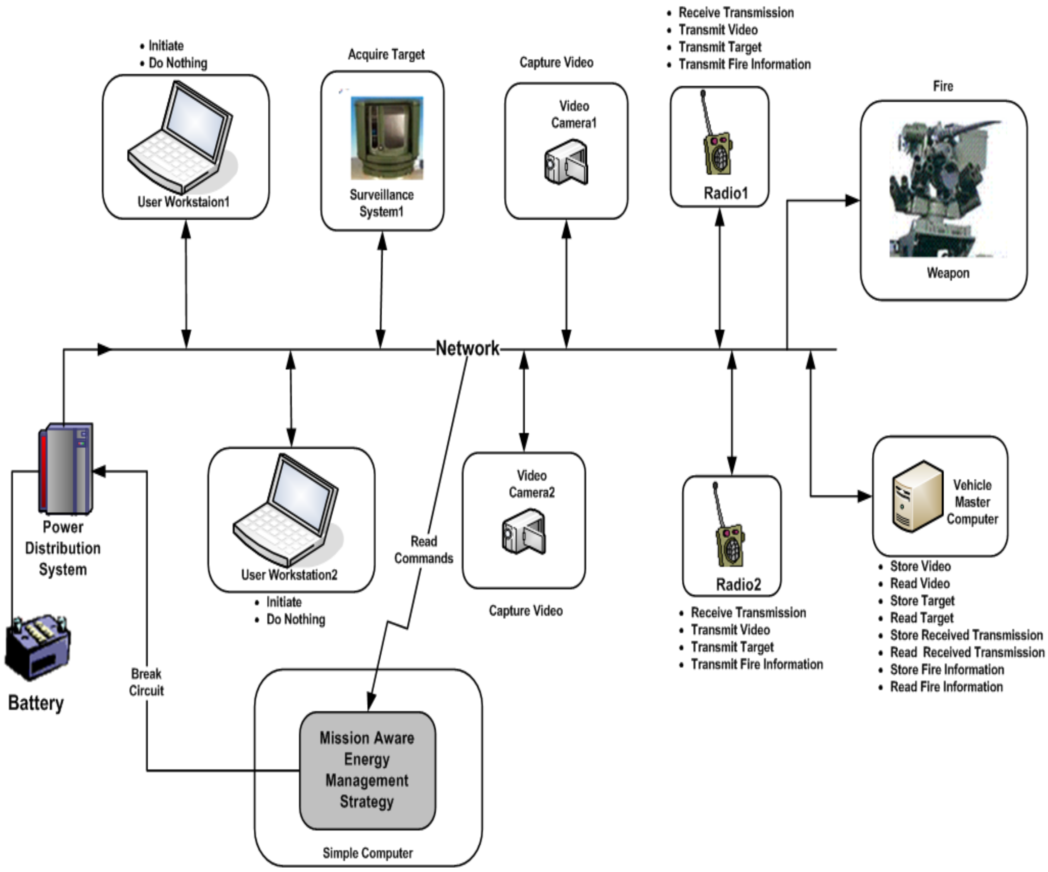


Fig. 6. A sample mission scenario activities.

Some examples of tasks of a mission are capturing activities of enemy forces, recording significant events and diagnostics information of systems, communicating with other Army ground vehicles, firing at the enemy forces, and conducting surveillance activities. The frequency of these activities is somewhat random and is completely dependent on the mission conditions. A mission scenario influences the usage of systems and electrical power generation requirements of the vehicle. The fuel consumption of the vehicle has a direct dependency on the systems electrical energy requirements. Therefore, awareness of how the soldiers conduct a mission using the systems in the vehicle allows researchers to develop techniques to minimize electrical energy requirements,to save fuel energy in Army ground vehicles, and to extend mission time. Fig. 7 shows an example of mission tasks.

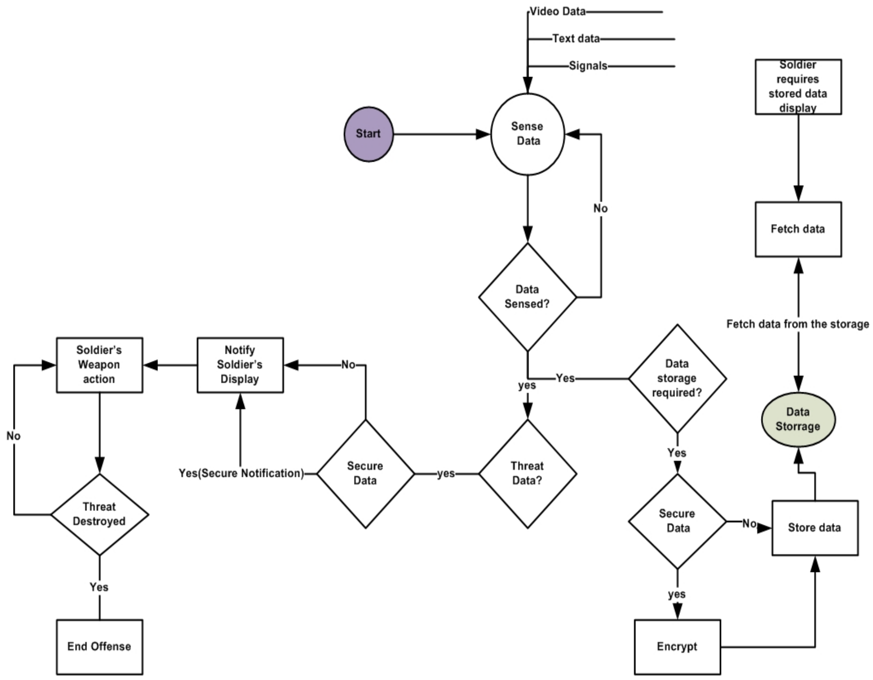


Fig. 7. A sample mission activities.

## 1.4 Energy Saving Strategy

This dissertation research focuses on electrical and fuel energy saving strategies for Army ground vehicles. The saving strategy is an approach used in the systems to minimize their energy consumption. In the current literature, researchers have developed and implemented several electrical energy saving strategies for electronic devices, wireless sensor networks, computing resources, and fuel energy saving strategies for automotive systems such as an engine. Although these approaches are reusable, they have limited application diversity. Some of the example strategies are as follows:

- Dynamically transition an electrical energy consuming system to a lower power consumption mode based on its activity level to save electrical energy
- Operate an automotive engine based on the road type and traffic conditions to save fuel energy

Fig. 8 shows the growth in fuel consumption by the military per soldier/day. The growth and the predictions for the future is very high. Similarly, the growth in crude oil price as shown in Fig. 9 is also rising. Efficient mission aware energy saving strategies is necessary for the Army. Chapter 2.2 discusses some of the recent energy saving strategies developed for aforementioned systems. The source for the pictures in Fig. 1, Fig. 2, Fig. 3, and Fig. 4 are from the world wide web.

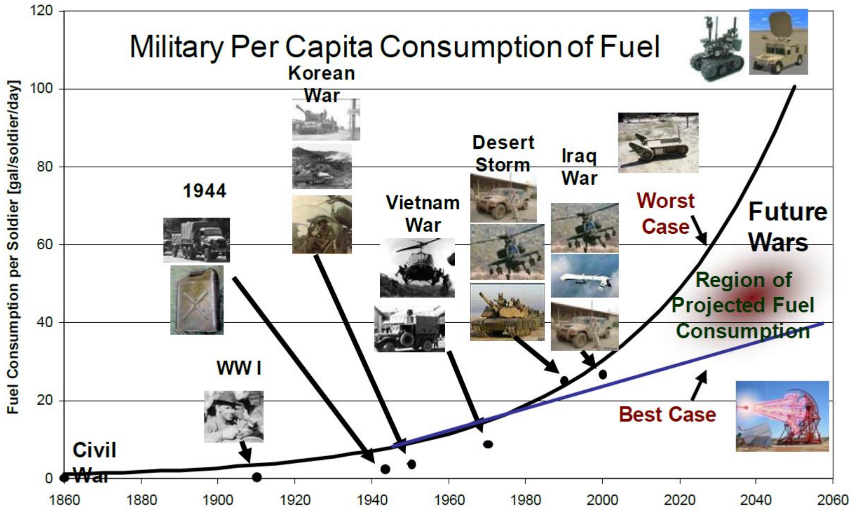


Fig. 8. Fuel consumption growth in military [2].

## 1.5 Energy Saving Strategy In Stationary Army Ground Vehicles

Armies conduct training exercises and surveillance missions of long durations and using stationary ground vehicles in the following two modes:

- Silent: The engine is turned off and a shared battery powers all the on-board systems for extended hours. Soldiers cannot recharge the battery due to the risk of enemy forces identifying the vehicle if the engine is running. Duration of a mission depends on the battery capacity.
- Normal: The engine is turned on and a low engine speed (idle) coupled with a low alternator speed generates electricity to power all the systems for extended hours. Increased

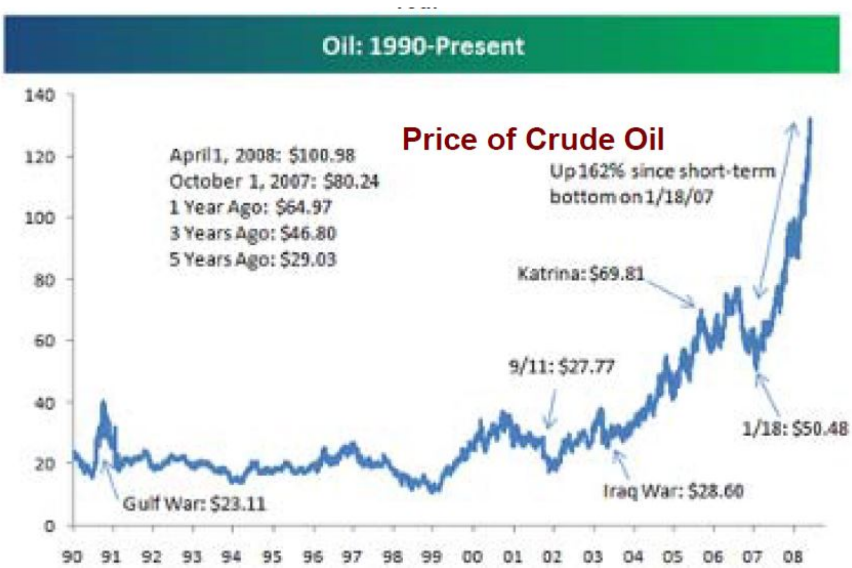


Fig. 9. Crude oil price growth [2].

electrical consumption of the systems let the engine control unit to change the engine speed to a next high-idle RPM, a situation that is less energy efficient.

The soldiers use multiple on-board systems to perform mission activities as shown in Fig. 6. The systems require electricity for their continuous operation. The process of electricity generation in a stationary Army ground vehicle is a physical phenomenon between the on-board electrical systems, engine, and the alternator. An engine consumes fuel energy and generates mechanical energy (torque) to operate an electrical machine such as an alternator to generate electricity. Excess energy is stored in a battery for future uses. To provide modern technology and to meet mission demands, the number of systems on an Army vehicle continues to increase. To meet growing energy requirements, the military invests in research to increase electric energy generation inside the vehicles. Although it is very important for the vehicle to increase its generation capability, manufacturers should also focus their attention on saving energy by minimizing consumption inside a vehicle i.e., more efficient use of energy.

The following energy saving strategies are required to meet the electrical energy requirements of the two surveillance mission modes as well as to save fuel energy:

- Silent surveillance mode: Minimize unnecessary battery discharges by dynamically controlling the power states of systems according to mission needs and available battery capacity. Chapter 4 focuses on this topic.
- Normal surveillance mode: Operate the engine at a fuel-efficient speed per unique electrical demand by combining the engine and alternator performance/efficiency maps, mission aware profiles of on-board systems electric current draw, and constraints of the engine and the alternator. Chapter 5 focuses on this topic.

The energy saving strategies must address the following challenges of the Army ground vehicle:

- Space, weight, and integration cost constraints
- Legacy system upgrades
- Non-proprietary and open standards based solutions
- Technology obsolescence and time to integrate

This dissertation research addresses all the aforementioned challenges and proposes online automatic approaches as energy saving strategies for Army ground vehicles. Chapter 4 and Chapter 5 provides a detailed information about the proposed strategies.

## 1.6 Engine Control Unit

A modern engine uses a programmable Engine Control Unit (ECU) to control its operations in real time using multiple sensor inputs, a microprocessor, software, look-up tables, performance maps, and a microcontroller. Many ECUs are proprietary and any significant modifications to it are very costly. Some ECUs allow individual users to develop custom program to obtain different behaviors of an engine. An ECU communicates with multiple sensors via an in-vehicle Controller Area Network (CAN). Some example ECU functions are cruise control, transmission control, idle speed control, and ignition control. A detailed case study related to ECUs is available in the following article [5].

## 1.7 Problem Statement

Major portions of a ground war and training exercises are spent on soldiers conducting surveillance missions using stationary Army ground vehicles. The vehicles should minimize their energy consumption and also meet the electrical energy requirements of a mission. However, the increasing electrical energy/power requirements of the systems to perform a mission increase fuel consumption. Unlike commercial passenger vehicles, Army vehicles work in a complex operational environment and they are subjected to large electric power demands with a variation between 2 to 32 kilowatts. However, the vehicles have limited power generation capability, especially when the vehicles are stationary, the engine is operating at idle speeds or the engine is turned off and a shared battery powers the systems. Although an Army vehicle is energy efficient, the efficiency does not meet the mission requirements. To support the electrical energy requirements of a mission, a conventional Army vehicle operates in an energy inefficient mode. Diminishing fuel energy availability and increased electrical energy consumption requirements of Army ground vehicles mandate the need for energy saving strategies. The strategy solutions should not be expensive, and they should meet size and weight requirements of the vehicle.

## 1.8 Contributions

This dissertation research contributes the following novel elements for stationary Army ground vehicles during surveillance missions:

- Theoretical models that represent operations and energy consumption behaviors of surveillance missions.
- Mission aware online energy saving strategies for both silent and normal surveillance missions.
- Simple and economical fuzzy logic approaches for:
  - Feedback controller and an algorithm for an engine ECU to manipulate engine

speeds based on the electrical load requirements.

– Representing engine and alternator performance maps.

– Deterministic algorithm for transitioning systems to their low power consumption modes based on mission conditions.

## 1.9 Document Organization

- Chapter 1 introduces the concept of mission aware energy saving strategy and the need for saving energy in Army ground vehicles.
- Chapter 2 describes the literature review of energy saving strategies of various systems such as electronic systems, wireless sensor networks, and automotive vehicles.
- Chapter 3 describes the proposed theoretical models of surveillance missions of an Army vehicle. These models are used to develop energy saving strategies for an Army ground vehicle.
- Chapter 4 describes the proposed models of an on-line approach and a mission aware energy saving strategy for silent surveillance missions of stationary Army ground vehicles. It also describes the proposed fuzzy deterministic algorithm used by the proposed energy saving strategy.
- Chapter 5 describes the proposed models of an on-line approach and a mission aware energy saving strategy for normal surveillance missions of stationary Army ground vehicles.
- Chapter 6 summarizes, concludes, and proposes future work for this dissertation.
- Appendices describe the author's publications and other related material to provide additional details of the research described in this document.

## 1.10 Conclusion

This chapter described the detailed background for the proposed dissertation research and the need for saving energy in stationary Army ground vehicles. Army ground vehicles use several on-board electronic systems to conduct military missions. Increasing electrical energy requirements of these systems increase fuel consumption, especially during stationary surveillance operations of the vehicle. This chapter also introduced the concept of mission aware energy saving strategies to minimize energy consumption in Army ground vehicles. The next chapter discusses the existing energy saving techniques and their limitations for using them in Army ground vehicles to save energy.

# CHAPTER 2 LITERATURE REVIEW

The previous chapter introduced the concept of mission aware energy saving strategy for stationary Army ground vehicles. This chapter reviews existing energy saving strategies of various systems such as electronic systems, wireless sensor networks, and automotive vehicles.

## 2.1 Introduction

In the literature, energy saving strategies are available in the following areas. However, they are applicable to specific situations and not suitable for all applications.

- Elements: Logic gates and transistors
- Components: Processor, memory, microchips, and hard drives
- Systems: Computers, sensors, weapons, routers, switches, and consumer electronic devices (hand held and other portable mobile devices)
- Networks: Data buses inside computers and sensors, power buses, network on chips, distributed systems, and sensor networks
- Power generation and power distribution systems: Engines, alternators, and batteries

Energy saving strategies are normally developed as hardware or software based solutions. The work performed in [6] - [11] describes the energy saving research for elements, components, and systems. Although potential interest exists in these areas, implementing such low level techniques are not economical for legacy systems in an Army vehicle. Section 2.2 reviews the recent published energy saving research focusing on minimizing energy consumption. It provides a background and a literature review.

A significant research has been done in Dynamic Power Management (DPM) for systems, components, and networks such as sensor networks. A DPM minimizes a given system's power consumption by dynamically putting them to a lower consumption mode such as sleep or hibernate. A detailed system level DPM is described in [12] with predictive and stochastic optimum policies and its implementation details.

A survey of energy efficient on chip communications [13] reveals a lot of circuit, system, and network level on chip power efficient techniques. A Dynamic Voltage Scaling (DVS) is one of the techniques used in embedded systems [14] to minimize power consumption. DVS lowers a given component's voltage when a given component is not needed for its peak performance. By this scaling technique, the power/energy consumption is minimized when the component is not active to perform high performance tasks. DVS implementation requires a design for many voltage variations, and this complicates component designs.

Physical systems exhibit several properties that are difficult to comprehend from the functional perspective. Therefore, several researchers perform experiments and gather data to analyze and develop mathematical models to establish relationship between the inputs and outputs of the system. However, in many cases, mathematical models using traditional approaches cannot be developed due to uncertainty and noise in the collected data. In this situation, researchers normally utilize machine learning, artificial intelligence, or soft computing techniques such as fuzzy logic [15], adaptive network fuzzy inference system [16], neuro-fuzzy, and neural network [17].

## 2.2 Review

### 2.2.1 Energy Savings In Networked Systems

Several network level energy saving techniques are available in the research to save energy in networked systems. Many researchers have published their research results for minimizing power consumption in wired and wireless networks. Although most of the researches are not focused primarily on military domain, they seem to find relevance in literature review. A group of sensors connect together to form a network. Mature wireless technology is gaining a lot of prominence in military vehicles such as an Army ground vehicle. The sensors perform many tasks that feed information to the soldiers on a vehicle. The sensor nodes process the data locally communicated. Many sensor nodes are battery operated and due to wireless media complexity an efficient energy management techniques are required to save energy. A typical WSN node has a microprocessor, a communication system (e.g. radios), a sensing device, and a battery power supply unit.

There is a concept called distributed systems i.e., a collection of computers connected to a network. They provide an integrated computing environment for processing, sharing, and coordinating user requested tasks. In a distributed system, any computer can have control and hence there is no centralized control. For such systems energy consumption minimization techniques can be applied.

Energy management techniques are widely used in WSNs and distributed systems to minimize their energy consumption. Currently, a lot of research has been done to minimize energy consumption in different aspects of Wireless Sensor Networks(WSN). However, most of them are not applicable to this dissertation research. This section discusses the applicable research in this area. Wireless Sensor Networks (WSN) are gaining prominence in Army ground vehicles and a survey [18] is available in the literature. Similar to WSNs, the distributed systems provide an integrated computing environment for processing, sharing, and coordinating user requested tasks.

To reduce energy consumption in WSNs, an Adaptive Sampling Algorithm (ASA)[19] minimizes the frequency of radio transmissions. However, the signal frequency and noisy environments impacts the performance. In an active combat field, the sensors have to perform actively and the operation requires minimum latency sensitivity and accurate signal reconstruction, but this approach does not handle them. Although the radio usage are reduced, the radios are not adapting to sleep mode to minimize its steady state power usage. Similar to ASA, an adaptive Low-Power-Listening (LPL) MAC protocols [20] reduce idle listening with a caveat of data losses. Unlike basic LPLs, the adaptive LPLs use lower duty cycles and energy efficient MAC protocols.

To save energy and to handle wireless traffic, a mechanism in [21] uses a positive or negative traffic condition messages to let the base station to receive or be in sleep mode to handle the traffic. During high traffic conditions, there is a possibility that too many messages be sent. This technique does not seem to align a mobile station's listening and message transfer intervals. This approach saves energy in mobile stations but the base station and other connected systems are still consuming energy. A doze timer solution in [22] minimizes wakeup time and maximizes sleep time to reduce energy consumption. Doze timer allows wireless stations to sleep until the timer elapses. To effectively implement this, a mandatory idle timer has to elapse before the doze timer can be started. If the idle timer is too long, there is a possibility that the doze timer may not be initiated.

A technique in [23] minimizes energy consumption of networked systems by powering off or transitioning them to a lower power states based on the users living pattern or movements. Although this is an interesting concept for home networks, it has a lot of complications to use within an Army vehicle. The space within a vehicle is restricted and the occupants may not leave their position for a long time. In this situation, there is no chance to minimize consumption. A network traffic based low-power technique [24] reduces energy consumption of a networked processor by identifying the minimum processing to handle a given task. Since minimum processing elements are used, processor consumes less energy.

A DPM for WSN [25] switches sensor nodes to a sleeping state based on the work load predictions. The sleep state time is static and it is node specific. Its value cannot be altered dynamically in response to various other external conditions. Static solutions do not gain consumption savings in an Army vehicle. In architecture for sensor nodes in [26] uses a concept of dispatching, delaying or discarding energy consuming tasks if the power supply unit determines that the system is running on the battery and waiting for renewable energy availability. Dispatching tasks are completely dependent on the power state manager which has no knowledge of anything else other than the available renewable energy. In a service specific power management solution [27], systems are assigned to a specific service. When a given service is accessed by a user, the power is supplied to its associated systems. Assume a given system's power was turned off manually. If a service associated with this system is invoked, the policy applied for this service automatically powers on all its associated systems including the manually powered off device. This solution has no awareness of the manually powered off systems.

A network based energy management in [28] uses energy events based on preconfigured policies to save energy. However, the policies are rigid and a central process determines when to exercise it on the networked systems. Configuring individual system's policy is a maintenance challenge and may disrupt the overall operations of a given system. There is no flexibility in this solution to handle unidentified events e.g., a network request for the system came in but the system was switched off per a configured policy. In an internet based wired networks, node level network data traffic consumes a lot of power and energy.

A solution in [29] explains the reduction of energy consumption in networked systems based on data traffic, data flow channels between paths and nodes, and network service requirements. This solution is purely network load based; a network switch or a router is powered off when there is a low network load is detected. The main savings comes from dynamically selecting the network configuration which meets service requirements and uses minimum power. But, this is always a challenging task and it requires prior knowledge of all systems in the network. In an Army vehicle, systems are added ad-hoc and keeping up with power aware network configuration is challenging.

Energy consumption in peer-to-peer (P2P) systems can be reduced using a minimum power consuming server from a group of servers for executing a given process [30]. In an Army vehicle, if video processing time is long and undefined, this approach cannot determine a best sever to process it. The additional limitation is that the approach tends to allocate processes to the minimum power consuming server until it is overloaded and then it allocates to the next minimum power consuming server. If most of the processes have the same computation and power consumption laxity, then the cumulative power reduction may not be substantial. In this technique, there is a situation where a single server executes all the processes other severs are idle and consuming energy.

Energy minimization techniques for server systems are discussed in [31]. Unlike the approach in [30], a related work in [33], powers down servers if they are not being used to fulfil a given process. A configuration based design in [32] balances network request messages based on a pre-set configuration to save power.

To reduce energy consumption in wireless sensor networks, an approach in [34] uses a set of timeframes to handle traffic. In other timeframes the WSN elements are sleeping to save energy. In Army ground vehicles, defining an optimum timeframes to handle traffic is the most complex part. This does not seem to address any possibility of data packet loss, performance concerns (latency), or data delivery urgency.

Energy saving techniques for the electronic systems depend on the system's idle time to achieve energy savings. However, it is always challenging to determine when a system will be idle and for how long. Incorrect workload estimation for a system impacts its performance and the overall strategy. Silent surveillance varies from mission to mission and from one type of combat vehicle to the other. A system in one vehicle exhibits a workload that is different than the same system in a different CV. There is no availability of mission and CV specific historic workload data for all the systems to model for silent surveillance. Therefore, the application of stochastic approaches namely, Markovian [35] and hidden Markovian model based energy management [36][37] [38] are very challenging to achieve.

To save energy in environmentally powered systems, an approach in [39] controls the energy distribution to sensor nodes based on the sensor systems stability control. This technique has no ability to allow external factors to influence the energy saving of the systems.

Moreover, it depends on the historic energy predictions.

### 2.2.2 In-Vehicle Energy Savings

In-vehicle power or energy management involves managing electric power generation and distribution, and balancing the electric load requests from on-board systems. The ultimate goal of the management approaches is to minimize energy consumption. Many proposed solutions are available but each has a specific focus on certain elements of energy management namely, strategies, energy management techniques, and power generation and distribution system improvements. A survey in [40] briefly introduces the concept of intelligent approaches in automotives to save energy.

The energy minimization systems engineering approach in [41] uses a hybrid technology to meet the high power demands and the increased requirements to stay operational during silent surveillance operations. The approach focuses on fuel efficiency and better understanding of energy/power consumption needs. The approach defines systems engineering values to each of the development phases and recommends appropriate trade spaces to get a good fuel efficient product. Although this meets the need for higher power generation with reduced impact on operational performance, it seems to neglect the fact that the methods could be applied to minimize in-vehicle power consumption to gain fuel efficiency and other heat related concerns than thriving for more power generation.

An energy saving on-line neural network approach in [42] uses road type and traffic conditions to management the power generation within the vehicle.A neural network interacts with the ECU and determines the required torque to generate the demanding power needs. This approach is not usefull during stationary operations of the vehicle. In a given combat situation, if a vehicle is running at lower idle ($<$ 800 RPM), it cannot compensate for any required torque to produce additional power. So this solution is more suitable when the engine is capable of running at required RPM and capable of producing required torque. This realized power control is drive cycle dependent. There is no complexity discussed for the frequently changing drive cycles. The solution assumes constant drive cycle for proposed power control.

An approach in hybrid electric vehicle [43] minimizes fuel consumption of the vehicle by operating the engine at an optimal point by using an advanced alternator. This approach focuses on the vehicles when they are moving. An another approach in an hybrid electric vehicle uses a 3-D terrain preview [44] to manage the battery operations of the vehicle to save fuel. In a stationary vehicle during a combat, the terrain might not change frequently and the vehicle might not gain any fuel savings using this type of approach. Terrain preview alone cannot provide substantial fuel savings while keeping all the systems operational at high performance. This proposal has no alternative strategy to handle if the combat situation changes while the battery is discharged and the engine has to stop to go on silent mode. In this approach, the battery is discharged, engine is not running, the systems have no generated/stored power to operate.

A controller approach in [47] saves fuel energy by automatically managing the operations of an engine, propulsion, and power distribution. However, this approach is very slow and limited due to the application of dynamic programming to extract required strategy information from the control policies. Moreover, this approach is applicable only for hybrid electric vehicles. Another controller approach in [48] manages the fuel savings in a vehicle with conventional drive train by controlling the battery charges when the engine is efficiently operating. An idle speed controller in [49] saves fuel by monitoring the operations of an engine and their disturbances. A fuzzy logic rule based energy saving strategy in hybrid electric vehicles [50] seem to save fuel and reduce emissions by applying suitable rule based control strategy. However, the approach seem to focus on managing the battery operations and may not meet the electrical demands of the vehicle.The approaches defined in this paragraph seem to focus only on saving fuel. The main objectives of this dissertation are to save fuel and also to meet the electrical demands of the vehicle, and thereby extend mission time.

An approach in [51] uses a software to monitor and manage the power states of all the networked systems in a vehicle. The main idea behind this approach is to balance the power demands based on the vehicle's capability to produce required energy. However, this approach does not seem to reduce any energy consumption. Moreover, this approach does not seem to save any energy. An artificial neural network approach in [52] tries achieve fuel economy. However,this approach seem to sacrifice on the amount of torque produced. This will be an impact for Army ground vehicles as they are power hungry.

As discussed in 2.2, significant research exists in the current literature to save energy in these candidates. However, most of the systems on Army vehicles are proprietary and making modifications to them are costly and time consuming. Moreover, modifying multiple systems to achieve energy saving is not practical or economical. Therefore, efficient energy saving strategies based on mission requirements using online and automatic computing techniques must be developed to minimize the modifications of the systems of an Army vehicle. The approaches proposed in this dissertation address this need. Chapter 4 and 5 discusses additional existing applicable energy saving literature.

In the literature, researchers [53], [54] recommend minimizing load disturbances and fuel-injection inaccuracies to save fuel in stationary vehicles. On the other hand, the adaptive algorithm [55] and hybrid control algorithm [56] approaches suggest operating the engines at lower engine speeds to achieve fuel savings [57]. A study [58] proposes to incorporate known idle speed constraints to obtain energy efficiency. Some researchers demonstrate fuel efficiency in a stationary vehicle's gasoline engine by efficiently controlling the operations of air valve and spark advances [59]. Most of these approaches lack techniques to handle Army ground vehicle's large load variations. These methods may trigger engine stalls if the predefined speeds cannot handle the demand. Moreover, these techniques require altering the physical properties of the vehicle.

## 2.3 Fuzzy Logic

Zadeh introduced the concept of fuzzy values to map human interpretation of uncertain phenomenon using a natural language for instance, John is tall and Doe is short. In this example, the terms 'tall' and 'short' are human interpretations of height. To conceptualize the application of fuzzy values, Zadeh introduced fuzzy sets [60] and also proposed a fuzzy logic approach [61] to handle them in real applications. A Fuzzy Logic System (FLS) for engineering applications [62] provides a method to map non-linear inputs to a scalar output using a fuzzification process, set of rules, an inference method, and a defuzzification components. An FLS approximates vague phenomenon using fuzzy sets. Fuzzification is a process of mapping a crisp input to a membership function. A set of rules are expressed in a natural language as (2.1). where S= Speed and F= Fuel consumption. The terms HIGH and HOT are fuzzy sets defined using the natural linguistic values. Inference is a method of aggregating the results of each rules on the fuzzy inputs. Defuzzification is a process of mapping a fuzzy value into a crisp output value. The article in [62] provides a detailed tutorial of FLS. The membership characteristics of elements of a fuzzy set can be characterized using membership function curves, namely, triangular, trapezoidal, bell-shaped, and Gaussian. Most of the fuzzy logic applications use triangular characteristic curves due to their simple computations. Fig. 10 shows a triangular membership curve.

$$if\, S = HIGH\, then\, F = HIGH \tag{2.1}$$

Fuzzy set theory provides union, intersection, and complement for fuzzy sets. They are normally expressed using membership grades. Let $X$ and $Y$ be the two fuzzy sets defined for an input $I$, and $\mu_X$ and $\mu_Y$ be the membership grades for $I$. In this situation, the union of $X$ and $Y$ using membership grades can be expressed as (2.2), the intersection can be represented as (2.3), and the complement of $X$ can be represented as (2.4). The union

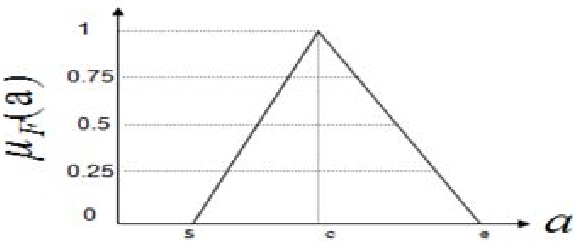


Fig. 10. A triangular membership characterization curve

operation is considered fuzzy $OR$ and the intersection is considered fuzzy $AND$ operation.

$$\mu_{X \cup Y}(I) = max(\mu_X, \mu_Y) \quad (2.2)$$

$$\mu_{X \cap Y}(I) = min(\mu_X, \mu_Y) \quad (2.3)$$

$$\mu_{\bar{X}} = 1 - \mu_X \quad (2.4)$$

Initial fuzzy logic models were purely rule based with if-then constructs. The rules contain two parts i.e., antecedent and consequent. Both parts seem to contain fuzzy values. Several new approaches are being worked in the literature and they all seem to go away from rule base and trying adopt to a trial and error process to finalize the system approximation process. Example of fuzzy logic applications can be found in the author's previous work about using fuzzy logic [63, 64, 65].

## 2.4 Factor Analysis

Factor analysis is a statistical approach [66] to reduce and summarize a large dataset with many factors into fewer meaningful factors. It simultaneously analyzes the interrelationship between multiple parameters of the dataset. When fewer factors are extracted from this process, they seem to have dependencies on other parameters of the dataset. All the work is performed mainly based on the correlation between the factors and the dependent variables.

Factor analysis uses several factor extraction methods namely, principle component or maximum likelihood. They both seem to have different impacts on the factor extraction process. However, it all depends on use of data for deriving meaningful factors. A survey of related literature of principle component analysis is available in [66].

The important aspects of factor analysis is to make sure the dataset is reduced to minimal dimension factors and the loadings on the factors are showing higher values for correlation for the extracted factors. In general, there will be an n number of factors that are uncorrelated to each other. Factor loadings are rotated using many different algorithms namely, Kaiser's Varimax rotation [67] to obtain higher fidelity in factor extractions. The Kaiser's approach extracts factors that have Eigenvalues of more than 1.

## 2.5 Conclusion

This chapter reviewed the current literature of energy saving approaches in networked and distributed systems, and automotive ground vehicles. The approaches in distributed and networked systems do not consider collaborated functions of the systems to minimize energy consumption. Therefore, applying mission aware solutions to them are very difficult and expensive. Energy consumption depends on mission conditions. However, no solution exists in the literature to address mission aware strategies. Existing proposals in the literature address additional power generation solutions than minimizing energy consumption in automotive ground vehicles. Most of the energy saving strategies are applied to moving vehicles rather than stationary vehicles. The approaches lack techniques to handle Army ground vehicle's large power demand variations. These methods may trigger engine stalls if the engine cannot handle the demand. Moreover, most of the existing techniques require altering the physical properties of the vehicle. Chapter 3 through Chapter 5 discusses additional limitations of the existing approaches and propose solutions to save energy based on mission conditions.

# CHAPTER 3 THEORETICAL MODELS: SURVEILLANCE MISSIONS

The previous chapter described the short falls of existing energy saving approaches in the current literature. This chapter describes the proposed theoretical models to allow strategies to save energy based on collaborated functions of systems in a network.

## 3.1 Introduction

Soldiers perform surveillance mission tasks in an Army ground vehicle using many systems in a sequence. A system services work requests from multiple systems. No theoretical model exists to represent surveillance mission behaviors. The three main entities of an Army ground vehicle are a power generation system, a battery, and a finite number of systems. Fig. 6 illustrates an example of networked distributed systems to help soldiers perform a mission in an Army ground vehicle. The power generation system manages the generation and distribution of power to all electrically powered systems until the energy is available. The battery has no recharging capability during silent mode of surveillance and the availability of fuel energy is challenging for a normal mode of surveillance. The power generation system controls the power supply of individual systems using a software controlled electric power switch. Each system has its own power supply channel, which allows the power distribution system to remotely turn the power supply of a system on or off on-demand without affecting the power supply of any other systems. Separate wiring exists between the power distribution system and other systems for electric power flow.

The behaviors of surveillance mission tasks can be somewhat random, and they tend to cause systems to operate with unpredictable workloads. That is, the workload of a system may increase or decrease throughout a mission with no predefined patterns established for it. Some examples of tasks of a surveillance mission are capturing events of enemy forces and recording significant events and diagnostics information of systems. In general, a surveillance task can be viewed as a workflow. The task can be broken into workflow steps where each system processes each step sequentially. For example, for an "event recording" task, the workflow steps are the following: Initiate (workstation), Record (recorder), and Store (computer). Soldiers can end the task at any time according to their priorities. A system can also end the task at any time depending on its internal logic. During surveillance, soldiers and automatic sensors use systems to initiate and manage tasks. Critical systems can sense hostile situations and even fires a weapon, whereas non-critical systems record and perform general tasks, namely, diagnostics, storage, and backup. Critical systems have strict latency and availability requirements when compared to non-critical systems. For the purposes of this document, a system can be a computer, video camera, or weapon.

Fig. 11 and Fig. 12show sample network setups with some sample systems that is normally used within an Army ground vehicle to communicate data between the systems.

This chapter describes the following proposed theoretical models to represent surveillance missions. These models can be used to develop mission aware energy saving strategies:

- Chapter 3.2: collaborated system model to determine the systems interactions online throughout a mission
- Chapter 3.3: systems usage algorithm to determine the systems usage online throughout a mission
- Chapter 3.4: surveillance energy consumption model to calculate the energy consumption of the systems and the available energy online during a mission

## 3.2 Collaborated System Model

Consider an example surveillance scenario where two soldiers perform a mission in an Army vehicle using one dedicated workstation per soldier. The vehicle has a surveillance system and two video cameras attached to the exterior of the vehicle. The vehicle is also equipped with two radios, a weapon, and a vehicle master computer with a hard drive. A central power

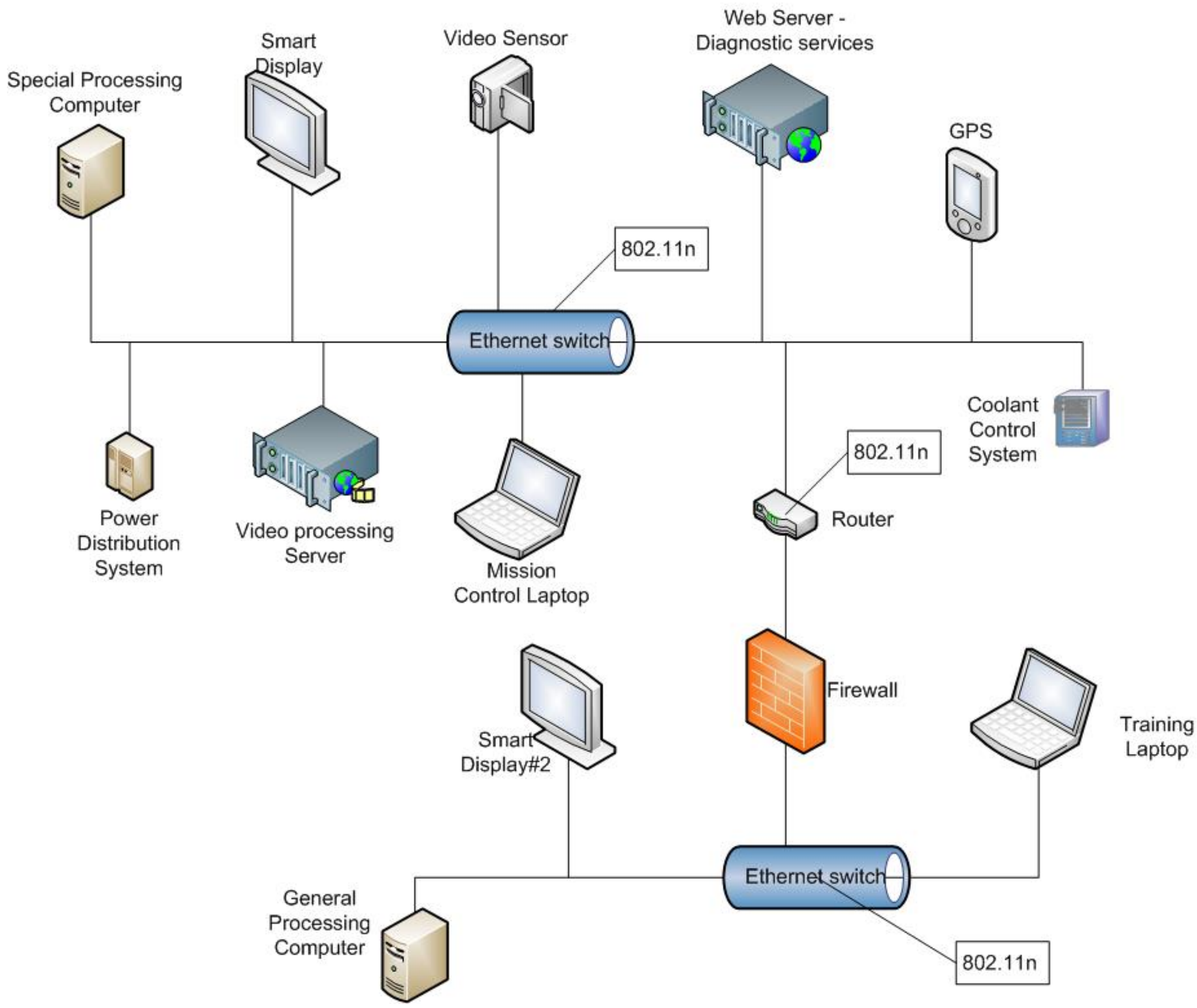


Fig. 11. Sample network setup

generation system supply power to the systems. The vehicle has a local area network with all the aforementioned systems connected to it. Table VII lists the systems used in the sample surveillance scenario and Table I lists the commands, their predecessor commands, and the systems that service them. Fig. 6 illustrates the systems and the commands serviced by the sample surveillance scenario and Fig. 13 shows a sample flow of commands executed in the sample surveillance scenario. The sequence of execution is complex and can take any sequence depending on the mission situation.

Fig. 6 also illustrates an example of the collaborated system model. It has a finite set

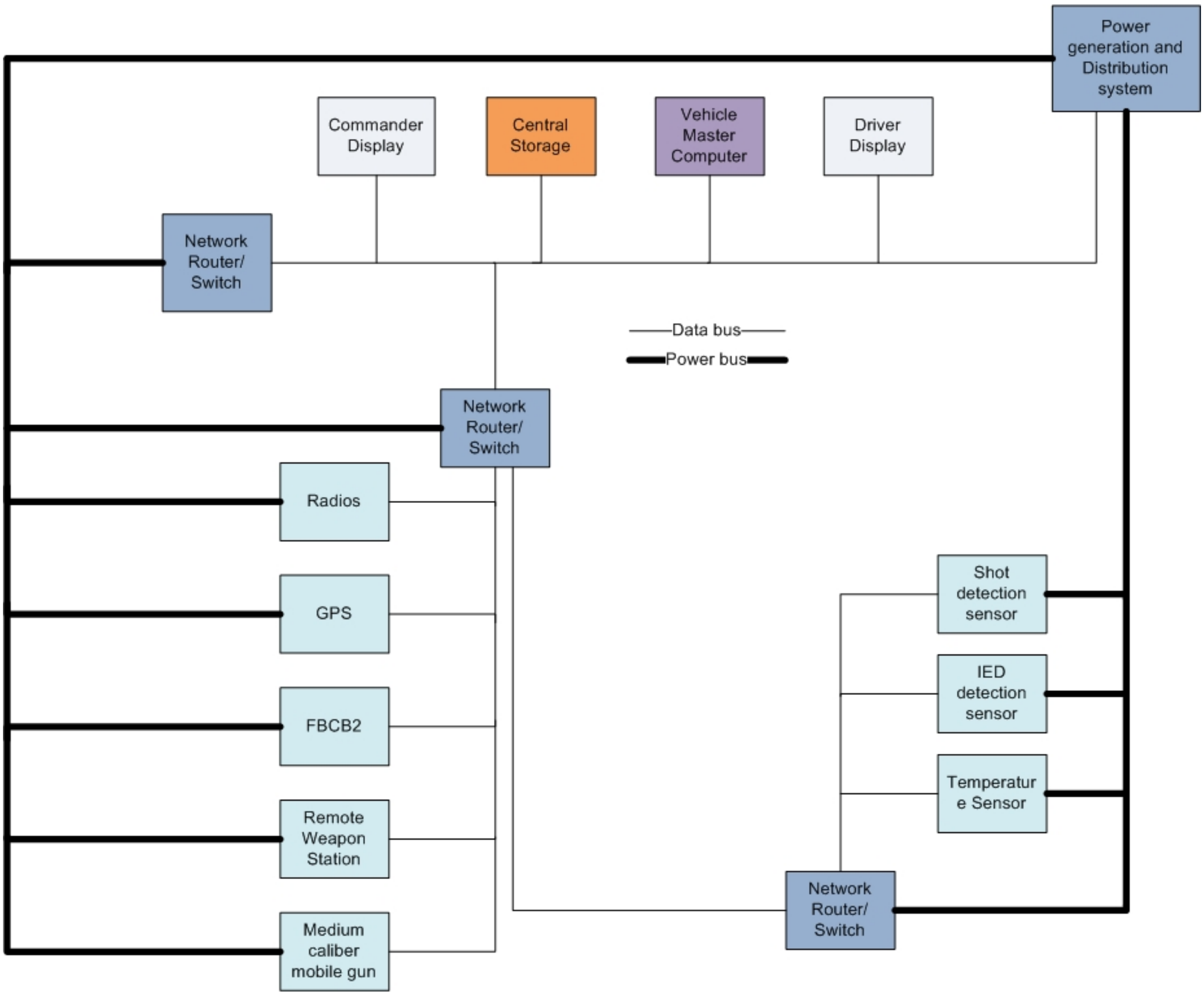


Fig. 12. Sample network setup with additional systems.

$S$ of number of networked systems as shown in equation 3.1 where $i = 1$ to $n$ number of systems in the set $S$.

$$S = \{s^i\} \tag{3.1}$$

An $i^{th}$ system $s^i$ of the set $S$ performs a task by issuing a command to itself or to a $p^{th}$ system $s^p$ of the set $S$ by sending work requests to it. Let $C$ in equation 3.2 be the set of all the commands used in an Army vehicle, where $j = 1$ to $m$ commands in the set $C$.

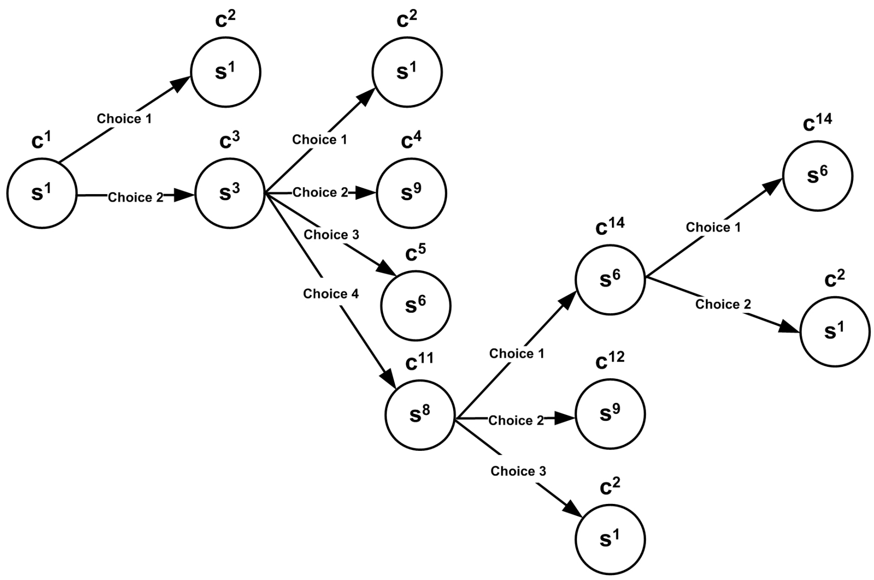


Fig. 13. An example command execution flow for a sample scenario.

$$C = \{c^j\} \tag{3.2}$$

Let $S_c$ be a set of ordered pairs of a system and a set of commands it services i.e., $C_s^i$ in equation 3.3 of an $i^{th}$ system $s^i$, where $C_s^i$ is the subset of the set $C$, and $i = 1$ to $n$ systems in the set $S$.

$$S_c = \{(s^i, C_s^i)\} \tag{3.3}$$

An $i^{th}$ system $s^i$ issues a command $c^j$ to itself or to multiple systems by sending work requests to them. The systems service the requests and complete the command. The frequency of issuing a command $c^j$ depends on the operational scenarios. At any time, multiple systems may issue same commands to a single system. For example, a radio and workstation can send $store$ command to a computer.

Each command $c^j$ can have $0$ to $k$ predecessor commands, for example, a system can issue a $store$ command only after a $record\ video$ or a $record\ events$ command. Conversely, a $capture\ video$ command may not have any predecessor commands.

Let $X$ be a set of ordered pairs of a command $c^j$ and a set of its predecessor commands $N^j$ in equation 3.4, where $N^j$ is the subset of the set $C$, and $j$ =1 to $m$ commands of the set $C$.

$$X = \{(c^j, N^j)\} \tag{3.4}$$

Let a system $s^i$ services $c^j$ commands, where $i = 1$ to $n$ systems and $j = 1$ to $m$ commands. Let each command $c^j$ have $k$ predecessor commands. Let $x^l$ be the number of times systems serviced an $l^t h$ predecessor command of $c^j$. Let $\lambda^j$ be the total number of times the systems service predecessor commands of $c^j$. $\lambda$ for a command $c^j$ is as shown in equation 3.5. At a given time, a system can service multiple instances of the same command.

$$\lambda^j = \sum_{l=1}^{k} x^l \qquad |0 \ \leq \ \lambda^j < \infty \tag{3.5}$$

Consider a scenario in which four systems $s^1$, $s^2$, $s^3$, and $s^4$ use four commands $c^1$, $c^2$, $c^3$, and $c^4$. Assume that $c^2$, $c^3$, and $c^4$ are the predecessor commands of $c^1$. Assume $s^1$ services $c^1$, and any of the three systems $s^2$, $s^3$, and $s^4$ issues $c^1$ to $s^1$; $s^2$ services $c^2$, $s^3$ services $c^3$, and $s^4$ services $c^4$. For example, at a given time, the $s^3$ might have serviced $c^3$ 10 times, $s^4$ might have serviced $c^4$ five times, and $s^1$ might have serviced $c^1$ four times. In this example, $s^3$ has serviced $c^3$ more than what $s^1$ has serviced $c^1$. The reason may be that systems might not have issued command $c^1$. It is possible to infer that the predecessor commands of a command $c^j$ control the frequency of $c^j$. Using this type of systems usage during a scenario, it is possible to estimate the frequency of commands a system serviced over a period of time compared to how many times the predecessor commands of each command have been serviced. In this example, based on the number of times the $c^2$, $c^3$, and $c^4$ have been serviced, it is possible to determine how many times $c^1$ has been serviced compared to the sum of the number of times that $c^2$, $c^3$, and $c^4$ have been serviced. This ratio is defined as the *servicing rate* $\beta$ in equation 3.6 of a command $c^j$ of a system $s^i$, where $y^j$ is the total number of times $s^i$ serviced a command $c^j$.

$$\beta_{c^j} = \frac{y^j}{\lambda^j} \; |0 \leq \; \beta_{c^j} \; < \; 1 \tag{3.6}$$

The $\beta$ value of an $i^{th}$ system $s^i$ can be expressed using the equation 3.7, where $z$ is the total number of commands that $s^i$ services i.e., the set $C^i_s$.

$$\beta_{s^i} = \frac{\sum_{j=1}^{z} \beta_{c^j}}{z} \; |0 \leq \beta_{s^i} < 1 \tag{3.7}$$

The workload of an $i^{th}$ system can be characterized using the value of $\beta_{s^i}$. The $\beta_{s^i}$ value of an $i^{th}$ system varies between 0 and 1 to indicate the degree of its busyness. If $\beta_{s^i}$ is 1 then the system is very busy. If $\beta_{s^i}$ is 0, then it is idle. The values between 0 and 1 indicate proportionate levels of busyness. Let $\beta_{pc^i}$ be the average $servicing\ rate$ in equation 3.8 of $1$ to $p$ systems that services $1$ to $f$ predecessor commands of the commands that the $i^{th}$ system services. The value of $\beta_{s^d}$ can be calculated using the equation 3.7.

$$\beta_{pc^i} = \frac{\sum_{d=1}^{p} \beta_{s^d}}{p} \; |0 \leq \beta_{pc^i} < 1 \tag{3.8}$$

Section 3.3 discusses an algorithm to compute the total servicing, sleeping, and idle time of a system based on the details of the all commands it services.

## 3.3 Systems Usage Algorithm

Algorithm 1 can capture the following details of each system since the beginning of a surveillance mission.

- The start, end, and elapsed time of a servicing instance of each command
- The start, end, and elapsed time of each idle instance
- The start, end, and elapsed time of each sleeping instance
- The total elapsed servicing time
- The total elapsed idle time
- The total elapsed sleeping time

Although capturing these details is an overhead task, the implementation of MAESS and other functions of the mission can use this information. The algorithm, in turn, is implemented as a centralized or distributed solution.

The Algorithm 1 assumes four power states for a system, namely, active, idle, sleep, and powered off. A system services multiple commands in its active state. In the idle state, it awaits new commands. Furthermore, it does not service commands in its sleeping and powered off states. A system in its idle state can service any commands it receives. However, a sleeping or powered off system has to transition to its active state prior to servicing any commands. The algorithm assumes the time to transition between states of a system is negligible.

Let an $i^{th}$ system experience $k$ number of idle instances, where $t_l$ is the elapsed time in seconds of an $l^{th}$ instance where $l = 1$ to $k$ instances. Let $t^i_{idle}$ be the total idle time of an $i^{th}$ system in equation 3.9.

$$t^i_{idle} = \sum_{l=1}^{k} t_l \tag{3.9}$$

Let an $i^{th}$ system experience a number of $x$ sleeping instances, and let $t_m$ be the elapsed time in seconds of an $m^{th}$ instance where $m = 1$ to $x$ instances. Let $t^i_{slp}$ be the total sleeping time of an $i^{th}$ system in equation 3.10.

$$t^i_{slp} = \sum_{m=1}^{x} t_m \tag{3.10}$$

Let an $i^{th}$ system experience a number $y$ of powered off instances and $t_n$ be the elapsed time in seconds of a $y^{th}$ instance where $n = 1$ to $y$ instances. Let $t^i_{pwroff}$ be the total powered off time of an $i^{th}$ system in equation 3.11.

$$t^i_{pwroff} = \sum_{n=1}^{y} t_n \tag{3.11}$$

Let $t^i$ be the total servicing time in seconds in which an $i^{th}$ system is powered on and servicing commands in equation 3.12, where $T^i$ is the total time of a mission.

$$t^i = T^i - (t^i_{idle} + t^i_{slp} + t^i_{pwroff}) \tag{3.12}$$

## 3.4 Surveillance Energy Consumption Model

Energy can be represented as shown in equation 3.13, where $P$ is the power in Joules (J)/Second (s) and $t$ is the time during which the power is consumed in seconds (s). If $P$ is not a constant, then $E$ will be $\int_0^t Pdt$.

$$E = f(P,t) = P * t \tag{3.13}$$

Let $E_s$ be the initial energy available in the battery at the beginning of a surveillance mission. The battery power can be represented as equation 3.14, where $V$ is the voltage of the battery, and $I$ is the current of the battery.

$$P = V * I \tag{3.14}$$

$E_s$ can be represented as equation 3.15, where $I_{amp-hr}$ is the capacity of the battery in ampere hours, and $V$ is the voltage of the battery.

$$E_s = V * I_{amp-hr} * 3600 \tag{3.15}$$

**Algorithm 1** Systems Usage Algorithm

**comment:** $c^j \; \varepsilon \; C \; and \; s^i \; \varepsilon \; S$

**for** $each \; c^j \; serviced$ **do**
    $c^j \leftarrow ID \; of \; c^j$
    $s^i \leftarrow ID \; of \; the \; system \; servicing \; c^j$
    $St^j \leftarrow start \; time \; of \; c^j$
    $Et^j \leftarrow end \; time \; of \; c^j$
    **comment:** current elapsed time of the command.
    $Elt^j \leftarrow Et^j - St^j$
    $store\,(c^j, s^i, St^j, Et^j, Elt^j)$
**end for**
**comment:** Instances of idle/sleeping/powered off states
**for** $each \; instance \; of \; sleeping/idle/powered \; off \; of \; s^i$ **do**
    $s^i \leftarrow ID \; of \; of \; system$
    $St^i \leftarrow start \; time \; of \; an \; instance$
    **comment:** First instance of a servicing command since $st^i$
    $Et^i \leftarrow start \; time \; of \; first \; instance \; of \; a \; command$
    **comment:** elapsed time of current instance.
        $Elt^i \leftarrow Et^i - St^i$
    **if** $s^i \; idle$ **then**
        $inst_{id} = IDLE$
    **else if** $s^i \; sleeping$
        $inst_{id} = SLEEP$
    **else**
        $inst_{id} = PWROFF$
    **end if**
    $store\,(s^i, St^i, Et^i, Elt^i, inst_{id})$
**end for**

TABLE I
COMMANDS SERVICED BY THE SYSTEMS

| ID | Command | Servicing System IDs | Predecessor Command IDs |
|---|---|---|---|
| $c^1$ | Initiate | $s^1$, $s^2$ | N/A |
| $c^2$ | Do nothing | $s^1$ - $s^8$ | N/A |
| $c^3$ | Acquire Target | $s^3$ | $c^1$, $c^{15}$ |
| $c^4$ | Store Target | $s^9$ | $c^3$ |
| $c^5$ | Transmit Target | $s^6$,$s^7$ | $c^3$,$c^6$ |
| $c^6$ | Read Target | $s^9$ | $c^1$, $c^{15}$ |
| $c^7$ | Acquire Video | $s^4$,$s^5$ | $c^1$,$c^{15}$ |
| $c^8$ | Store Video | $s^9$ | $c^7$ |
| $c^9$ | Transmit Video | $s^6$,$s^7$ | $c^7$,$c^{10}$ |
| $c^{10}$ | Read Video | $s^9$ | $c^1$,$c^{15}$ |
| $c^{11}$ | Fire (Shoot) | $s^8$ | $c^3$,$c^7$, $c^{15}$ |
| $c^{12}$ | Store Fire Information | $s^9$ | $c^{11}$ |
| $c^{13}$ | Read Fire Information | $s^9$ | $c^1$ |
| $c^{14}$ | Transmit Fire Information | $s^6$,$s^7$ | $c^{11}$, $c^{13}$ |
| $c^{15}$ | Receive Transmission | $s^6$,$s^7$ | N/A |
| $c^{16}$ | Store Transmission | $s^9$ | $c^{15}$ |

TABLE II
SYSTEMS CURRENT CONSUMPTION

| ID | System | Active Current (Amperes) | Idle Current (Amperes) | Sleeping Current (Amperes) |
|---|---|---|---|---|
| $s^1$ | Work Station 1 | 8.8 | 3.0 | 0.4 |
| $s^2$ | Work Station 2 | 8.8 | 3.0 | 0.4 |
| $s^3$ | Surveillance System | 7.0 | 4.0 | 0.7 |
| $s^4$ | Video Camera 1 | 2.0 | 1.2 | 0.05 |
| $s^5$ | Video Camera 2 | 2.0 | 1.2 | 0.05 |
| $s^6$ | Radio 1 | 5.5 | 2.5 | 0.2 |
| $s^7$ | Radio 2 | 5.5 | 2.5 | 0.2 |
| $s^8$ | Weapon | 4.0 | 1.5 | 0.5 |
| $s^9$ | Vehicle Master Computer | 12.4 | 4.5 | 1.5 |

Let $E_t$ be the total energy consumed at a given time since the beginning of a mission. It is represented as shown in equation 3.16, where $t^i$, $t^i_{idle}$, and $t^i_{slp}$ are the total time spent by an $i^{th}$ system since the beginning of a mission in its active, idle, and sleep states, respectively.

$I^i$, $I^i_{idle}$, and $I^i_{slp}$ are the currents consumed in amperes by an $i^{th}$ system in its active, idle, and sleep states, respectively. $V^i$, $V^i_{idle}$, and $V^i_{slp}$ are the voltages at an $i^{th}$ system in its active, idle, and sleep states, respectively. $n$ is the total number of systems used in the mission. $t^i_{idle}$, $t^i_{slp}$, and $t^i$ can be calculated using the equation 3.9, 3.10, and 3.12, respectively.

$$E_t = \sum_{i=1}^{n} t^i I^i V^i + \sum_{i=1}^{n} t^i_{idle} I^i_{idle} V^i_{idle} + \sum_{i=1}^{n} t^i_{slp} I^i_{slp} V^i_{slp} \tag{3.16}$$

The assumption is that the soldiers use a defect free battery for each surveillance mission to be safe and have successful missions. In this case, the discharge characteristics of the battery follow the manufacturers' published data.

Let $E_e$ be the remaining energy in the battery at a given time as shown in the equation 3.17, where $\varphi$ is the constant energy loss. This research assumes it as 5%. The actual value of $\varphi$ for practical implementations be calculated by measuring the real discharge characteristics of the battery and then finding the Root Mean Square (RMS) error of the calculated energy.

$$E_e = E_s - (E_t + \varphi E_t) \tag{3.17}$$

Let $E_n$ be the energy level of the battery at which it warns a vehicle to end the surveillance and return to recharging mode by turning on the engine and escaping the battle zone. Table VII lists some of the current draws of the systems. The size and weight of the vehicle influences the energy consumption of the vehicle when it is mobile. However, during surveillance, the vehicle is stationary and the engine is not operating. Due to this, size and weight impacts of the vehicle on the system's energy consumption are negligible.

## 3.5 Conclusion

This chapter described the proposed theoretical models that represent uncertain behaviors of a surveillance mission using servicing rate of a system and its energy consumption.

The proposed models include surveillance, collaborated system, systems usage algorithm, and surveillance energy consumption models. The proposed models can be applied to any collaborated systems such as sensor networks, data centers, and event driven systems. The energy management strategies discussed in Chapters 4 and 5 describes the application of these theoretical models to save energy in stationary Army ground vehicles.

## 3.6 Disclaimer

Disclaimer: Reference herein to any specific commercial company, product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the Department of the Army (DoA). The opinions of the authors- expressed herein do not necessarily state or reflect those of the United States Government or the DoA, and shall not be used for advertising or product endorsement purposes.

# CHAPTER 4 SILENT SURVEILLANCE: ENERGY SAVING STRATEGY

The previous chapter described the surveillance mission theoretical models to allow strategies to save energy based on collaborated functions of systems in a network. This chapter describes the application of the theoretical models, and the mission aware energy saving strategy for silent surveillance missions of a stationary Army ground vehicle.

## 4.1 Introduction

Electrical energy requirements of Army ground vehicles namely, Combat Vehicle (CV) during silent surveillance missions are growing [68]. The main reason for this growth is the increase of electrically powered in-vehicle systems, namely Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance devices [3]. During silent surveillance, CVs are stationary and their engines are off while a shared battery power all the systems for extended hours [69]. The soldiers cannot recharge the battery frequently due to the risk of enemy forces identifying the CV if the engine were running.

In a silent surveillance mission, soldiers perform collaborative tasks using a network of multiple systems. Long duration silent surveillance is challenging to achieve due to various vendor specific systems with their unique energy management approaches. To address this shortfall, a basic Energy Saving Strategy (ESS) in a CV allows users to control the circuit breakers to power systems on or off as needed to manage the limited power. During stressful mission conditions, the users may not have the patience to perform this process for long time. Therefore, a mission based online and automatic single ESS is necessary for optimizing the battery usage of the collaborative systems of a CV.

A CV can use advanced energy storage systems [70] [4] and additional energy systems [2] [1] to fill the energy gap. However, the integration of new energy storage systems to thousands of military vehicles is costly and time consuming. In addition, the integration has to overcome the size and weight constraints of the CV. In the literature, a large number of ESS techniques are discussed, but they are typically useful in a single user environment or standalone systems such as a computer, a hand held device, or a sensor with their own dedicated batteries. Each system uses its own unique proprietary ESS solution and is costly to modify them to meet the silent surveillance needs.

Energy saving techniques for the electronic systems depend on the system's idle time to achieve energy savings. However, it is always challenging to determine when a system will be idle and for how long. Incorrect workload estimation for a system impacts its performance and the overall strategy. Silent surveillance varies from mission to mission and from one type of combat vehicle to the other. A system in one vehicle exhibits a workload that is different than the same system in a different CV. There is no availability of mission and CV specific historic workload data for all the systems to model for silent surveillance. Therefore, the application of stochastic approaches namely, Markovian [35] and hidden Markovian model based energy management [36][37] [38] are very challenging to achieve.

Mission aware ESS can use Dynamic Voltage Scaling [71] and Dynamic Power Management [12] techniques to reduce the energy consumption of a system by controlling the voltage and energy state transitions, respectively. However, accurate management depends on the fidelity of the workload determination of a system, specifically the idle time. Extensive research work exists in workload prediction based ESS. A survey in [12] summarizes many adaptive, heuristic, and stochastic based ESS approaches for real-time embedded systems. Although most of these approaches seem relevant, the solutions are based on historical data, which is very difficult to obtain for silent surveillance.

The novel techniques in the literature, namely static time-out [7], renewal theory [72], adaptive learning tree [73], and a sliding window and an interpolation technique [74] handle the challenges introduced by the earlier approaches of dynamic power management and dynamic voltage scaling. However, they are too analytical and complex for implementations within a

CV, especially when handling non-deterministic workloads of mission activities. The events based on configurable management policies [75] can reduce energy waste. Nevertheless, the policies seem to be rigid for the purposes of silent surveillance. Configuring policies for individual systems creates a larger maintenance footprint and disrupts operations during a mission. A Rulebased ESS described in [76] optimizes the renewable energy supply within the space station. However, this approach seems to have issues for load scheduling activities for any events which are less than 12 hours. Lithium-ion based capacitors [77] can be used as a power source for the CVs but, they require power infrastructure redesigns inside a CV. A battery management system in [78] manages the power inside an unmanned aerial vehicle using Li-ion batteries. Conversely, this approach seems to require a special power bus and hardware for power conversion, which may be challenging to work within a CV's environment.

The Mission Aware System Level Power management technique [79] for ESS in radios use mission scenarios that are extracted from static mission profiles. An approach in [46] extracts sequences of events and road types from a static mission plan. It mainly uses the information to optimize the power demand prediction of a vehicle during a mission. A mission-aware approach described in [80] provides a static scheduling scheme to manage power in embedded systems. However, this technique works on known static mission data prior to starting a mission. These approaches ignore the impact of dynamically changing mission profiles and the interactions between multiple systems. Moreover, the approaches in [79] and [80] have no online capabilities.

To the best knowledge, none of the published ESS research in the literature addresses the impacts of collaborative interactions of multiple systems on the workload characteristics of a given system. This is mainly due to the lack of theoretical models needed to understand silent surveillance or collaborative functions. Moreover, no published research deals with the ESS of a CV for silent surveillance missions, especially to handle the uncertain phenomena of silent surveillance. To address the aforementioned shortfalls of developing an ESS based on systems usage during a mission, this research proposes the following:

- Theoretical models and algorithms to represent silent surveillance namely, silent surveillance Model, Collaborated Systems Model, Systems Usage Algorithm, and the silent surveillance Energy Consumption Model
- Mission Aware Energy Saving Strategy (MAESS) for silent surveillance missions of a CV using the above theoretical models

The MAESS transitions systems to their appropriate power consumption states online to optimize their energy consumption based on the mission activities and the estimation of energy available in the battery of a CV.

The MAESS maximizes the duration of a silent surveillance mission with minimal impacts to operational performance and systems availability. In addition, it ensures the battery has a predefined threshold energy remaining to restart the CV to escape from the battlefield before recharging the battery. Since silent surveillance is complex and challenging, the MAESS optimizes the systems usage and minimizes the battery discharges according to mission needs, and maximizes the availability of systems to obtain longer successful missions.

This document is organized as follows. Section 4.2 introduces the proposed MAESS. Section 4.3 describes the theoretical foundations of the silent surveillance phenomena. The details in Section 4.3 form the basis of a solution for the MAESS. Section 4.6 discusses the computer simulation and experiment results of the MAESS using sample silent surveillance scenarios. Section 4.7 describes implementation approach for the proposed enery saving strategy in a real vehicle setup. Section 4.8 concludes this chapter.

## 4.2 MAESS

The high-level MAESS for silent surveillance missions of a CV includes these activities:

- Online Monitoring of activities of a mission, determination of systems usage, and the corresponding energy consumption

- Calculation of the amount of energy left in the battery to determine whether to continue or end the mission
- Determination of the systems that must be transitioned to powered off, powered on, and sleep states to optimize the energy consumption and to achieve a successful mission

The MAESS controls the electrical power states of the systems according to the needs of the silent surveillance mission without affecting the operational performance and availability of the systems until the battery has sufficient energy to continue the mission, thus minimizing unnecessary battery discharging. For simplicity, the MAESS assumes the energy consumption of transitioning systems between different power states, and the time they take to transition are minimal.

In explaining the MAESS, this research uses example operational data. The implementation of the MAESS in a real environment shall use the appropriate operational data, namely commands, systems, and their actual energy consumption values. The authors propose and discuss the following theoretical models and algorithm for the MAESS:

- Section 4.3.1: silent surveillance model for the operational environment of the MAESS
- Section 4.3.2: collaborated system model to determine the systems interactions online throughout a mission
- Section 4.3.3: systems usage algorithm to determine the systems usage online throughout a mission
- Section 4.3.4: silent surveillance energy consumption model to calculate the energy consumption of the systems and the available energy online during a mission
- Section 4.3.5: MAESS System model and an algorithm to implement the MAESS using silent surveillance model, collaborated system model, systems usage algorithm, and silent surveillance energy consumption model

## 4.3 System Models

This section describes the theoretical formulations of the silent surveillance phenomena using multiple elements or behaviors of silent surveillance. The details of this section provide a basis for the MAESS for silent surveillance missions of a CV.

### 4.3.1 Silent Surveillance Model

Chapter 3.1 describes the details of this section.

### 4.3.2 Collaborated System Model

Chapter 3.2 describes the details of this model.

### 4.3.3 Systems Usage Algorithm

Chapter 3.3 describes the details of this model.

### 4.3.4 Silent Surveillance Energy Consumption Model

Chapter 3.4 describes the details of this model. For the systems hosted in a CV, the vendors typically publish the values for the current draws and voltages of the systems in active, idle, and sleeping states. An in-house experimental data validates the published values for various systems. The implementation of the MAESS uses the values of Table VII and the equation 3.16 to determine the actual power consumption values for each system at its active, idle, and sleeping states. The voltage values of the systems vary between 8 to 28 volts. The battery voltage is normally between 24 to 28 volts. Operating temperatures have an impact on the battery's discharge and electrochemical characteristics. The temperature ranges between

-60 F to and 194 F. In general, the military vehicles use battery management systems to measure the state of charge or state of energy of a given battery. The implementation of the MAESS can use this information to determine appropriate power state transitions for the on-board systems. The size and weight of the CV influences the energy consumption of the vehicle when it is on the move. However, during silent surveillance, the vehicle is stationary and the engine is not operating. Due to this, size and weight impacts of the vehicle on the system's energy consumption are negligible.

### 4.3.5 MAESS System Model and Algorithm

To explain the MAESS, this section assumes a limited number of systems, commands, rules, and operational characteristics for silent surveillance. The actual implementation varies as silent surveillance characteristics change. However, the approach remains the same. Section 4.6 discusses the off-line simulation of the MAESS using a sample silent surveillance scenario with example systems and commands.

The MAESS system model uses the theory discussed in Section 4.3 and its elements are as follows:

- $S$: A finite set of system IDs in a CV i.e., $j = 1, 2, 3....n$, where $n > 0$
- $C$: A finite set of command IDs used in a silent surveillance mission i.e., $c = 1, 2, 3....m$, where $m > 0$
- $X$: A finite set of command IDs and their associated predecessor command IDs of each command as shown in equation 3.4 used in a silent surveillance mission. This depends on the systems and the commands used in a CV during silent surveillance.
- $S_c$: A finite set of system IDs and the commands they execute as shown in equation 3.3 for each system used in a silent surveillance mission. This depends on the systems and the commands used in a CV during silent surveillance.

- $\beta_{sj}$: The $servicing\ rate$ of a system $j$ based on the equation 3.7
- $\beta_{pcj}$: The average $servicing\ rate$ as shown in the equation 3.8 of $1$ to $p$ systems that services $1$ to $f$ predecessor commands of the commands that the $j^{th}$ system services
- $E_t$: Energy consumed by the systems based on the equation 3.16
- $E_e$: The silent surveillance energy consumption as shown in the equation 4.1. It is the modified version of the equation 3.17. The modification includes the addition of the value of $\varphi$ variable. It is assumed to be 0.05 (5%).

$$E_e = E_s - (E_t + 0.05E_t) \tag{4.1}$$

- $E_n$: The energy threshold to end the mission based on the equation 4.2, where $E_s$ is the energy of the battery at the beginning of a mission based on the equation 3.15.

$$E_n = 0.2 * E_s \tag{4.2}$$

- Algorithm 1: The operation of storing the details of the commands serviced, and the instances of idle, powered off, and sleeping instances of each systems
- Algorithm 2: The operation of MAESS using the theoretical model elements above

Analytical mathematical models for MAESS require certain assumptions and constraints. However, the complexity of a silent surveillance mission and the resulting non-deterministic usage of systems complicate the formulation of mathematical models. Moreover, silent surveillance has no predefined or certain phenomenon.

During silent surveillance missions, the $servicing\ rate$ of systems may change over a period of time; the energy level of the battery is dependent on it. Characterizing and modeling this for silent surveillance missions using traditional mathematical techniques such as algebra and calculus is a complex task.

In general, mission experts express the *servicing rate* of systems using natural linguistic terms, namely *low*, *high*, and *medium*. These terms are context dependent; for example, the *servicing rate* of 0.5 seems low to one soldier, but it may appear high for another soldier on a different mission. Therefore, it is a very complex and time-consuming process to develop a solution for MAESS using just the traditional mathematical models.

To address this complexity and shortcoming, the author of this research proposes to use a Fuzzy Logic System (FLS) [81] and fuzzy sets [60]. To the best of the authors' knowledge, there is no concept of an FLS-based MAESS. An FLS provides if-then fuzzy rules based models using the knowledge of the silent surveillance missions. Algorithm 2 illustrates the operational MAESS. The MAESS uses the proposed Fuzzy Deterministic Inference Algorithm (FIA) to determine the systems that need power state transitions. The Section 4.4 describes details.

Silent surveillance has peak and steady-state electrical load profiles depending on the type of CV and systems used in a given mission. Most of the profiles are based on the known mission scenarios. However, due to security reasons, mission scenarios are not readily available for all the cases. In many situations, the energy density and electro-chemical property of the battery has a great dependency on how it behaves to meet the electrical consumption requirements of the systems. Therefore, the MAESS implementation shall use the electro-chemical property as one of the inputs for determining the appropriate capacity of the battery to meet the electrical needs of the CV. As an additional remedy, the soldiers could be trained to handle mission scenario specific energy shortfall.

The systems usage algorithm can capture commands processed by all the applicable systems in a CV. Using the data collected by this algorithm, the MAESS algorithm processes actions for one system at a time for any number of systems. However, the implementation can run with multiple instances of the MAESS to process more systems concurrently. Based on this capability and no dependency on the number of systems it can handle, the MAESS approach is easily scalable.

**Algorithm 2** MAESS Algorithm

**comment:** $c^j \varepsilon C$ $and$ $s^j \varepsilon S$

$E_s \leftarrow$ determine from the equation 3.15;
$E_n \leftarrow$ determine from the equation 4.2;
**for** $each$ $c^j$ $serviced$ **do**
  $DB_1 \leftarrow$ use Algorithm1 to store details of $c^j$;
**end for**
**for** each $instance$ of a sleeping/idle/powered off of $s^j$ **do**
  $inst \leftarrow$ sleeping/idle/powered off instance of $s^j$;
  $DB_2 \leftarrow$ use Algorithm1 to store $inst$ details;
  **if** $inst$ is $IDLE$ **then**
    $\beta_{s^j} \leftarrow$ determine from the equation 3.7;
    $\beta_{pc^j} \leftarrow$ determine from the equation 3.8;
    $E_t \leftarrow$ determine from the equation 3.16;
    $E_e \leftarrow$ determine from the equation 4.1;
    **if** $E_e \leq E_n$ **then**
      Power off $s^j$;
    **else**
**comment:** Decision for $s^j$ using FLS Rules and inference.
      $D^j \leftarrow$FLS Inference $(E_t, \beta_{s^j}, \beta_{pc^j})$;
    **end if**
    **if** $D^j = Sleep$ **then**
      Send $s^j$ to sleep mode;
    **else if** $D^j = off$ **then**
      Send $s^j$ to powered off mode;
    **else**
      Send $s^j$ to active mode;
    **end if**
  **end if**
**end for**

## 4.4 Fuzzy Deterministic Inference Algorithm

The synthesis of any sensor data is required based on the time and pattern of the data. For example, in the engine compartment, the rate of change of temperature may increase, decrease or stay at the same level for a particular length of time. In this case, the intelligent system must monitor the temperature readings over a time period from the sensor and analyze the patterns. The rate of change can take values that are greater than zero. In general, subject matter experts express the data values in subjective terms, namely, low, medium, and high values. There is no precise definition for the values of low or high. Therefore, the traditional analytical techniques lack approaches to handle subjective linguistic terms. An intelligent system and a new approach is necessary to collect the required data and synthesis them to take actions. Moreover, the system must handle linguistic definitions of the rate of change of values.

Fuzzy logic [61] provides a reasoning mechanism for synthesizing vague and uncertain linguistic parameters. In the literature, fuzzy logic has been used in multiple different areas. However, they use either rule based heuristics or analysis of histograms and images. Most of all the fuzzy logic applications in the literature seem to use the Mamdani approach for designing a rule based system. The Mamdani approach allows users to express fuzzy rules of a system using linguistic terms. Therefore, the experts tend to define the rules using natural language and it increases the complexity of a rule base. As the rule base increases, the memory space and computations required to process them increases. In addition, they all use output membership functions for approximation and it requires more memory and computations.

The work described in [82], [83] proposes rule reduction approaches to achieve computational efficiency. On the other hand, the authors seem to introduce complex algorithms for reducing the rules and creating a new set of membership functions from them. The approaches described in [82], [83] complicate the subject matter experts to define new rules or modify the existing rules. Conversely, singleton fuzzy set approaches in [84] and [85] provide a model for using real numbers in the consequent part of a fuzzy rule, and lets the fuzzy inference approximate the output based on the combined weighted average of all the rule antecedents. However, they require defining multiple fuzzy singletons or real numbers to obtain the results. The weighted averages may not be the output the system is expecting to perform some actions. Therefore, additional processing or memory is required before using the output results. The approaches defined in [86] and [87] also follow the similar approximation approaches and require defining multiple real numbers or fuzzy singletons. None of these approaches have approximation methods for producing a deterministic output using one real number or a fuzzy singleton, for example, outputting a deterministic value of 0.25 or 0.5 depending on the implication of the appropriate rule antecedents.

A fuzzy non-controller type of system processes fuzzy inputs and produces a deterministic output. The output is non-fuzzy and it can have multiple deterministic values based on the rules implication. This type of system is required for taking any deterministic actions. The author proposes a novel Fuzzy Deterministic Inference Algorithm (FIA). The algorithm must be simple with less memory and computation requirements. It must minimize the complexity of future rule modifications. In addition, it must aid in implementing an electronic chip using simple architecture and minimal number of logic elements. The FIA works well with most of the non-controller type applications that use fuzzy inputs and require a deterministic output. The FIA is an extension and alternative to the fuzzy singleton algorithm. The weighted average approach of the traditional Mamdani singleton method requires more processing and is more time consuming as the number of fuzzy rules increase. Therefore, the proposed FIA provides a an algorithm that requires less storage space, and is more efficient to synthesize fuzzy inputs and to produce a deterministic output. An application of the proposed FIA is available in the author's previous work [88].

The model is expressed as shown in (4.3). Let $k$ be the expected output of a fuzzy system,

$J$ be the output matrix based on the $m$ rules of the system, $x_i$ be the $i^{th}$ row number of the output of the $J$ matrix, and $y_{ij}$ be the $j^{th}$ column number of the $i^{th}$ row of the output of the $J$ matrix. Where i = 1 to n rows and j = 1 to m columns of the output matrix $J$. The FIA assumes that the rule implication aggregation uses fuzzy $OR$ operator.

$$k = J(x_i, y_{ij}) \tag{4.3}$$

The value of $x_i$ can be calculated using (4.4). Let $I_1$ be the value of the first input variable of the system, $\mu_{p1}$ and $a_{p1}$ be the corresponding membership grade and output coefficient of the $p^{th}$ linguistic input membership function (fuzzy set), respectively. Where $p =$ 1,2,..,n linguistic input membership functions of the first input variable. The value of $\mu_{p1}$ can be calculated using (5.12).

| $T_e$ (temperature) \ M (moisture) | low | medium | high |
|---|---|---|---|
| low | In | In | St |
| medium | In | St | Sp |
| high | In | St | Sp |

Fig. 14. Mamadani rules approach for the engine compartment

Let $V$ be the vector of membership grades ($\mu$) of membership functions of the $1^{st}$ input variable, and $V_a$ be the vector of output coefficients of the corresponding membership functions. Let $z$ be the index of maximum $\mu$ i.e., $\mu_{max1}$ (4.6) of the $1^{st}$ input variable in $V$.

$$x_i = V_a(z) \tag{4.4}$$

$$V(p) = (\mu_{p1}(I_1)) \tag{4.5}$$

$$\mu_{max1} = max(V(p)) \tag{4.6}$$

The value of $y_{ij}$ can be calculated using (4.7). Let $I_l$ be the value of $l^{th}$ input variable of the system where $l = 2$ to $X$ inputs, $\mu_{pl}$ and $a_{pl}$ be the corresponding membership grade and output coefficient of the $p^{th}$ linguistic input membership function (fuzzy set) of the $l^{th}$ input, respectively where $p =$ 1,2,..,n linguistic input membership functions. The value of $\mu_{pl}$ can be calculated using (5.12).

Let $W_l$ be the vector of membership grades ($\mu$) of membership functions of the $l^{th}$ input. Let $W_{al}$ be the vector of output coefficients of the corresponding membership functions of the $l^{th}$ input. Let $z_l$ be the index of maximum $\mu$ i.e., $\mu_{maxl}$ (4.9) of the $l^{th}$ input in $W_l$.

$$y_{ij} = \sum_{l=2}^{X} W_{al}(z_l) \tag{4.7}$$

$$W_l(p) = (\mu_{pl}(I_l)) \tag{4.8}$$

$$\mu_{maxl} = max(W_l(1), W_l(2), ..., W_l(p)) \tag{4.9}$$

The FIA implementation procedure is as follows:

**Step#1:** Arrange fuzzy if-then rules in a matrix format as shown in Fig. 14. Let $J$ be the $n\ X\ m$ output matrix consisting of all the outputs for the unique combinations of the membership functions, where $n$ is the number of rows and $m$ is the number of columns.

**Step#2:** Identify unique linguistic outputs in $J$ and assign unique numbers starting from 1. Let $\lambda$ bet the total number of unique outputs. Replace all the linguistic output variables in $J$ with the assigned unique numbers 1,2,3..,$\lambda$. Let $\alpha_{ij}$ be the assigned output number for the $i^{th}$ row and $j^{th}$ column of $J$.

TABLE III
UNIQUE OUTPUT LINGUISTIC VARIABLES

| **Variable** | **Assigned Number** |
|---|---|
| $Normal$ | 1 |
| $Idle$ | 2 |
| $Sleep$ | 3 |

**Step#3:** For each input in $J$, assign a unique number to each unique linguistic input variable using an increment of one starting from one. Fig. 16 illustrates an example assignment.

**Step#4:** Let $\vartheta_j$ be the total number of linguistic input variables in the $j^{th}$ column that have no output coefficients and $\theta_j$ be the total number of linguistic input variables that have output coefficients. Let $a_i$ be the output coefficient of a linguistic input variable where $i$ is 1 to $\theta j$. Determine delta output coefficient $\xi_j$ using (4.10) and assign it to all the linguistic input variables that have no output coefficients in the $j^{th}$ column. If any of the remaining columns have any linguistic input variables in the same positions as the $j^{th}$ column, then assign their output coefficients with the output coefficients of the corresponding linguistic input variables in the $j^{th}$ column. For example, assume that $1^st$ column has $low$ and $high$ linguistic input variables, and 0.33 and 1.35 be the output coefficients of $low$ and $high$ linguistic variables, respectively. Assume $3^rd$ column has $low$ and $medium$, and $4^{th}$ column has $medium$ and $high$ linguistic input variables. In this situation, the $low$ variable in $3^rd$ column gets 0.33, and the $high$ value in the $4^{th}$ column gets 1.35. Repeat Step#4 for all the remaining columns to make sure all the linguistic input variables have output coefficients. After performing all the assignments, the final matrix looks as shown in Fig. 15 and Fig. 16.

$$\xi_j = \frac{j - \sum_{i=1}^{\theta_j} a_i}{\vartheta_j} \;\; | \;\; j \; = \; 1, 2, 3 ... m \; columns \tag{4.10}$$

**Step#5:** Let $\vartheta_k$ be the total number of linguistic input variables in the $k^{th}$ row that have no output coefficients and $\theta_k$ be the total number of linguistic input variables that have output coefficients. Let $a_i$ be the output coefficient of a linguistic input variable where $i$ is 1 to $\theta_k$. Determine delta output coefficient $\xi_k$ using (4.11) and assign it to all the linguistic input variables that have no output coefficients in the $k^{th}$ row. Since a row can have only input variable, repeat Step#5 for all the remaining rows to make sure all the linguistic input variables have output coefficients. After performing all the assignments, the final matrix looks as shown in Fig. 15 and Fig. 16.

$$\xi_k = \frac{k - \sum_{i=1}^{\theta_k} a_i}{\vartheta_k} \;\; | \;\; k \; = \; 1, 2, 3 ... n \; rows \tag{4.11}$$

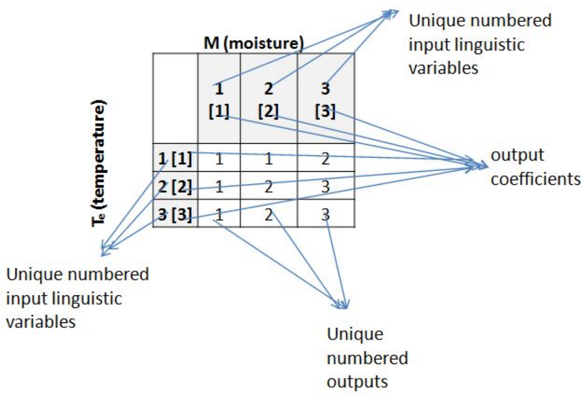


Fig. 15. Engine compartment rule matrix with output coefficients.

**Step#6:** As shown in (4.12), let $N$ be the total number of inputs of an a system. Let $I_i$ be the vector of all the numerically assigned linguistic input variables of the $i^{th}$ input

| | | IV ( Current & Voltage) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 1 [0.5] [0.5] | 1 2 [0.5] [1.5] | 1 3 [0.5] [2.5] | 2 1 [3.5] [0.5] | 2 2 [3.5] [1.5] | 2 3 [3.5] [2.5] | 3 1 [6.5] [0.5] | 3 2 [6.5] [1.5] | 3 3 [6.5] [2.5] |
| $T_b$ (temperature) | 1 [1] | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 1 |
| | 2 [2] | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| | 3 [3] | 2 | 2 | 3 | 2 | 2 | 3 | 2 | 2 | 3 |

Fig. 16. Battery compartment rule matrix with output coefficients.

(Step#3), where $i = 1, 2, 3..., N$. Let $\lambda i$ be the total number of linguistic input variables of the $i^{th}$ input. Let $a_i$ be the output coefficient of the $i^{th}$ linguistic input variable. Based on (4.12), the engine and battery compartment linguistic input variables of the IDSPF can be represented as (4.13) and (4.14), respectively.

$$I_i(N)(N) = (1, 2, .., \lambda i)(a_1, a_2, ..a_N) \mid i = 1, 2, 3..., N \tag{4.12}$$

$$\begin{aligned} I_{T_e}(3) &= (1, 2, 3)(1, 2, 3) \\ I_M(3) &= (1, 2, 3)(1, 2, 3) \end{aligned} \tag{4.13}$$

$$\begin{aligned} I_{T_b}(3) &= (1, 2, 3)(1, 2, 3) \\ I_I(3) &= (1, 2, 3)(0.5, 3.5, 6.5) \\ I_V(3) &= (1, 2, 3)(0.5, 1.5, 2.5) \end{aligned} \tag{4.14}$$

The output matrix $J$ (Fig. 15 and Fig. 16), equations (4.13), and (4.14) serve as the knowledge for inferring the output of a fuzzy system. The following equations serve as the FIA engine: (5.12), (4.3), and (4.7).

## 4.5 Simulation and Experiment Setup

Experiments were conducted in a battery lab to test the discharge characteristics of a lead acid battery while meeting the electric current demands for two silent surveillance mission scenarios. The demand was simulated using a centrally controlled cycler circuits system that has multiple current and voltage profiles. The cycler was controlled using software and electrical load profiles. The test was conducted in multiple temperature conditions. The following setups were used for the various temperature conditions:

- A water bath setup for testing the battery discharges at $25$ and $40^o$ Centigrade temperature. In this setup, a 14 volt battery was immersed in the temperature controlled water bath. The water bath was used to change the temperature environment for the battery. The water bath can run from $13$ to $71^o$ Centigrade temperature. Normally, a 15 minute transition time was taken to transition from high to low temperature. However, 20 to 30 minutes were taken to transition from low to high temperature depending on the volume of water in the bath. The battery core takes six hours to reach to $0$ or $40^o$ Centigrade temperature and 12 hours for $-18$ and $-60^o$ Centigrade. Fig. 17 shows the water bath setup.
- A Thermotron chamber for testing the battery discharges at $-10^o$ Centigrade. The Thermotron runs between $-50$ to $-100^o$ Centigrade.

The simulation was conducted for two mission scenarios using a custom random workload generator for the sample systems used in the study. The computer simulation was conducted for a scenario for two hours per ESS type namely, MAESS and baseline ESS. Based on the simulation data, for a scenario, two load profiles were extracted, one with MAESS and the other one with the baseline ESS. Fig. 18 and Fig. 19 show the load profiles used in the experiment. The discharge characteristics of the battery were tested using the load banks created from the simulated load profiles. To simulate the silent surveillance conditions, the

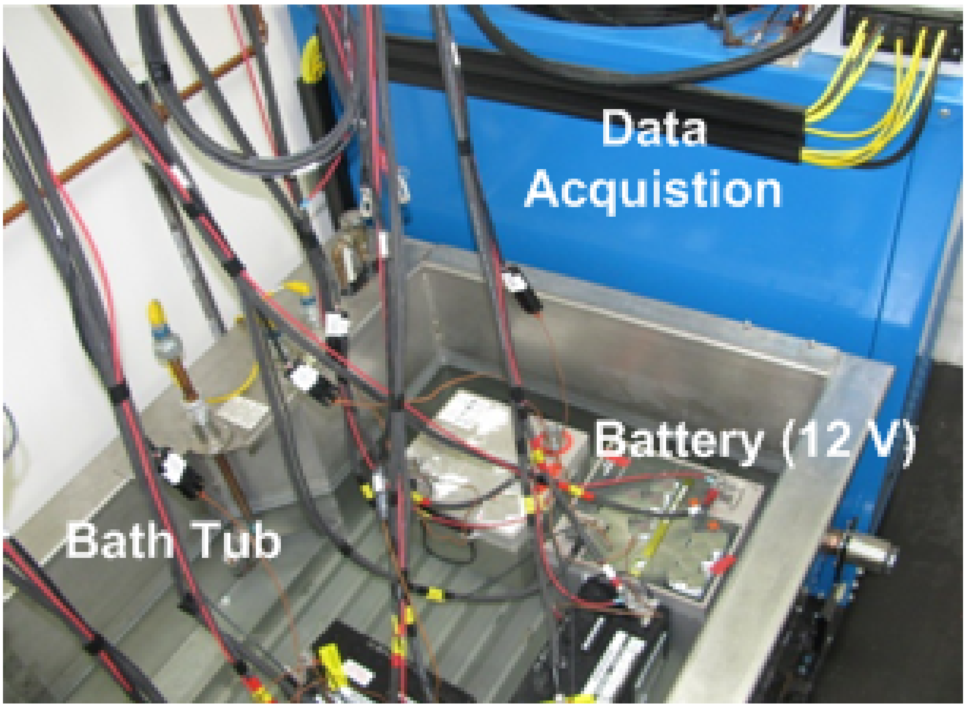


Fig. 17. Battery testing setup.

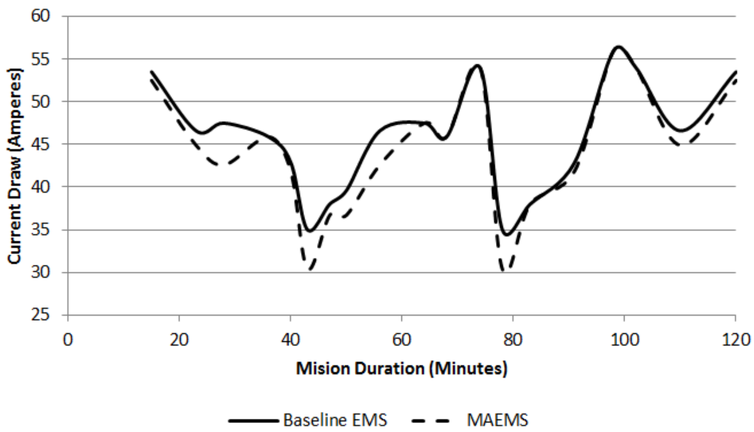


Fig. 18. Scenario 1 load profile.

battery charging was disabled during the testing. Due to the constraints of the lab at the time of testing, the load profile values were halved. Table IV lists the battery type and the temperatures used in the experiment. Section 4.6 describes the validation results.

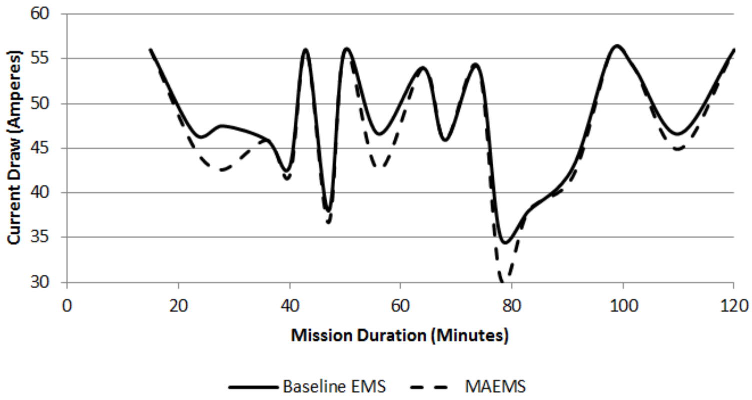


Fig. 19. Scenario 2 load profile

TABLE IV
BATTERY CHARACTERISTICS USED IN THE EXPERIMENT

| **Battery Type** | **Temperature ($^o$ Centigrade)** | **Voltage (Volts)** |
|---|---|---|
| Lead-Acid | 25 | 12 - 14 |
| Lead-Acid | 40 | 12 - 14 |
| Lead-Acid | -10 | 12 - 14 |

## 4.6 Results and Discussions

The MAESS transitions a system to a lower power consuming state based on the ratio of servicing rate of a system and its predecessor systems, and the availability of battery power. The MAESS performs minimal state transitions and ensure systems availability based on the mission needs. On the contrary, the existing approaches described in Section 4.1 transition a system based on its predetermined idle patterns and power consumption penalty of a transition. Therefore, the systems may undergo multiple unnecessary transitions that affect the systems availability. On the other hand, the systems may stay powered on for a long time.

Table V lists the total current draws from the systems per scenario for the two ESS types. The MAESS approach seems to consume 3.41% less current than the baseline ESS for the scenario 1 and 2.2% less for the scenario 2. The battery experiment results are shown in Table VI. The energy consumption seem to vary with the temperature. In all the three temperature conditions, the MAESS approach seems to consume less energy than the baseline ESS for the scenario 1 scenario 2. Fig. 20 and Fig. 21 graphically illustrates the different energy consumption for the two scenarios at various temperatures.

TABLE V
TOTAL SYSTEMS CURRENT DRAW PER MISSION SCENARIO

| **Scenario Number** | **Duration (Minutes)** | **Baseline ESS (Amperes)** | **MAESS (Amperes)** | **MAESS Savings (%)** |
|---|---|---|---|---|
| 1 | 120 | 869 | 839.3 | 3.41 |
| 2 | 120 | 917.9 | 897.7 | 2.2 |

TABLE VI
ENERGY CONSUMPTION AT DIFFERENT TEMPERATURES.

| **Scenario Number** | **Duration (Minutes)** | **Temperature ($^o$ Centigrade)** | **Baseline ESS (Watt-Hour)** | **MAESS (Watt-Hour)** | **MAESS Savings(%)** |
|---|---|---|---|---|---|
| 1 | 120 | 25 | 584.20 | 566.70 | 3 |
| 2 | 120 | 25 | 607.3 | 596.6 | 1.8 |
| 1 | 120 | 40 | 588 | 572 | 2.8 |
| 2 | 120 | 40 | 610.8 | 599.5 | 1.9 |
| 1 | 120 | -10 | 566.6 | 561.5 | 0.9 |
| 2 | 120 | -10 | 599.4 | 589.6 | 1.7 |

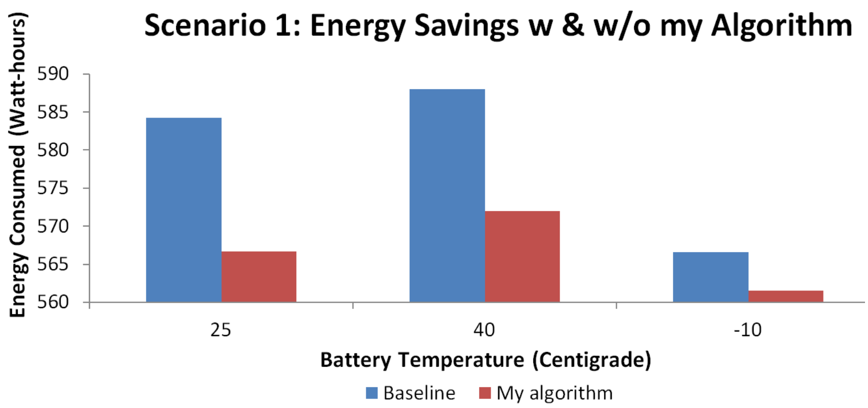


Fig. 20. Scenario 1 battery test results

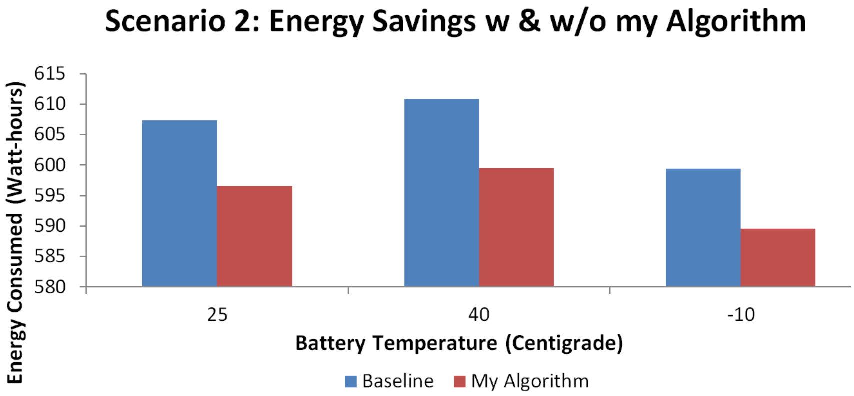


Fig. 21. Scenario 2 battery test results

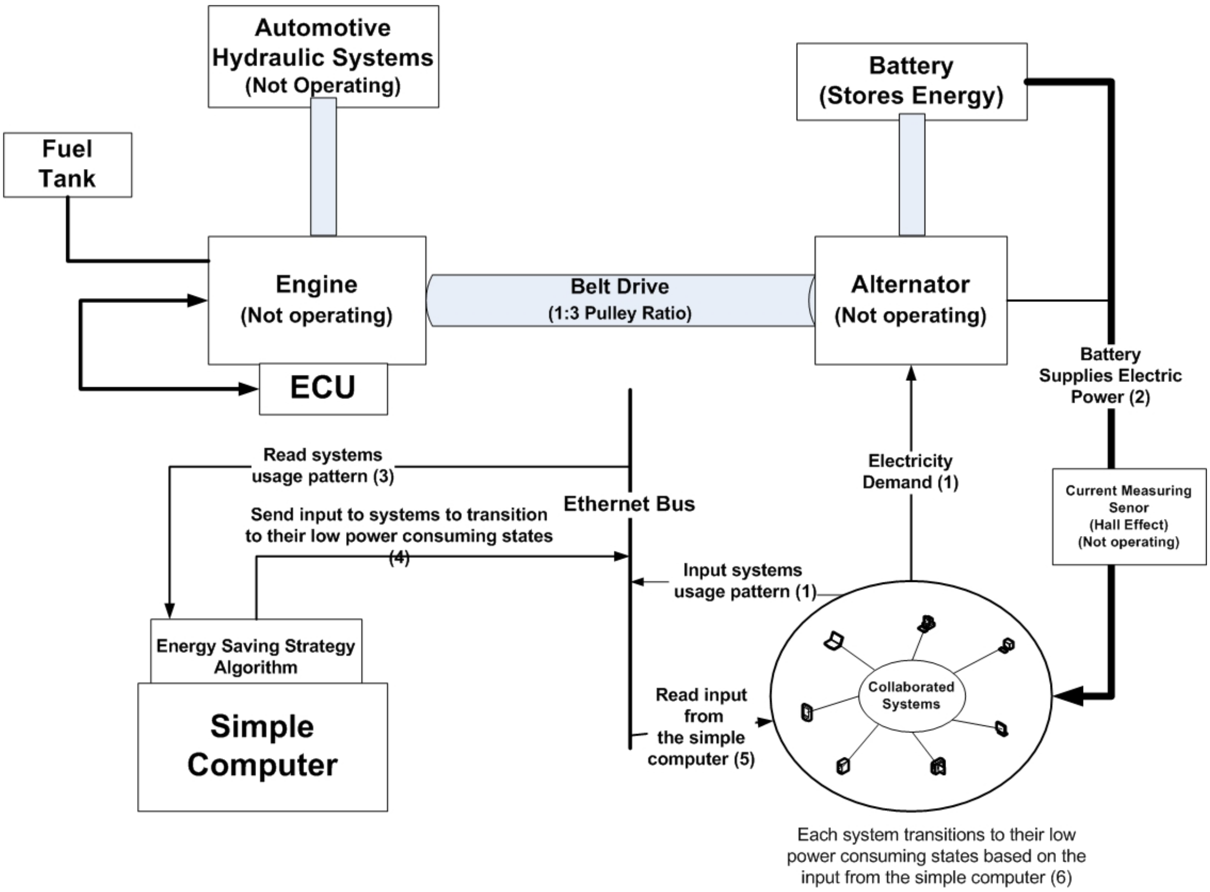


Fig. 22. Silent mode: sequences and events

## 4.7 Implementation Approach

The experimental setup is always different from real implementation in a live vehicle. Unlike experimental laboratory, the real vehicle lacks all the instrumentation to validate all the results. Therefore, most of the validation experiments are performed in a lab set up and the strategy is implemented on a real vehicle based on the lab results.

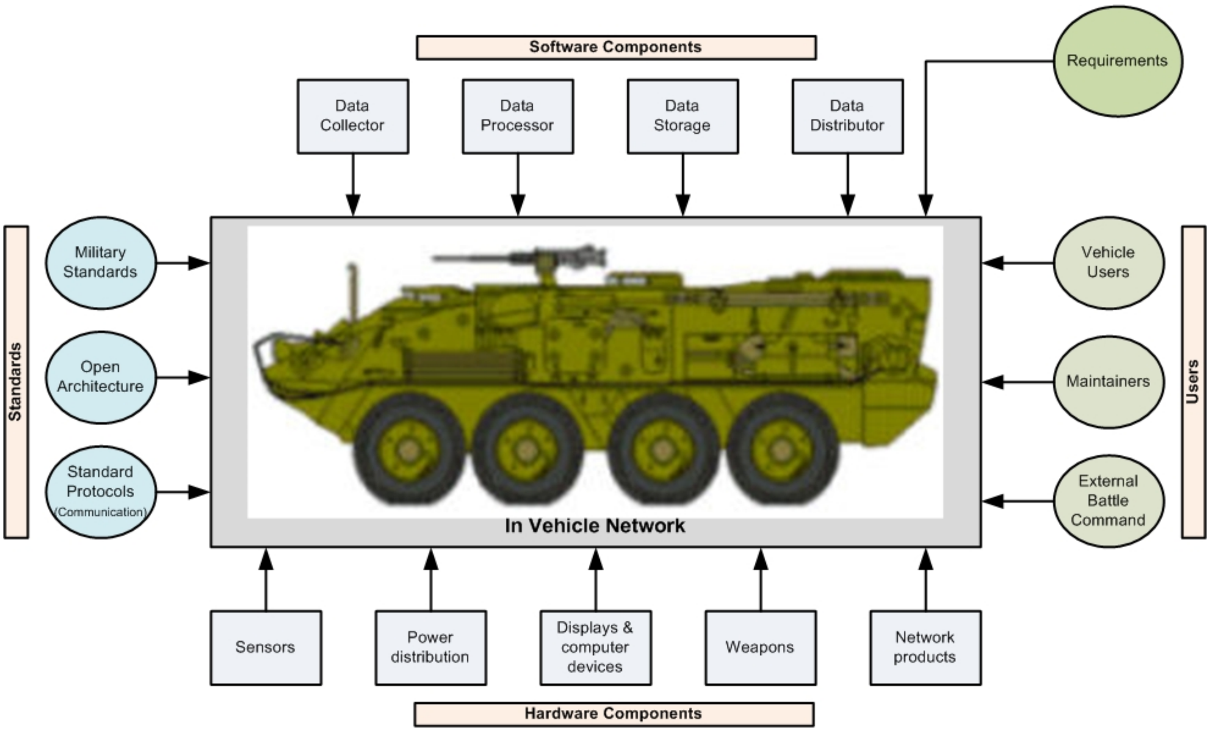


Fig. 23. In-vehicle network architecture context

An implementation procedure of the proposed energy saving strategy is as follows:

- Develop software to implement the proposed algorithms using C, C++, Java, or Matlab programming languages
- Host the software in a simple computer that has a microprocessor and two physical interfaces namely, Ethernet and CAN. Most of the Army ground vehicles may have Ethernet and CAN networks to communicate among the systems in the vehicle. To obtain data information to successfully implement the approach, an efficient in-vehicle

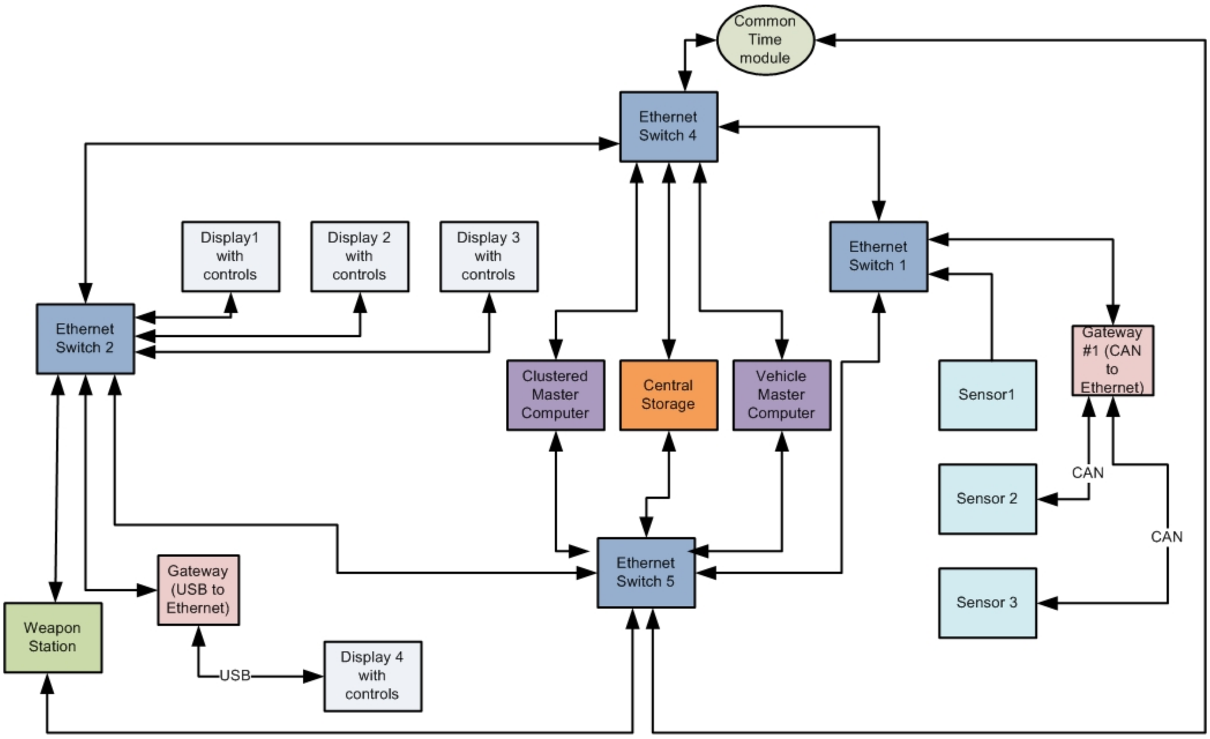


Fig. 24. Proposed in-vehicle network architecture

network is required. Fig. 23 and Fig. 24 proposes an architecture.

- Connect the simple computer to the vehicle network for communicating with the systems and the ECU
- Allow the software version of the algorithms to communicate with appropriate systems to achieve energy savings using either CAN or Ethernet protocols
- Use a current measuring sensor near the alternator to measure the current draw from the systems. The sensor shall have a CAN interface to communicate with the CAN bus
- Provide a software function for the driver to switch between the normal operation and the energy saving operation

Fig. 22 shows a schematic of the sequence of events and operations of a conventional Army ground vehicle after implementing the proposed energy saving strategy to save battery energy when the engine is off and the vehicle is stationary. The operation of the proposed energy saving algorithms in a real vehicle is as follows for silent surveillance mission of the vehicle:

- Driver turns the engine off and the vehicle is not moving. The battery supplies power to the systems
- The energy saving algorithm software monitors the systems usage constantly and transitions systems to their power saving mode based on the mission conditions and their busyness servicing requests.
- This process ends when the battery state of charge is not sufficient to continue the mission. The driver starts the vehicle to recharge the battery or to escape from the battle field

## 4.8 Conclusion

This chapter described the proposed mission aware energy saving strategy for silent surveillance missions of a stationary Army ground vehicle. The computer simulations and a battery test show that the proposed approach minimizes battery discharge based on the needs of a mission without affecting the operational performance of the systems. Therefore, it extends the duration of a silent surveillance mission that results in a successful mission. Experiments show that the proposed approach consumes 3% less energy than the baseline approach for one scenario and 1.8% less for the second scenario. The implementation can either be a centralized or distributed solution. The proposed centralized solution of the approach minimizes the modifications to the existing systems. Therefore, the implementation cost is minimal. Since the approach can handle any number of systems, it is a flexible and scalable solution. The next chapter describes the mission aware energy saving strategy for normal surveillance missions of a stationary Army ground vehicle.

## 4.9 Disclaimer

Disclaimer: Reference herein to any specific commercial company, product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the Department of the Army (DoA). The opinions of the authors- expressed herein do not necessarily state or reflect those of the United States Government or the DoA, and shall not be used for advertising or product endorsement purposes.

# CHAPTER 5 NORMAL SURVEILLANCE: ENERGY SAVING STRATEGY

The previous chapter described the application of surveillance mission theoretical models, and the mission aware energy saving strategy for silent surveillance missions of a stationary Army ground vehicle. This chapter describes the mission aware energy saving strategy for normal surveillance missions of a stationary Army ground vehicle.

## 5.1 Introduction

Energy savings in stationary Army ground vehicles is the primary goal of the proposed research in this section. Fuel-energy savings is critical for extending mission time. Additionally, energy saving is a mandatory requirement for the military due to their major consumption requirements [3]. A Defense Science Board report [3] triggered the development of alternative energy sources namely, fuel cell, and high capacity electric storage [2] systems. However, they require expensive and time-consuming implementations for combat vehicles.

During warfare, soldiers use multiple systems to perform extended hours of mission in stationary combat vehicles. The missions require a continuous supply of electricity to operate on-board systems. However, stationary vehicle engines operate at fixed idle speed and meet limited vehicle power demands. In many cases, the power requirements of the mechanical accessory systems are somewhat constant. In contrast, increased electrical consumption of the systems changes the load on the alternator and the engine. The Engine Control Unit (ECU) reacts to the change and injects fuel accordingly or changes the engine speed to a high-idle RPM, a situation that is less energy efficient. Furthermore, engines may stall if the demand is more than a given speed can handle.

For military surveillance missions, the combat vehicles operate in stationary modes as a power generator for long durations. The inefficient engine speeds during the stationary operations of the engine increase fuel consumption. Therefore, energy efficiency in stationary vehicles is very important for the Army combat vehicles. The proposed research focuses on operating the engine of an Army ground vehicle such as a stationary Combat Vehicle (CV) at electrical load specific fuel-efficient engine speeds rather than at predefined high-idle RPM increments to meet the demands. Stationary vehicles provide power to operate on-board mechanical and electrical systems. However, the non-stationary vehicles provide power to propulsion as well as on-board systems.

The process of electricity generation in a stationary CV is a physical phenomenon between the on-board electrical systems, engine, and the alternator. Thus, most of the existing techniques focus on altering or enhancing the physical properties of this behavior. However, it is possible to experiment and observe the phenomena, and capture data points to develop mathematical or heuristic models. Researchers can use the models to optimize this procedure for achieving fuel efficiency while meeting the electrical demands. Developing a true model to represent this physical process is a complex task for traditional mathematical methods. To avoid this intricacy, researchers focus on heuristic approaches. Nevertheless, the current literature lacks heuristic approaches to improve fuel efficiency of stationary CVs and also to meet the on-board systems electrical needs. The proposed research addresses this gap.

In the literature, researchers [53], [54] recommend minimizing load disturbances and fuel-injection inaccuracies to achieve fuel efficiency in stationary vehicles. On the other hand, the adaptive algorithm [55] and hybrid control algorithm [56] approaches suggest operating the engines at lower RPMs to achieve fuel economy [57]. A study [58] proposes to incorporate known idle speed constraints to obtain energy efficiency. Some researchers demonstrate fuel efficiency in a stationary vehicle's gasoline engine by efficiently controlling the operations of air valve and spark advances [59]. Most of these approaches lack techniques to handle CV's large load variations. These methods may trigger engine stalls if the predefined speeds cannot handle the demand. Moreover, these techniques require altering the physical properties of the vehicle.

Several heuristic fuel efficiency techniques, such as fuzzy logic [90],[91], [92] and neural networks [42], [93] focus on manipulating the energy storage and power split strategies. Another research study [46] uses a machine learning approach to achieve fuel economy while meeting the power demands of a non-stationary vehicle. A study [43] proposes to use an energy management strategy to minimize energy losses in the operation of an alternator, engine, and battery system to achieve fuel-efficiency.

All the aforementioned and similar approaches in the literature require alterations of the dynamic properties of the non-stationary vehicles to achieve fuel economy. Introduction of bi-directional power converter and additional energy storage [94] can lead to better fuel efficiency during stationary operations of a CV. On the other hand, an additional converter and energy storage has cost, weight, and space constraints. A fuzzy logic controller [95] in a hybrid electrical vehicle controls the engine to operate at fuel-efficient regions based on power demands. However, this approach works only on hybrid electric vehicles due to the presence of a high-voltage battery.

A high-idle speed control method [96] uses fixed idle speed increments to meet the demands and to minimize fuel consumption. Another system [97] switches the idle speeds between 600 RPM to 1100 RPM using a timer based solution. These approaches do not determine fuel-efficient idle speeds to meet the needs. Moreover, a human element is also involved in the decision process, a situation that leads to inefficient engine speeds. A system and a method [98], which is closest to the proposed approach uses an optimal speed adjuster to meet the power demand and to achieve fuel savings. However, this approach uses only the relationship between the generator speed and the demand. It does not incorporate the engine's fuel efficiency properties.

Many existing high-idle speed controllers do not handle the engine and alternator maximum output capacity, combined power demand from the alternator and the mechanical accessory systems, and engine's and alternator's performance characteristics to achieve fuel savings in stationary vehicles. Moreover, the existing approaches depend on the alternator and engine types. To the best knowledge, no approach exists in the literature that deals with achieving fuel-efficiency in stationary CVs and meeting the electrical demands of the vehicle. The following distinct contributions differentiate the proposed methodology from the existing techniques:

- An on-line Fuzzy Logic System (FLS) based Mission Aware Soft Computing Fusion (MASCF) algorithm as a feedback controller to approximate a fuel-efficient engine speed per unique electrical demand by combining the followings:
  - Engine and alternator performance/efficiency maps
  - Mission aware profiles of on-board systems electric current draw
  - Engine and alternator constraints
- FLS models of alternator and engine performance characteristics

This chapter is organized as follows: Section 5.2 describes the theoretical MASCF system model, and Section 5.3 describes the MASCF solution architecture and the algorithm. Section 5.4 describes the simulation and experiment setup. Section 5.5 presents the computer simulation and experiments results. Section 5.6 describes an approach to implement the proposed solution. Section 5.8 concludes this chapter.

## 5.2 MASCF System Model

The MASCF approach addresses a conventional stationary CV that has a diesel internal combustion engine, a drivetrain, an automatic transmission, a belt-driven alternator, batteries, and electrical systems. During stationary operations of a CV, the systems' electrical demands put a load on the alternator. The alternator and mechanical accessory systems put a combined load on the engine. The engine spends fuel and produces the mechanical power to operate the automotive systems and the alternator. The alternator produces the necessary current output to meet the on-board systems demand.

In a stationary CV without the MASCF approach, the ECU operates the engine at a predefined speed $\omega_{eng}$ to meet the energy demand. If the load power exceeds the maximum capacity of the engine at a given $\omega_{eng}$, the engine stalls. If a given speed is not able to meet the vehicle needs, the driver or the ECU will increase $\omega_{eng}$ to a next predefined high-idle RPM. The new $\omega_{eng}$ may not be fuel-efficient to meet the demand. Section 5.2.1 provides the system model with a theoretical background for realizing the MASCF approach. Section 5.3 describes the MASCF solution architecture and the algorithm.

### 5.2.1 Theoretical model

The fuel efficiency $S_e$ of a given $\omega_{eng}$ is shown in (5.1), where $F_c$ is the fuel consumption of the engine to produce power at the given $\omega_{eng}$. The minimum value of $S_e$ among various combinations of $\omega_{eng}$ and the power produced, determines the fuel-efficient $\omega_{eng}$ for a given engine load torque $T_{eng}$.

$$S_e \;= \frac{F_c}{f(T_{eng}, \omega_{eng})} \tag{5.1}$$

The expression of the $T_{eng}$ is as shown in (5.2). The values of automotive systems torque $T_{auto}$ change with the $\omega_{eng}$, the value of alternator torque $T_{alt}$ is a function of the on-board systems electric current consumption demand $I_s$, and the alternator speed $\omega_{alt}$. The alternator speed depends on the engine speed. This study assumes a constant horsepower requirements from the mechanical accessory systems $H_{auto}$, a 20% of $T_{alt}$ and $T_{auto}$ values to cover the losses, and a pulley ratio of 1:3 between the engine and the alternator.

$$T_{eng} = 3.2f(I_s, 3\omega_{eng}) + 1.2(\frac{H_{auto}}{\omega_{eng}}) \tag{5.2}$$

$F_c$ at a given $\omega_{eng}$ can be represented as (5.3). If the engine can operate at $\omega_{eng}$ that has lower values of $S_e$ to meet the demand $I_s$, the fuel efficiency can be improved.

$$F_c \ = S_e * f(T_{eng}, \omega_{eng}) \tag{5.3}$$

Current measuring sensors can be used to determine the total electrical load $I_s$ of the vehicle. As an alternate approach, based on the author's previous work [99], systems total $I_s$ can be determined using the expression shown in (5.4) and the Systems Usage Algorithm [99], where $I^i_{slp}$= 1 to n sleeping systems, $I^i_{idl}$ 1 to n idle systems, and $I^i_{act}$ 1 to n active systems current consumption values in a CV. Table VII shows an example of current draws of several CV's systems. The idle systems accept work requests and immediately fulfils the requests. However, the sleeping systems have to transition to active mode before fulfilling any requests.

$$I_s = \sum_{i=0}^{n} I^i_{slp} + \sum_{i=0}^{n} I^i_{idl} + \sum_{i=0}^{n} I^i_{act} \tag{5.4}$$

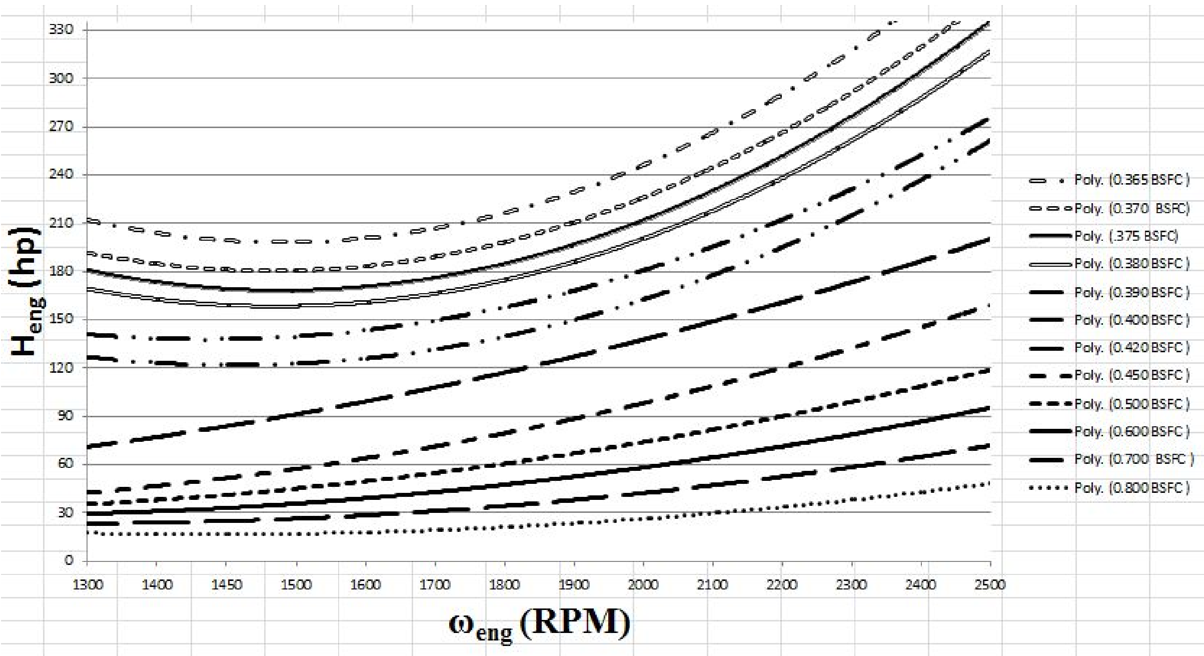


Fig. 25. Example engine BSFC map

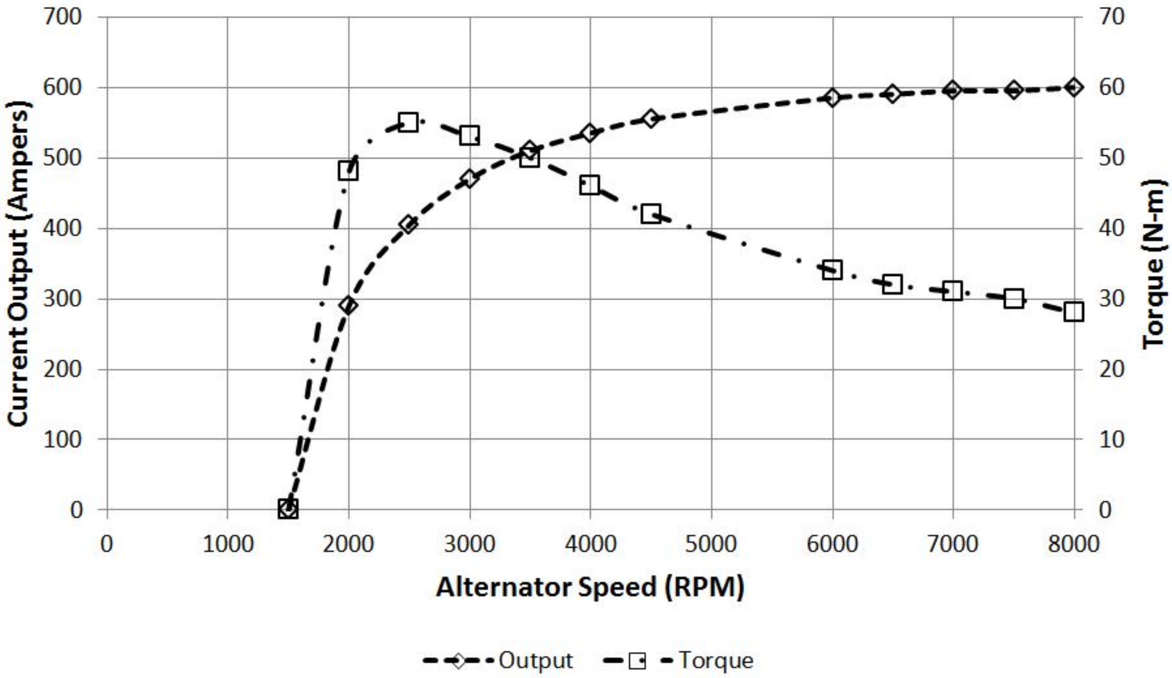


Fig. 26. Example alternator performance map

Engine experiments of various combinations of $\omega_{eng}$ and $T_{eng}$ allows the development of an engine efficiency map. An example is as shown in Fig. 25. Similarly, a combination $\omega_{alt}$ and $I_s$ load allows developing an alternator performance map that can represent the $T_{alt}$ that the alternator puts on the engine to generate a given $I_s$ at a given $\omega_{alt}$. An example alternator efficiency map is shown in Fig. 26. By combining the information in the performance maps, and estimated $I_s$ values, it is possible to approximate a fuel-efficient $\omega_{eng}$ by identifying the combination of lowest $F_c$ and its associated $\omega_{eng}$ that can meet the demand. In the literature, multiple look-up tables and linear interpolation techniques are used to approximate values from a map data. However, creating look-up tables for MASCF is complex and time consuming. Section 5.3 presents the proposed novel FLS models and MASCF algorithm to handle this situation.

An FLS [100] based system maps non-linear inputs to a scalar output using fuzzy sets [62], a fuzzification process, a set of rules, an inference method, and a defuzzification processes. A fuzzification process maps a crisp input to a membership function. A set of rules in natural language provide an approximation model. In the example rule (5.5), $I$ = current, $S$ = engine speed, and $F$ = fuel consumption. The terms $high$, $medium$, and $low$ are fuzzy sets. An inference process aggregates the results of each rules, and a defuzzification process maps a fuzzy value into a crisp output value. Mathematically, a fuzzy set $X$ in an universe of discourse $Y$ is defined as (5.6). The $\mu_X$ is a membership degree between (0,1) of value $y$ in a fuzzy set $X$.

$$if\ I = low\ \&\ S = medium\ then\ F = medium \tag{5.5}$$

$$X = \{(y, \mu_X(y))\,|y \in Y\} \tag{5.6}$$

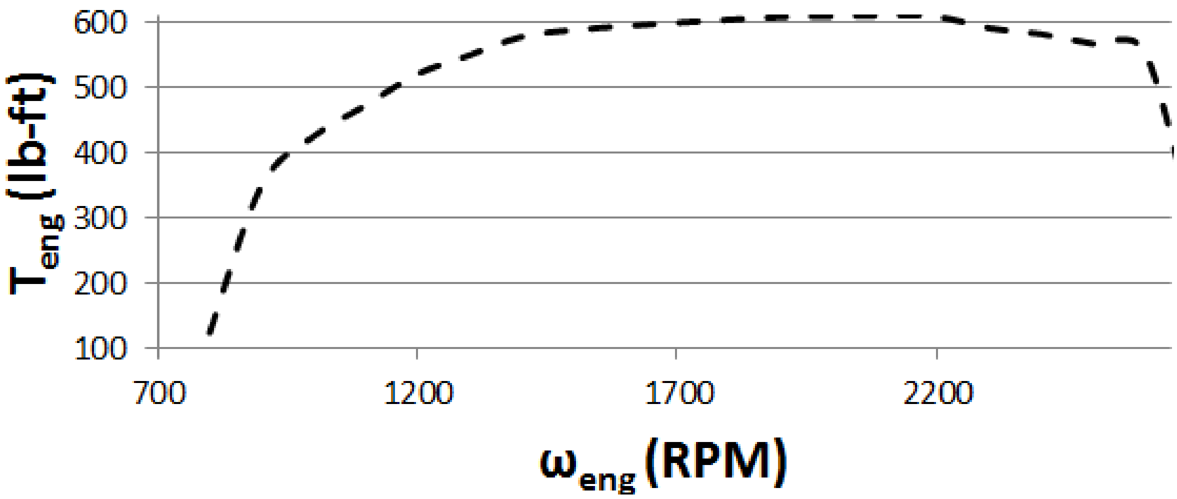


Fig. 27. Example maximum engine torque output

Sugeno-Takai [101] based FLS models for estimating the $T_{eng}$ and $F_c$ are shown in (5.7) and (5.8), respectively. $R^i_{alt}$ (5.9) and $R^i_{eng}$ (5.10) are fuzzy rule bases for evaluating $T_{eng}$ and $F_c$, respectively. $A^j$, $B^j$,$C^j$ and $D^j$ are membership functions for the alternator speed, current consumption demand, engine speed, and engine torque demand, respectively. $w_i$ is the degree of fulfillment of an $i^{th}$ rule in and j= 1 to 3.

$$T_{eng} = 3.2(\frac{\sum_{i=1}^{9} w_i R_{alt}^i}{\sum_{i=1}^{9} w_i}) + 1.2(\frac{H_{auto}}{\omega_{eng}}) \tag{5.7}$$

$$F_c = \frac{\sum_{i=1}^{9} x_i R_{eng}^i}{\sum_{i=1}^{9} x_i} \tag{5.8}$$

$$R_{alt}^i : if\ \omega_{alt} = A^j\ \&\ I_s = B^j\ then\ T_{alt}^i = f(\omega_{alt}, I_s) \tag{5.9}$$

$$R_{eng}^i : if\ X^i\ then\ F_c^i = f(\omega_{eng}, T_{eng}) \tag{5.10}$$
$$where\ X^i :\ \omega_{eng} = C^j\ \&\ T_{eng} = D^j$$

The input membership functions $A^j$ and $B^j$ use a triangular membership curve. The fuzzification of inputs using these functions are expressed in (5.11)[101]. Similarly, the input membership functions $C^j$ and $D^j$ uses the generalized Bell membership functions (5.12)[101]. The $s$, $c$, and $e$ are the start, center, and end range of a fuzzy set, respectively. $\mu_{F(a)}$ is the membership grade and $a$ is the input value to be fuzzified. The membership grade of $a$ is zero at $s$ and $e$, but at $c$ the membership grade of $a$ is 1. The values between $s$ and $e$ have different grades of membership based on the values of $a$ and function expressions (5.11) and (5.12).

$$\mu_F(a) = max(min(\frac{a-s}{c-a}, \frac{e-a}{e-c}), 0) \tag{5.11}$$

$$\mu_F(a) = \frac{1}{1 + |\frac{a-e}{a}|^{2c}} \tag{5.12}$$

Fig. 26 and Fig. 27 show that a given alternator and engine has output limits at a given $\omega_{eng}$ and $\omega_{alt}$, respectively. Therefore, these limits should be part of the $\omega_{eng}$ approximation to meet the demand $I_s$. Sugeno-Takai [101] based FLS models for estimating the $T_{emax}$ and $I_{max}$ are shown in (5.13) and (5.16), respectively. $R^i_{meng}$ (5.14) and $R^i_{malt}$ (5.16) are fuzzy rule bases for evaluating $\omega_{eng}$ and $\omega_{alt}$, respectively. The $x_i$ is the degree of fulfillment of an $i^{th}$ rule in (5.14), and j= 1 to 3. The input membership functions $E^j$ and $F^j$ use a triangular membership curve and the fuzzification of inputs using these functions are expressed in (5.11)[101].

$$T_{emax} = \frac{\sum_{i=1}^{3} x_i R^i_{meng}}{\sum_{i=1}^{3} x_i} \tag{5.13}$$

$$R^i_{meng} : if\ \omega_{eng} = E^j\ then\ T^i_{emax} = f(\omega_{eng}) \tag{5.14}$$

$$I_{max} = \frac{\sum_{i=1}^{3} x_i R^i_{malt}}{\sum_{i=1}^{3} x_i} \tag{5.15}$$

$$R^i_{meng} : if\ \omega_{alt} = F^j\ then\ I^i_{max} = f(\omega_{alt}) \tag{5.16}$$

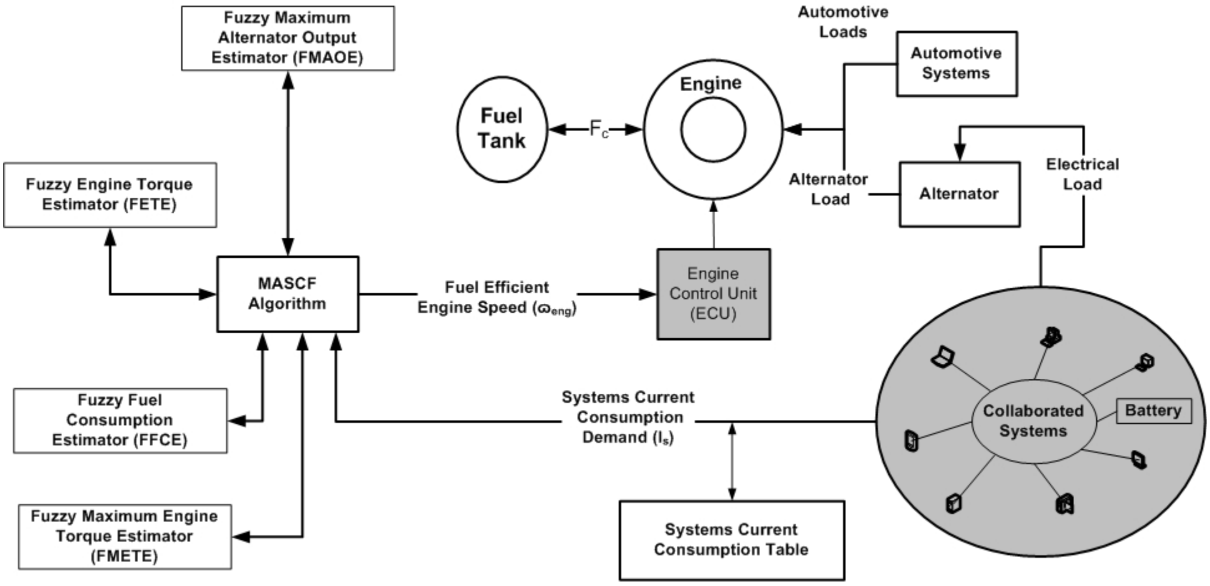


Fig. 28. The MASCF system architecture

## 5.3 MASCF Solution Architecture

The schematic of the MASCF solution architecture is shown in Fig. 28 and it has the following high-level processes:

- Monitor the electrical systems usage within a CV and estimate $I_s$
- Approximate $T_{alt}$ that the alternator will put as a load on the engine to meet $I_s$
- Determine $T_{eng}$ based on the torque demands $T_{alt}$ and $T_{auto}$
- Approximate $\omega_{eng}$ that can generate $T_{eng}$ or more with a minimal $F_c$ value

In addition to the proposed fuzzy system several other technologies such as adaptive neuro fuzzy, neural network, and factor analysis methods. However, the process was too complicated and time consuming. Moreover, those approaches did not provide good results. The simple fuzzy systems seem to provide good results than the other approaches. Appendix section shows some of the discussions about them.

The MASCF solution architecture elements are as follows:

### 5.3.1 Fuzzy Engine Torque Estimator (FETE)

The FETE is the implementation FLS model of (5.7), (5.9), and (5.11). The inputs are the $I_s$ and $\omega_{eng}$, and the output is the $T_{alt}$ that the alternator puts on the engine to meet the demand. The FETE is implemented based on the alternator performance experimental data as shown in sample Fig. 26. The fuzzy rules are derived based on the distribution of experiment data. The torque distribution and the fuzzy rules of the FETE FLS model are represented in Fig. 29 and Fig. 30, respectively. Fig. 31 and Fig. 32 show the fuzzy membership functions used in the FETE for the alternator speed and current demand inputs, respectively. The MASCF algorith uses the FETE model for calculating the $T_eng$ value for a given load $I_s$.

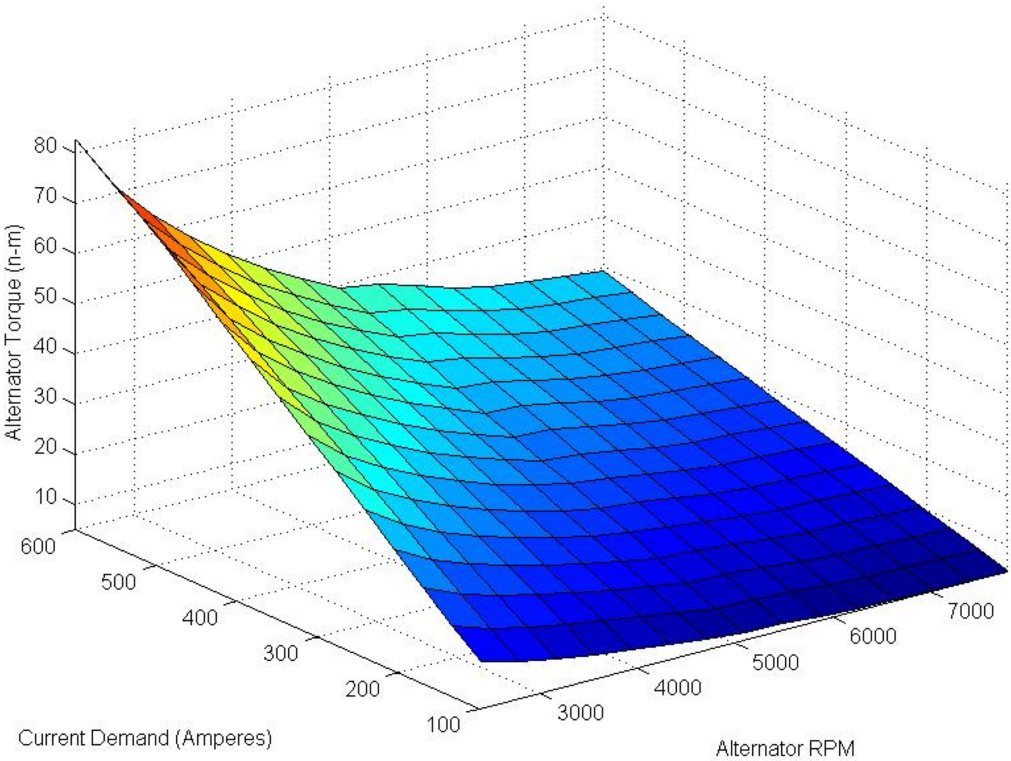


Fig. 29. Fuzzy torque distribution of FETE FLS model.

1. If (AlternatorRPM is in1mf1) and (CurrentDemand is in2mf1) then (AlternatorTorque is out1mf1) (1)
2. If (AlternatorRPM is in1mf1) and (CurrentDemand is in2mf2) then (AlternatorTorque is out1mf2) (1)
3. If (AlternatorRPM is in1mf1) and (CurrentDemand is in2mf3) then (AlternatorTorque is out1mf3) (1)
4. If (AlternatorRPM is in1mf2) and (CurrentDemand is in2mf1) then (AlternatorTorque is out1mf4) (1)
5. If (AlternatorRPM is in1mf2) and (CurrentDemand is in2mf2) then (AlternatorTorque is out1mf5) (1)
6. If (AlternatorRPM is in1mf2) and (CurrentDemand is in2mf3) then (AlternatorTorque is out1mf6) (1)
7. If (AlternatorRPM is in1mf3) and (CurrentDemand is in2mf1) then (AlternatorTorque is out1mf7) (1)
8. If (AlternatorRPM is in1mf3) and (CurrentDemand is in2mf2) then (AlternatorTorque is out1mf8) (1)
9. If (AlternatorRPM is in1mf3) and (CurrentDemand is in2mf3) then (AlternatorTorque is out1mf9) (1)

Fig. 30. Fuzzy rules for the FETE FLS model.

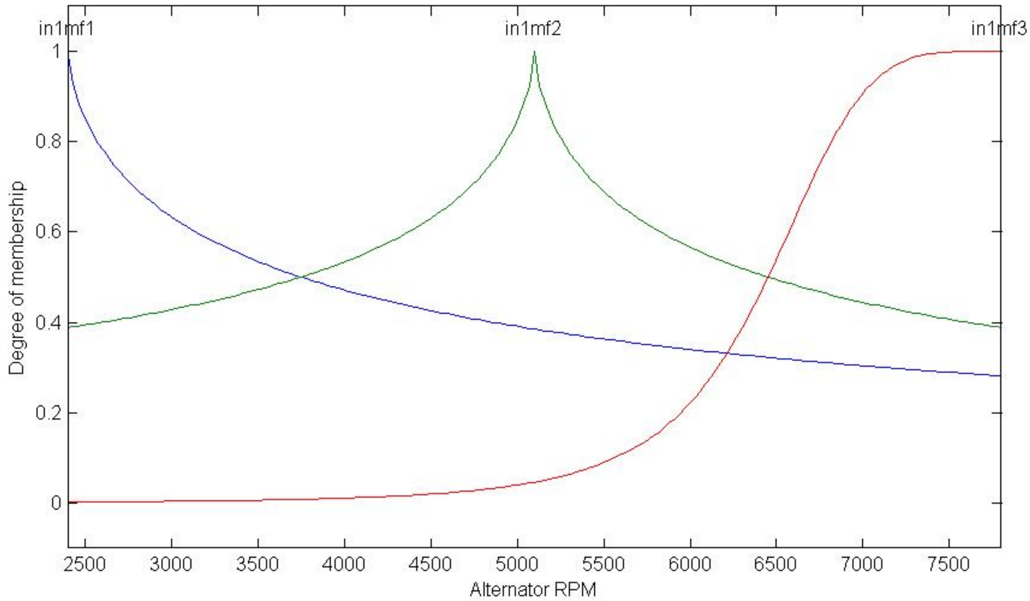


Fig. 31. Alternator speed input membership functions of FETE model.

### 5.3.2 Fuzzy Fuel Consumption Estimator (FFCE)

The FFCE is the implementation FLS of (5.8), (5.10), and (5.12). The inputs to this model are the $T_{eng}$ and the $\omega_{eng}$. The output is the $F_c$ of the engine to meet demand. The FFCE is implemented based on the engine fuel consumption and torque efficiency experimental data. Fig. 25 shows an example efficiency map. The fuzzy rules are derived based on the distribution of experimental data. Fig. 33 and Fig. 34 represents the fuel consumption map and the fuzzy rules of the FFCE FLS model. Fig. 35 and Fig. 36 show the fuzzy membership

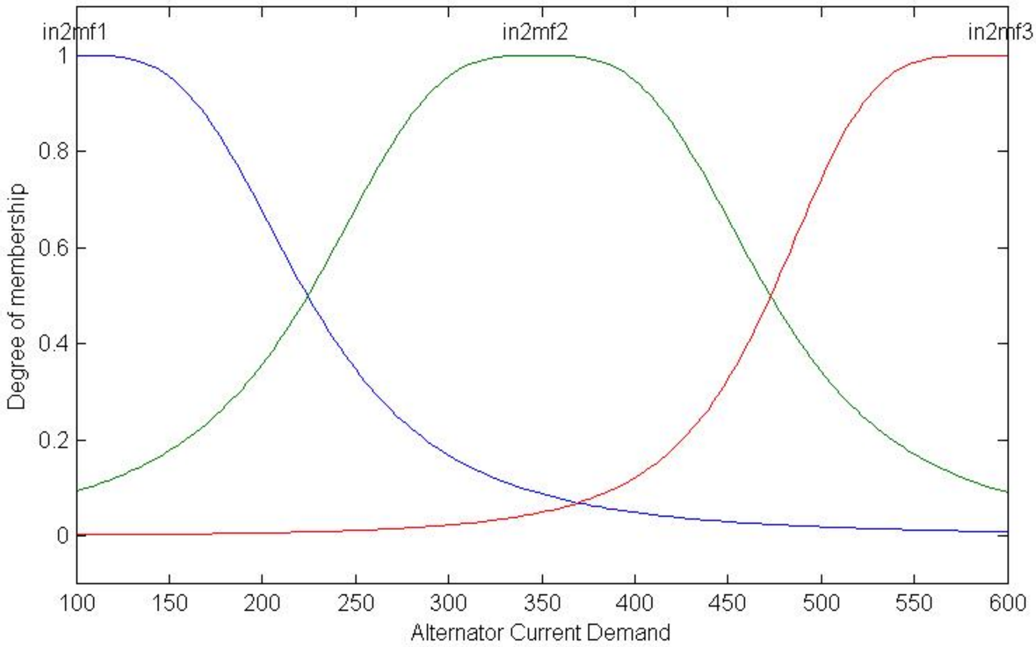


Fig. 32. Current demand input membership functions of FETE model.

functions used in the FECE for the engine speed and engine torque demand inputs, respectively.

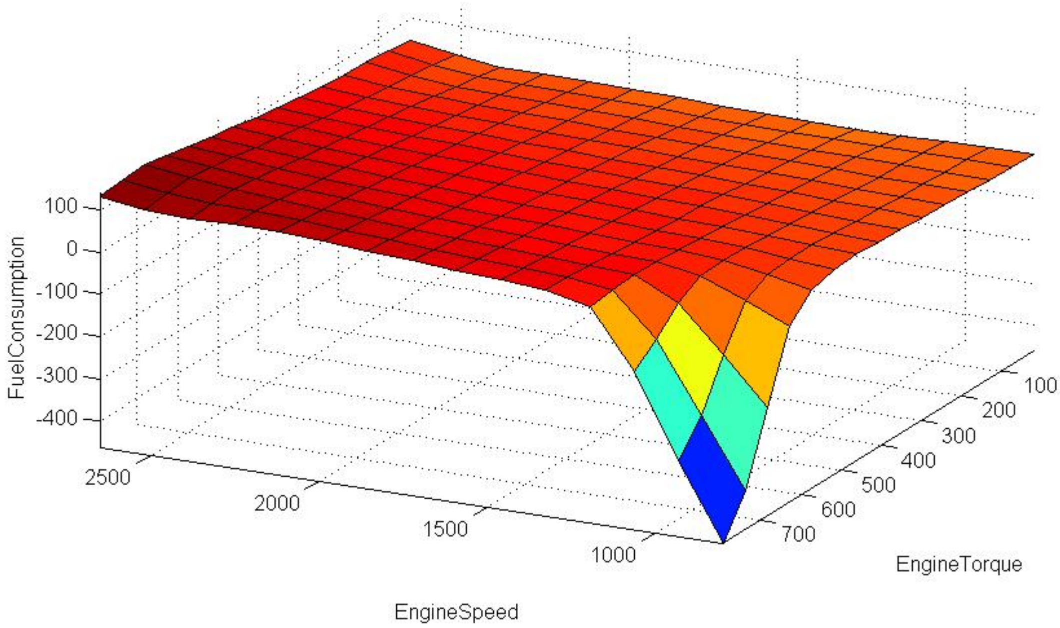


Fig. 33. Fuzzy consumption distribution of FFCE FLS model.

1. If (EngineSpeed is in1mf1) and (EngineTorque is in2mf1) then (FuelConsumption is out1mf1) (1)
2. If (EngineSpeed is in1mf1) and (EngineTorque is in2mf2) then (FuelConsumption is out1mf2) (1)
3. If (EngineSpeed is in1mf1) and (EngineTorque is in2mf3) then (FuelConsumption is out1mf3) (1)
4. If (EngineSpeed is in1mf1) and (EngineTorque is in2mf4) then (FuelConsumption is out1mf4) (1)
5. If (EngineSpeed is in1mf2) and (EngineTorque is in2mf1) then (FuelConsumption is out1mf5) (1)
6. If (EngineSpeed is in1mf2) and (EngineTorque is in2mf2) then (FuelConsumption is out1mf6) (1)
7. If (EngineSpeed is in1mf2) and (EngineTorque is in2mf3) then (FuelConsumption is out1mf7) (1)
8. If (EngineSpeed is in1mf2) and (EngineTorque is in2mf4) then (FuelConsumption is out1mf8) (1)
9. If (EngineSpeed is in1mf3) and (EngineTorque is in2mf1) then (FuelConsumption is out1mf9) (1)
10. If (EngineSpeed is in1mf3) and (EngineTorque is in2mf2) then (FuelConsumption is out1mf10) (1)
11. If (EngineSpeed is in1mf3) and (EngineTorque is in2mf3) then (FuelConsumption is out1mf11) (1)
12. If (EngineSpeed is in1mf3) and (EngineTorque is in2mf4) then (FuelConsumption is out1mf12) (1)
13. If (EngineSpeed is in1mf4) and (EngineTorque is in2mf1) then (FuelConsumption is out1mf13) (1)
14. If (EngineSpeed is in1mf4) and (EngineTorque is in2mf2) then (FuelConsumption is out1mf14) (1)
15. If (EngineSpeed is in1mf4) and (EngineTorque is in2mf3) then (FuelConsumption is out1mf15) (1)
16. If (EngineSpeed is in1mf4) and (EngineTorque is in2mf4) then (FuelConsumption is out1mf16) (1)

Fig. 34. Fuzzy rules for the FFCE FLS model.

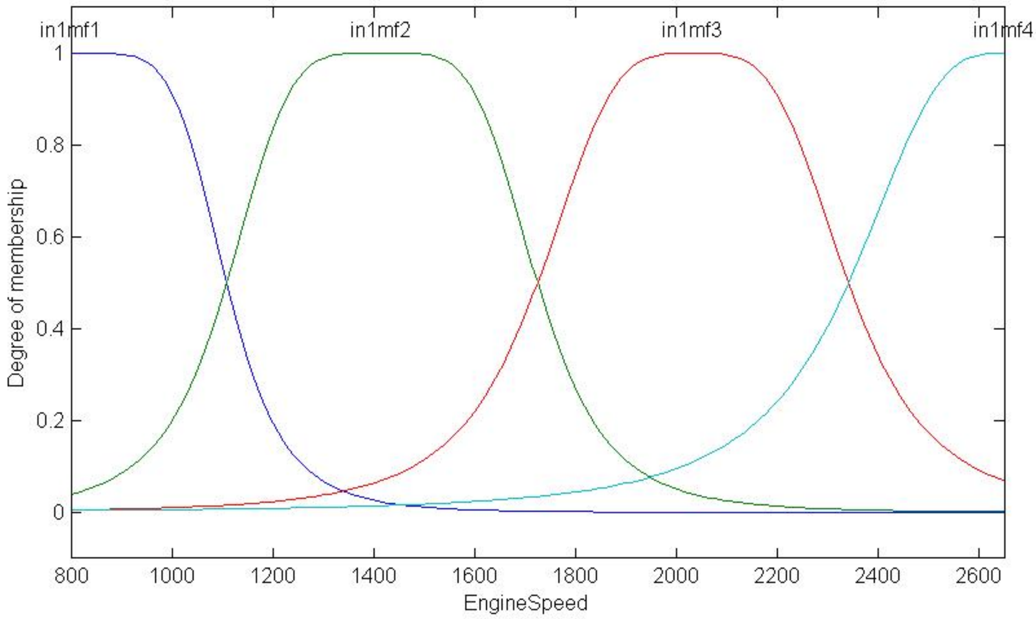


Fig. 35. Engine speed input membership functions of FECE model.

### 5.3.3 Systems Current Consumption Table (SCCT)

This table stores the current draws of each of the on-board systems in a CV. Table VII shows an example. This table is used by the MASCF algorithm to calculate the total electricity demand of the systems.

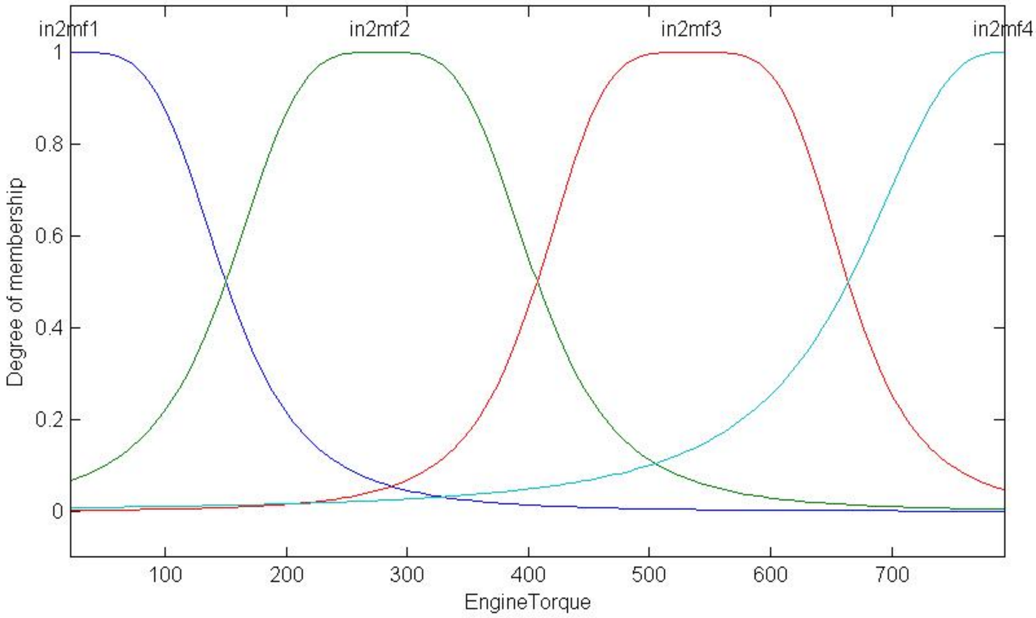


Fig. 36. Engine torque input membership functions of FECE model.

### 5.3.4 Fuzzy Maximum Alternator Output Estimator (FMAOE)

The FMAOE is the implementation FLS model of (5.15), (5.16), and (5.11). The input to this model is the alternator speed. The output is the maximum current the alternator can generate at a given alternator speed. The FMAOE is implemented based on the experimental data as shown in Fig. 26.

### 5.3.5 Fuzzy Maximum Engine Torque Estimator (FMETE)

The FMETE is the implementation FLS of (5.13), (5.14), and (5.11). The input to this model is the engine speed. The output is the maximum torque the engine can generate at a given engine speed. The FMETE is implemented based on the experimental data as shown in Fig. 27.

TABLE VII
EXAMPLE SYSTEMS CURRENT DRAWS IN AMPERES

| System | Active Current (Amperes) | Idle Current Amperes | Sleeping Current Amperes |
|---|---|---|---|
| Work Station | 8.8 | 3.0 | 0.4 |
| Surveillance System | 7.0 | 4.0 | 0.7 |
| Video Camera | 2.0 | 1.2 | 0.05 |
| Radio | 5.5 | 2.5 | 0.2 |
| Weapon | 4.0 | 1.5 | 0.5 |

### 5.3.6 MASCF Algorithm

Fig. 37 shows the overall context of all the MASCF algorithm. It consists of an engine, ECU, alternator, Fuzzy feedback controller, and sensors. The sensors connected to the engine are used for defining power-fuel consumption-emissions metric. Fig. 38 shows the expanded diagram of the feedback controller that is used to control the engine speed to achieve fuel savings. The inputs to this controller are measured current and engine speed.

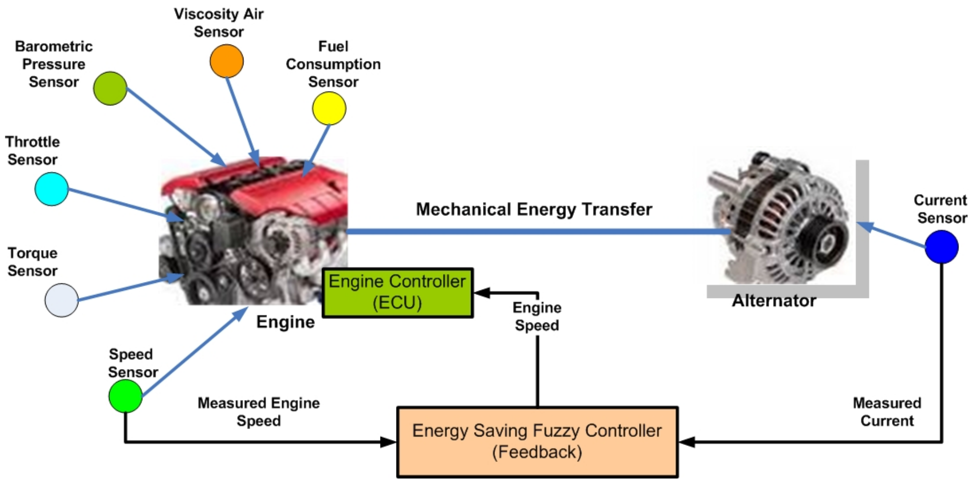


Fig. 37. MASCF system context.

The MASCF algorithm interacts with the FETE, FFCE, FMAOE, FMETE, and SCCT components and approximates the fuel-efficient $\omega_{eng}$ based on the current consumption demand of the systems. The Algorithm. 3 shows the detailed steps. The estimated $\omega_{eng}$ value is

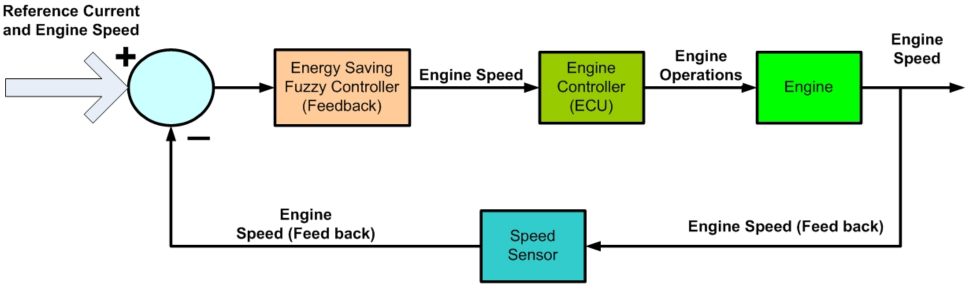


Fig. 38. Fuzzy feedback controller.

sent to the ECU to operate the engine at that speed. Unique combinations of the estimated demand and approximated engine speed are stored in the memory for reuse when the ECU encounters the already calculated engine speed for a given demand. This temporary storage reduces the computations if the engine needs to meet the known demands for multiple times. The algorithm is a feedback controller to the ECU. Fig. 39 shows the communications between the different elements to execute the MASCF algorithm and run the engine fuel efficient speed to save fuel. Fig. 40 describes the context of the proposed energy saving strategy for normal surveillance missions.

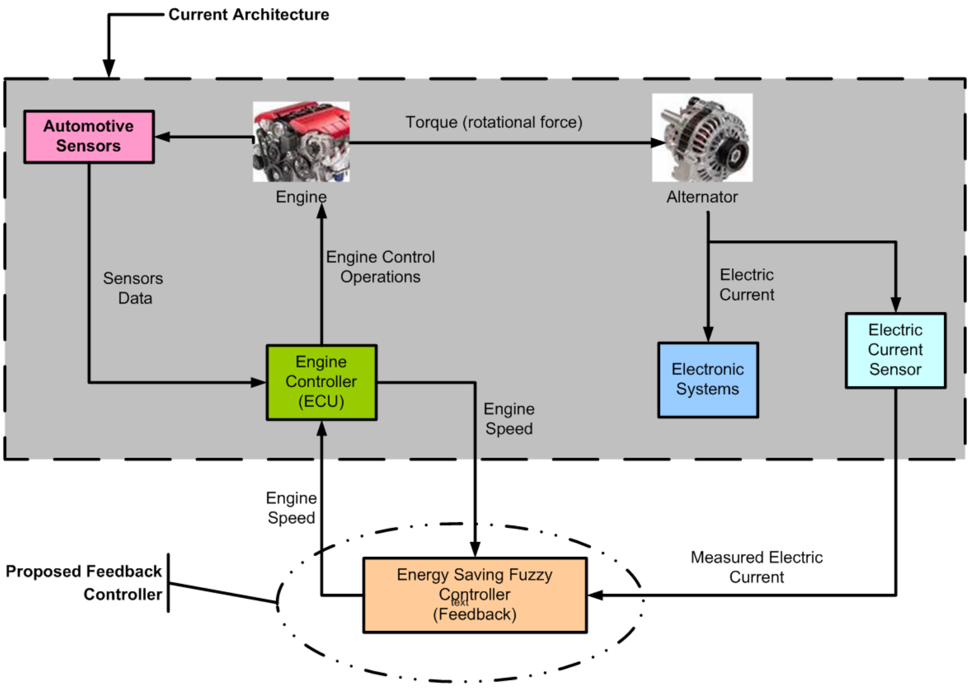


Fig. 39. Fuzzy feedback controller.

**Algorithm 3** MASCF Algorithm

$\omega_{eng} \leftarrow 0;$
$F_{eng} \leftarrow 0;$
$H_{auto} \leftarrow Mechanical\ systems'\ constant\ horsepower;$
$R_{min} \leftarrow Minimum\ engine\ RPM;$
$R_{max} \leftarrow Maximum\ engine\ RPM;$
$R_{inc} \leftarrow RPM\ Increment;$
$I_s \leftarrow Estimate\ demand\ using\ (5.4);$
**if** $SpeedInMemory(I_s)$ **then**
  $\omega_{eng} \leftarrow getSpeedFromMemory(I_s);$
**end if**
**if** $\omega_{eng} == 0$ **then**
  $w_1 \leftarrow R_{min};$
  **while** $w1 <= R_{max}$ **do**
    $I_{max} \leftarrow Approximate\ using\ FMAOE\ (w_1 * 3);$
    **if** $I_s <= I_{max}$ **then**
     Comment: Engine torque calculation
     $T_{alt} \leftarrow Approximate\ using\ FETE\ (w_1 * 3,\ I_s);$ $T_{auto} \leftarrow H_{auto}/w1;$
     $T_{eng} \leftarrow 3.2(T_{alt}) + 1.2T_{auto};$
     Comment:Fuel consumption calculation
    $T_{max} \leftarrow Approximate\ using\ FMETE\ (w_1);$
    **if** $T_{eng} <= T_{max}$ **then**
      $F_c \leftarrow Approximate\ using\ FFCE\ (w_1,\ T_{eng});$
      **if** $F_{eng} == 0\ ||\ F_c <= F_{eng}$ **then**
       $F_{eng} \leftarrow F_c;$
       $\omega_{eng} \leftarrow w_1;$
      **end if**
     **end if**
    **end if**
    $w_1 \leftarrow w_1 + R_{inc};$
  **end while**
**end if**
$return\ \omega_{eng};$

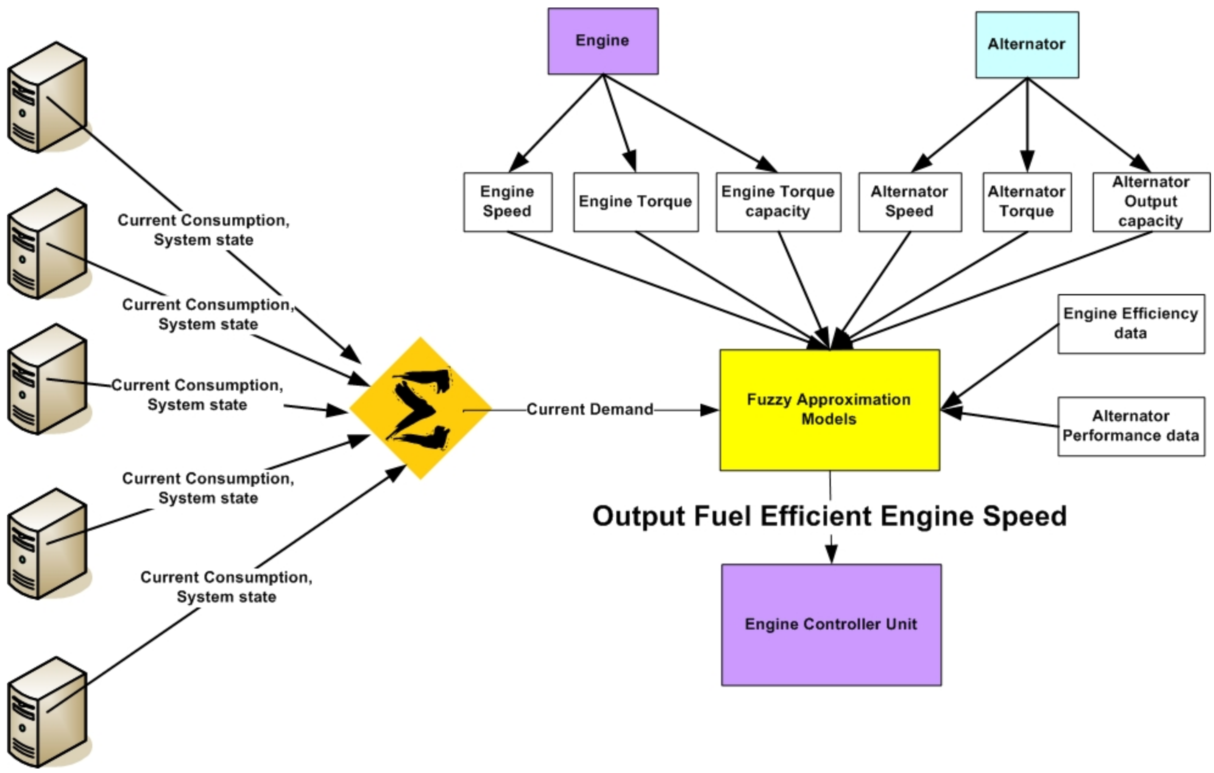


Fig. 40. Data map of the MASCF algorithm.

## 5.4 Simulation and Experiment Setup

To validate the proposed MASCF approach for normal surveillance missions, simulation and experiments were conducted. The experiments were to test the fuel savings characteristics of a conventional diesel engine while meeting the electric current demands. The simulation and the experiment used two engine configurations namely, a baseline engine with MASCF, and an engine with three high-idle RPM increments (800,1200, and 1600). The simulation used an Autonomie based Matlab/Simulink vehicle model. Table VIII shows the major parameters of the vehicle configuration used for the simulation and experiments. Fig. 41 shows the experiment setup used. The setup consists of an engine connected to a dynamometer with no alternator, and a CAN bus manager,and data acquisition system.

The experiments used the electrical load profiles based on the Action Maneuver Battle Lab

TABLE VIII
DIESEL ENGINE VEHICLE MODEL PARAMETERS

| **Parameter** | **Value** |
|---|---|
| Maximum Engine power | 261 kW |
| Maximum Engine RPM | 2700 |
| Maximum Alternator Output | 28 kW (at 77$^o$ F) |
| Maximum Alternator RPM | 8000 |
| Engine to Alternator Pulley Ratio | 1:3 |
| Mechanical accessories power | 35-45 kW |

(UAMBL) and Combined Arms and Support Task Force Evaluation Model (CASTFOREM) mission scenarios [104]. Table VII shows the example systems and their current draws. The simulation and experiments were conducted using the common load profiles of mission scenarios. Table IX shows the load profile with an assumption of 28 V voltage for electricity distribution. The automotive systems such as fuel pump is driven by the engine. Therefore, in addition to electrical demands, the experiments had to assume automotive power loads of 35 kW. Since the stationary vehicle performance was being tested, the propulsion power demands were assumed to be 0. Based on the alternator efficiency curves, the electrical output generated from the alternator was assumed to be at 80% efficiency of the mechanical energy input.

TABLE IX
POWER DEMANDS FOR THE MISSION SCENARIOS

| **Total Power (kW)** |
|---|
| 44 |
| 48 |
| 54 |
| 57 |
| 60 |
| 62 |
| 69 |

For accurate instrumentation and measurement, the alternator was offline and a dyno with a torque sensor was used for experiments. The experiments used the estimated torque values for determining the amount of water to flow through the dynamometer to simulate the power load on the engine. A user interface was used to input the required engine speed and torque values for the engine to run without the algorithm. Fuel consumption, torque produced, and engine speed readings were captured from a user screen. Horsepower value was calculated using the measured engine speed and the torque values. Calculated horsepower value was specified using the user interface to activate the proposed algorithm and to run engine with the algorithm identified engine speed. Fuel consumption, torque produced, and engine speed readings were captured again. The power demand (kW) is calculated based on the measured engine speed and torque for both the options. These readings have the columns of power (kW) and fuel consumption for with and without the proposed algorithm. The readings were plotted as shown in Fig. 42, the graph 1 with the proposed algorithm is better than the graph 2 without the proposed algorithm. Hence there is energy savings.

The validation environment used a controlled ambient temperature as well as a high temperature conditions for the fuel and air inlets, coolant, and intake manifold air. The experiments validated the MASCF approach using two types of fuel, induced failures, fuel pressure, and two fuel temperatures. To protect the confidentiality of the results and proprietary data, this dissertation research does not describe the fuel types used in the test.

## 5.5 Results and Discussion

Fig. 42 and Fig. 43 show the experimental results of the proposed MASCF approach when compared with the baseline vehicle configuration without the proposed algorithm. This test results were for normal ambient temperature of $77^o$ F. During the experiments, for the tested power demand, the engine configuration with the MASCF approach consumed an average of 24.30 pounds/hour fuel. The engine configuration with fixed high-idle RPM increments and no MASCF consumed an average of 24.74 pounds/hour fuel. The baseline engine stalled for most of the tested loads and could not meet the vehicle demands. The MASCF approach was

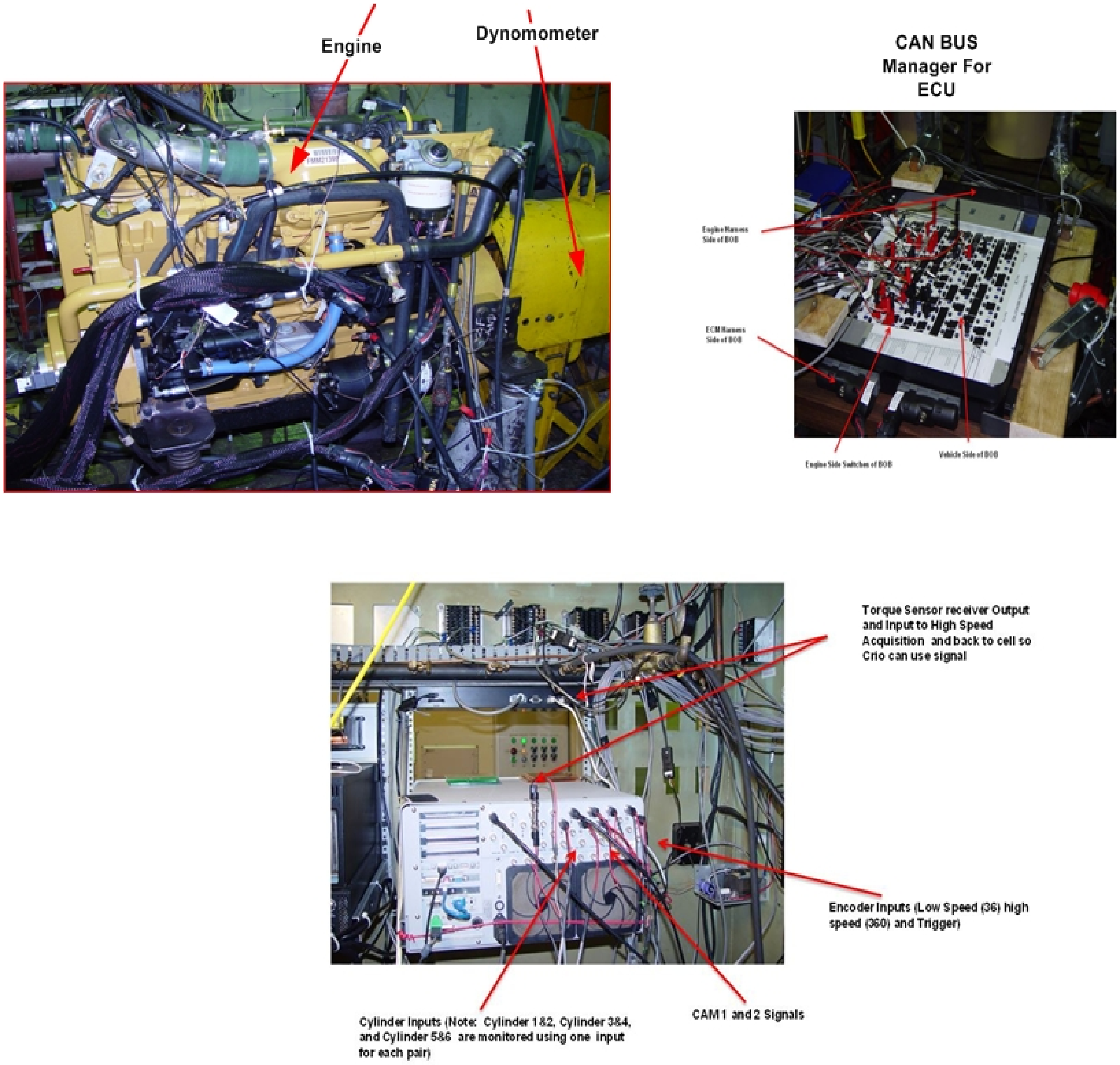


Fig. 41. Test bench setup:engine, CAN Bus manager, and data acquisition

at 0 - 4.9% more efficient than the vehicle configuration that had three fixed high-idle RPM increments for the tested power loads of 44 - 69 kW. Fig. 44 shows the actual fuel consumed vs. predicted. Although there are differences, the overall idea of predicted fuel savings is to determine the fuel efficient engine speed. The difference is due to the dynamic environment of the actual engine setup vs. simulation.

Based on the engine results and the other engine experiments, Fig. 45 shows the efficiency

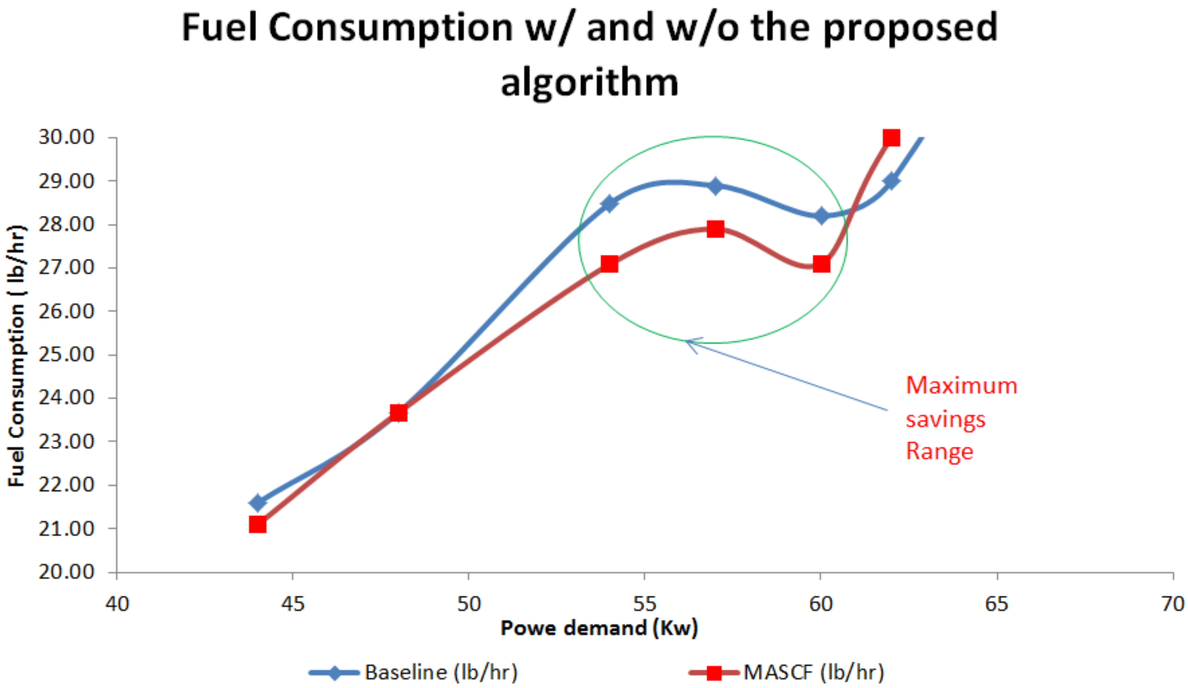


Fig. 42. Experiment results of the engine experiments

points of an engine at various RPMs and horsepower demands. The Brake Specific Fuel Efficiency (BSFC) indicates the amount of fuel spent while producing an unit horsepower. Lower the efficiency point for a given RPM, higher the fuel savings.

During the fuel map experiments, the fuel types, fuel temperature, induced failures, and fuel pressure influenced different $T_{eng}$ values than the MASCF estimated values. Therefore, the engine power had different actual values. This behavior of the engine affects the performance of the MASCF approach. Future work in this area addresses these impacts and modifies the solutions to handle these concerns. For the fuel type 1, Fig. 46 shows the different power generated at the same RPM for two different temperatures i.e., $77^o$ F and $120^o$ F. Similarly, for the fuel type 2, Fig. 46 shows the different power generated at the same RPM for two different temperatures i.e., $77^o$ F and $120^o$ F.

During the fuel map experiments, the induced failures and fuel pressure also influenced different $T_{eng}$ values than the MASCF estimated values. Therefore, the engine power had

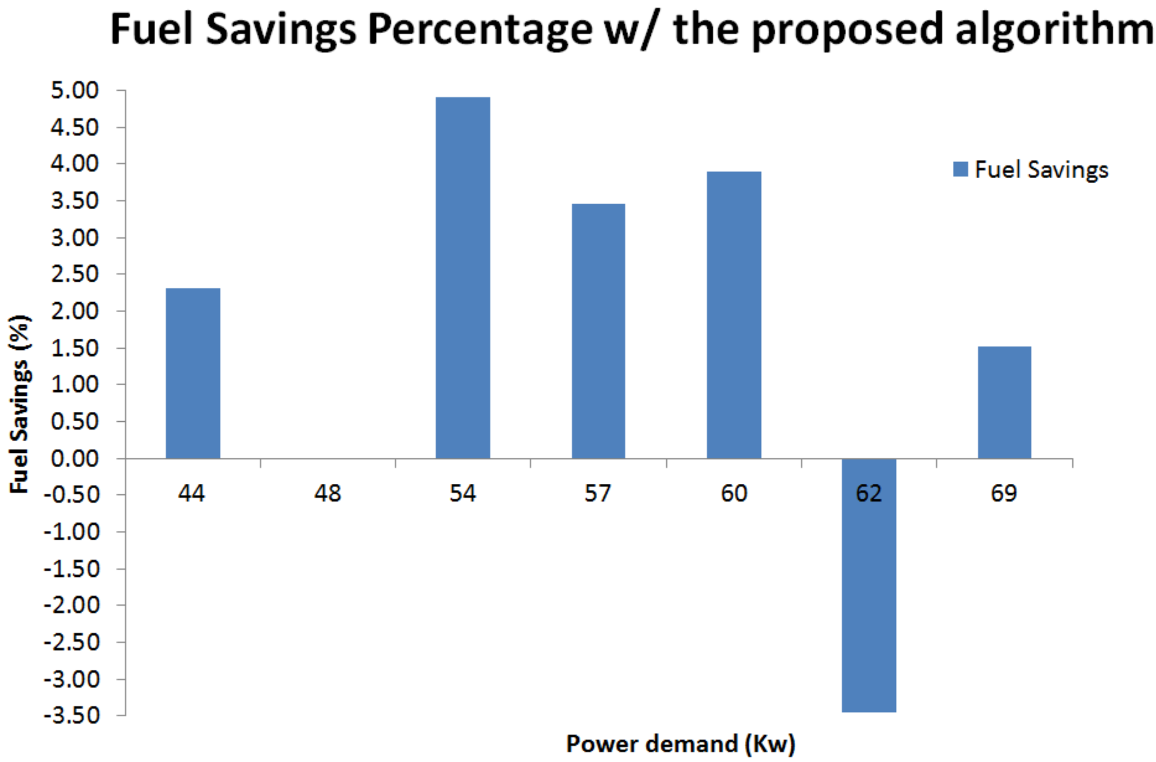


Fig. 43. Experiment results in terms of percentage savings

different actual values. This behavior of the engine affects the performance of the MASCF approach. Future work in this area addresses these impacts and modifies the solutions to handle these concerns. For induced failures, Fig. 48 shows the different power generated at the same RPM than the engine with no induced failures. Similarly, for the fuel pressure, Fig. 49 shows the different power generated at the same RPM than the engine with no induced failures. These behaviours were mainly observed at higher RPMs.

The MASCF approach stores the frequently estimated $\omega_{eng}$ for a given $I_s$ and reuses it to minimize the computation. Therefore, it will improve the execution time of the calculations.

## 5.6 Implementation Approach

Experimental setup is always different from real implementation in a live vehicle. Unlike experimental laboratory, the real vehicle lacks all the instrumentation to validate all the results.

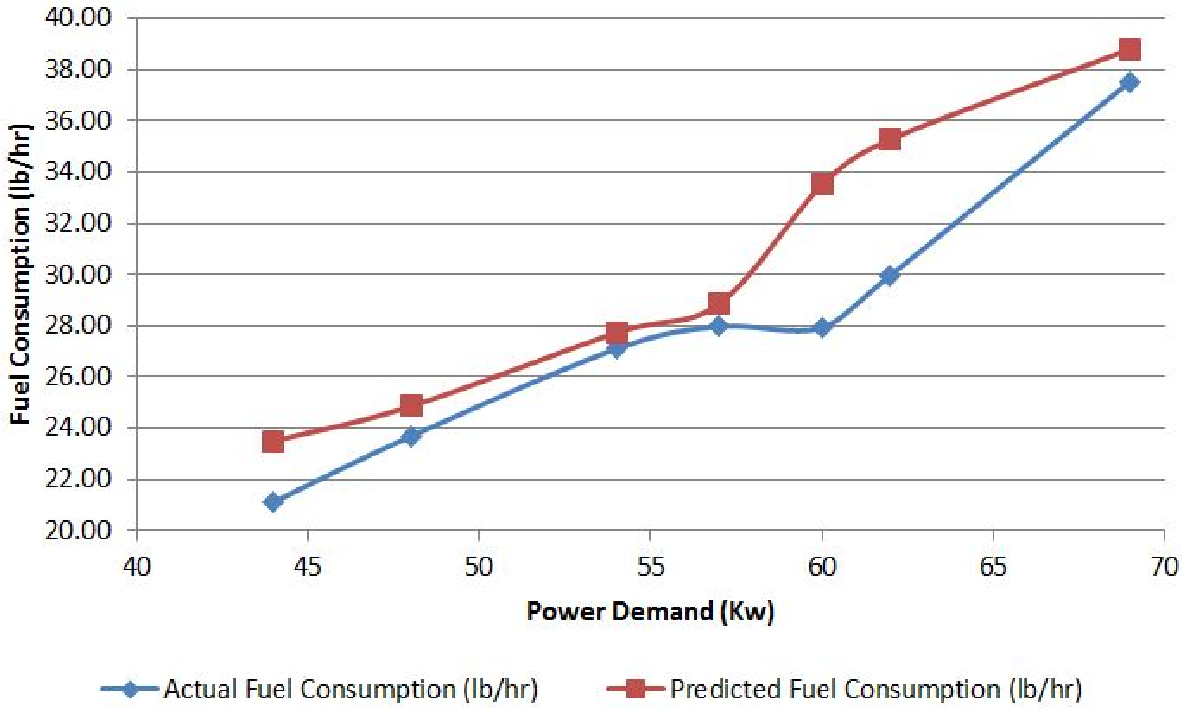


Fig. 44. Predicted vs. actual fuel savings.

Therefore, most of the validation experiments are performed in a lab set up and the strategy is implemented on a real vehicle based on the lab results. An implementation procedure of the proposed energy saving strategy is as follows:

- For a given engine, perform engine experiments and determine fuel consumption values for various horsepower and RPM ranges. Normally, engine and dynamometer setup is used to conduct such experiments.
- Similarly perform alternator experiments and determine the electricity generated for various horsepower and RPM ranges.
- Based on the engine experiments, collect the data for torque (lb-ft), fuel consumption (lb/hr), RPM, and horsepower. Similarly, based on the alternator experiments, collect the data for torque (lb-ft), electricity generated (amperes), and RPM, and horsepower.
- Based on the engine and alternator experiments data develop the fuzzy models as

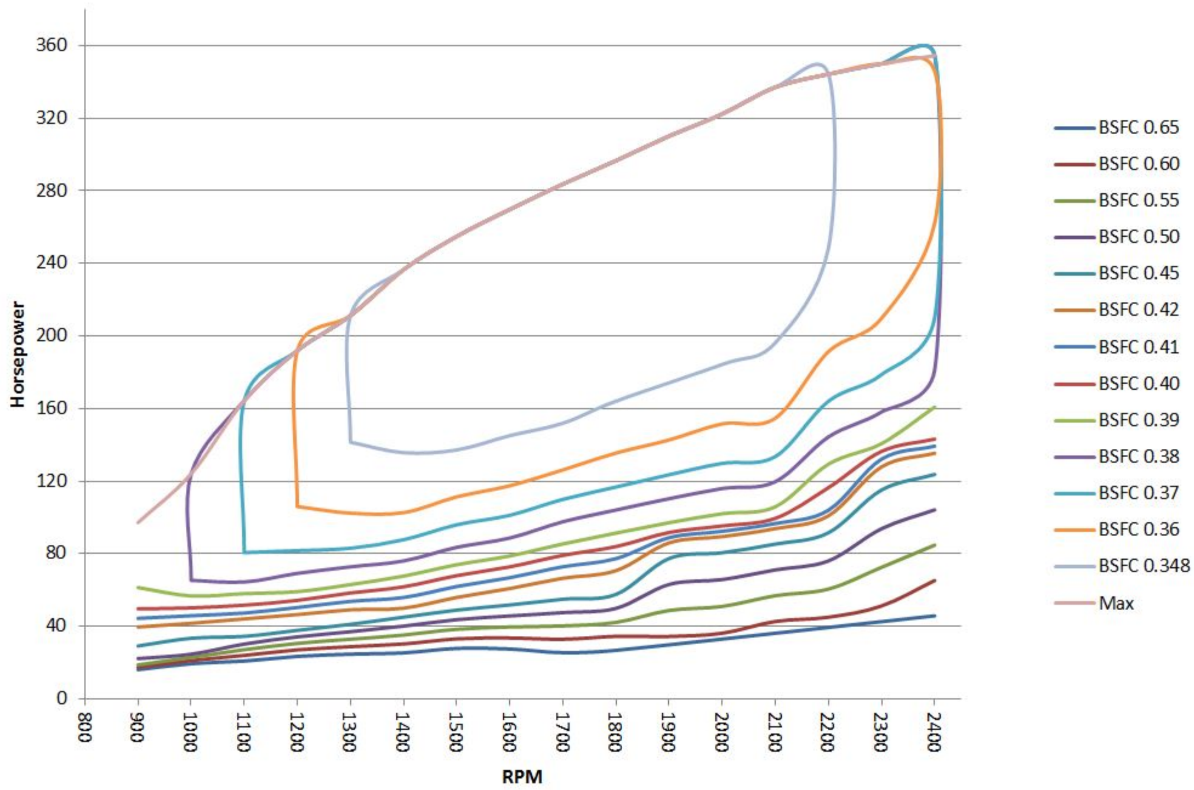


Fig. 45. Fuel map of a given engine.

described in Chapter 5.3.

- Develop MASCF algorithm software using C, C++, Java, or Matlab programming languages.
- Host the software in a simple computer that has a microprocessor and two physical interfaces namely, Ethernet and CAN. Most of the Army ground vehicles may have Ethernet and CAN networks to communicate among the systems in the vehicle.
- Connect the simple computer to the vehicle network for communicating with the systems and the ECU
- Modify the Engine Control Module (ECM) software to receive engine speed input from the CAN bus and to operate the engine at that speed. Since the manufacturer ECM code is proprietary, In a real implementation, a custom ECM software will be developed.
- Allow the software version of the algorithms to communicate with appropriate systems

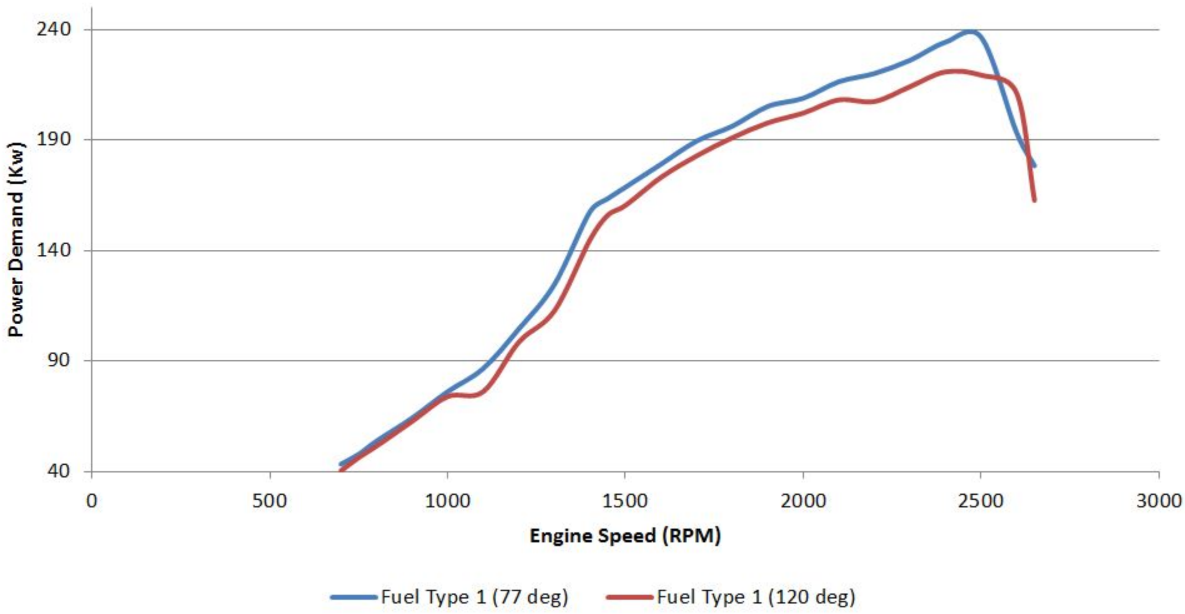


Fig. 46. Fuel type1: temperature impacts on engine power generation

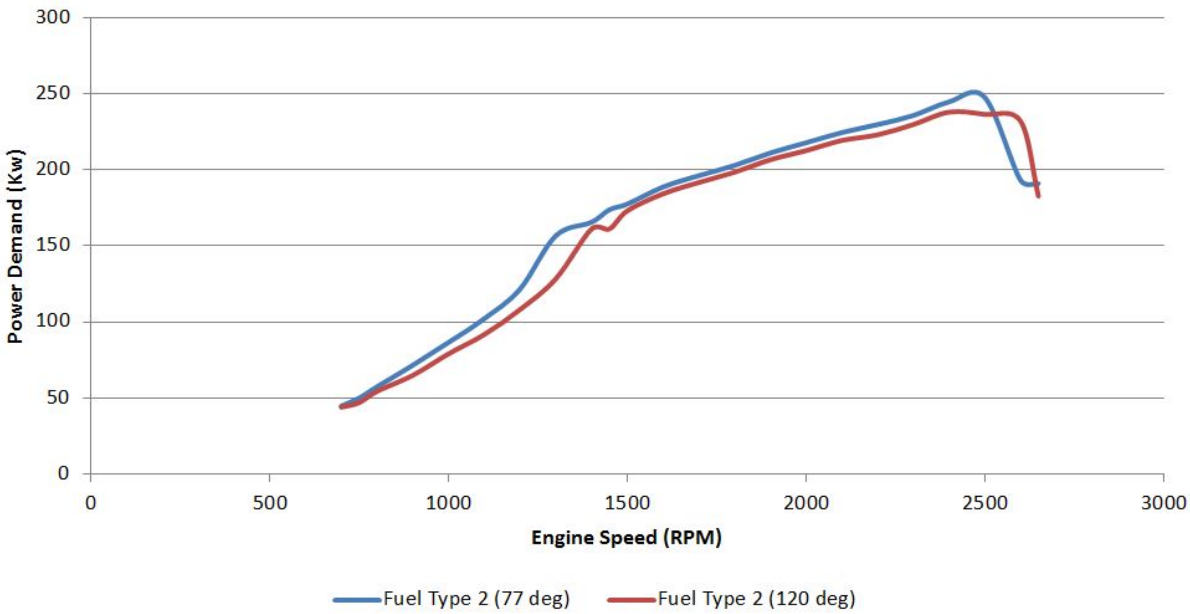


Fig. 47. Fuel type2: temperature impacts on engine power generation

to achieve energy savings using either CAN or Ethernet protocols

- Use a current measuring sensor near the alternator to measure the current draw from

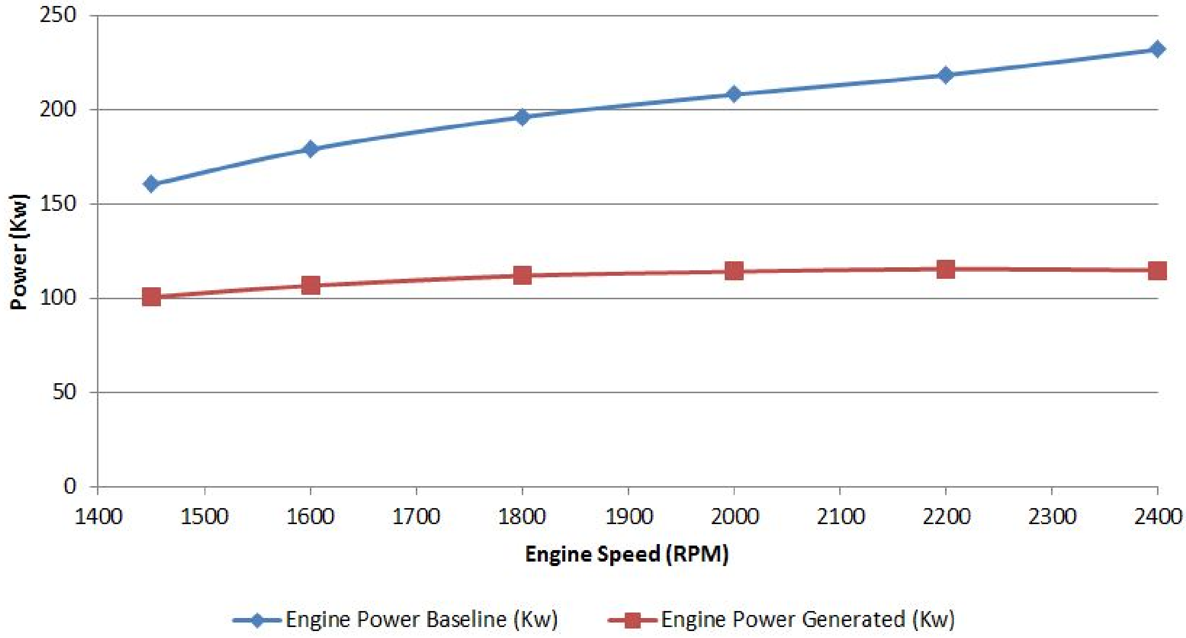


Fig. 48. Induced failures impacts on the engine power generation

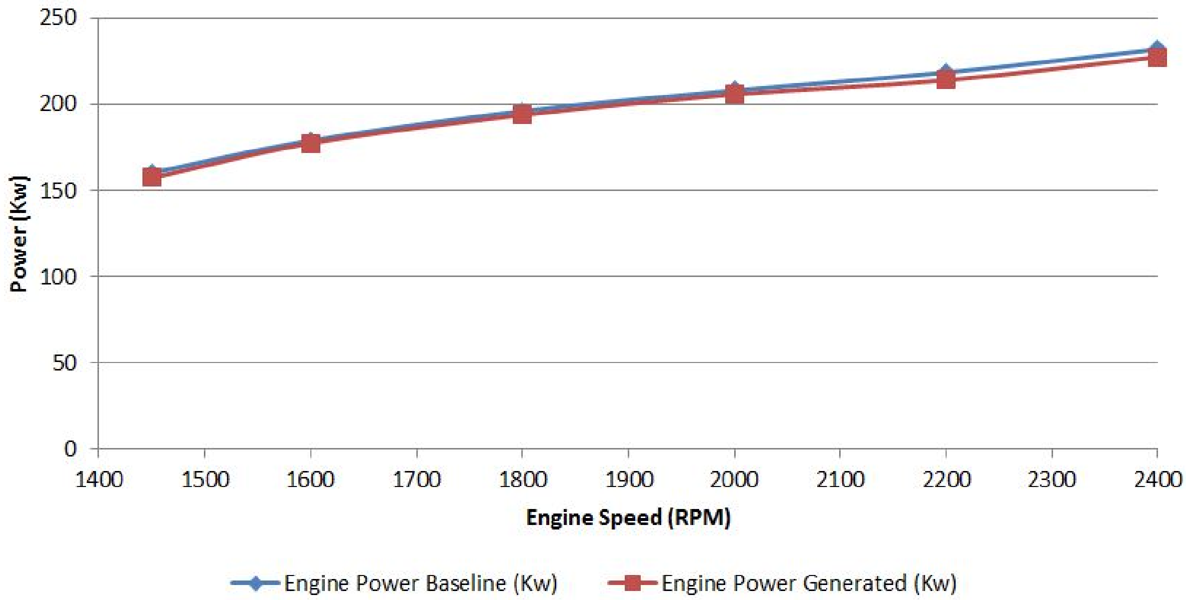


Fig. 49. Fuel pressure impacts on engine power generation

the systems. The sensor shall have a CAN interface to communicate with the CAN bus

- Provide a software function for the driver to switch between the normal operation and the energy saving operation

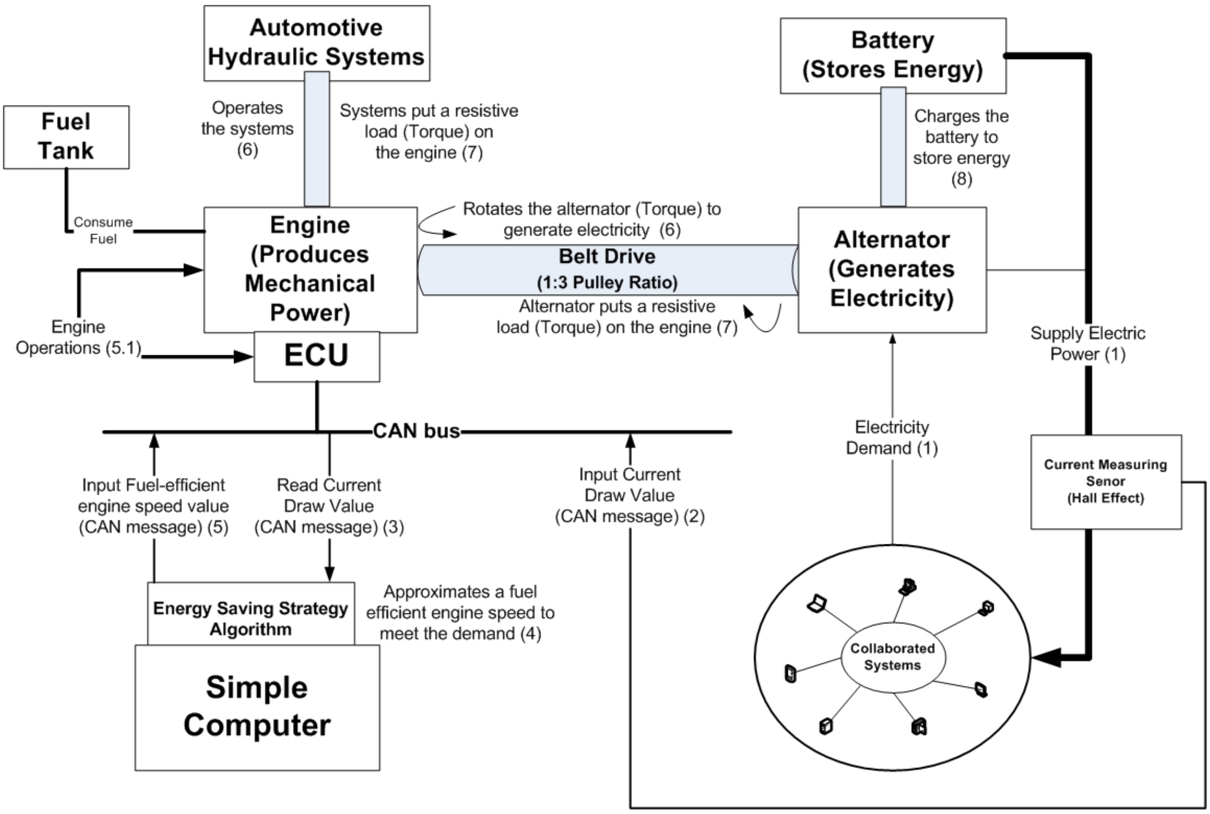


Fig. 50. Normal mode: sequences and events

Fig. 50 shows a schematic of the sequence of events and operations of a conventional Army ground vehicle after implementing the proposed energy saving strategy to save fuel when the engine is on and the vehicle is stationary. The custom software communicating with the ECM is a feedback controller to maintain the engine speeds according to the mission needs. The operation of the proposed energy saving algorithms in a real vehicle is as follows for normal surveillance mission of the vehicle:

- Driver starts the engine and shifts the gear position to either park or neutral. In this situation, the vehicle is not moving.
- The engine drives the alternator to generate electricity. The alternator supplies power to the systems

- The current measuring sensor measures the current drawn from the systems and inputs the measured value to the CAN bus
- The energy saving algorithm software (feedback controller) reads the current sensor input value, approximates a fuel efficient engine speed value and inputs it into the CAN bus
- The ECU reads the engine speed value from the CAN bus and operates the engine at that speed to save fuel and also to meet the demands of the vehicle
- This process continues if the current speed is not sufficient to meet the demand as well as to saving fuel

## 5.7 Summary

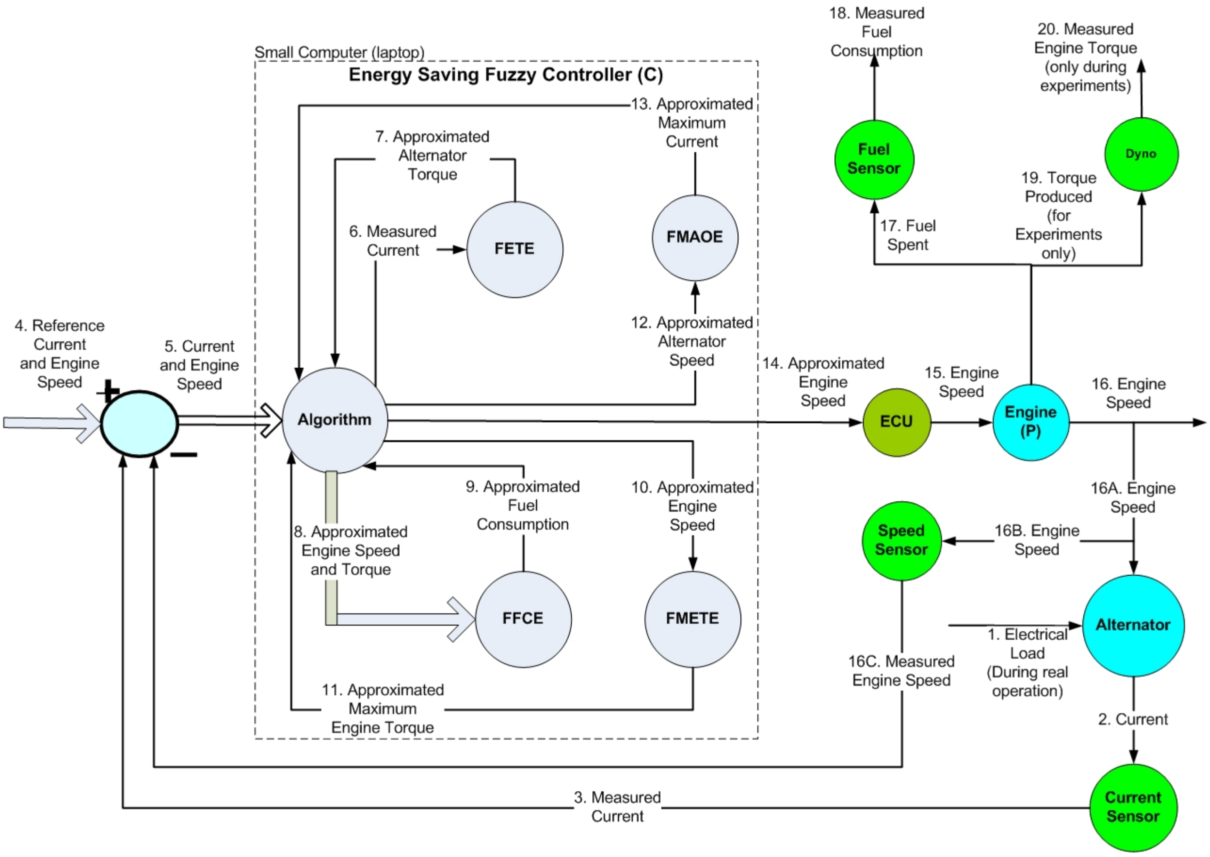


Fig. 51. Line diagram of the MASCF context

The line diagram in Fig. 51 contains an engine, ECU, alternator, dynamometer (dyno), electrical load, and current, engine speed, and fuel consumption measuring sensors. The load is different from non Army ground vehicles. The author has designed a controller (C) that is shown in this diagram. The inputs to the controller are measured electric current (3) and engine speed (16C)values . The diagram of the controller is shown along with a plant (P) and feedback loop. As shown in the figure, the controller has four fuzzy systems namely, Fuzzy Engine Torque Estimator (FETE), Fuzzy Fuel Consumption Estimator (FFCE), Fuzzy Maximum Alternator Output Estimator (FMAOE), and Fuzzy Maximum Engine Torque Estimator (FMETE). The fuzzy systems are modeled based on the measured values of engine torque, engine speed, engine fuel consumption, current, alternator speed, and alternator torque.

During real operations of the vehicle, inputs to the FETE are the measured (during run time) values of alternator produced electric current (3) and engine speed (16C), and the output is the approximated alternator torque value. Inputs to the FFCE are the approximated values of engine speed and torque, and the output is a approximated value of engine fuel consumption. Input to the FMAOE is the approximated value of alternator speed and the output is the approximated value of maximum electric current that the alternator can generate. Input to the FMETE is the approximated value of engine torque and the output is the approximated value of maximum engine torque. The author has written the proposed algorithm using a Matlab program that uses FETE, FMAOE, FMETE, and FFCE fuzzy systems. The algorithm calculates the engine torque and determines the engine speed value(14) that the engine needs to run to save fuel. The algorithm is stored in a small computer as shown in the figure. The algorithm communicates with ECU through CAN bus to control the speed of the engine.

For accurate instrumentation and measurement, the alternator was offline and a dyno with a torque sensor was used for experiments. A user interface was used to input the required engine speed and torque values for the engine to run without the algorithm. Fuel consumption (18), torque produced (20), and engine speed(16C) readings were captured from a user screen.

Horsepower value was calculated using the measured engine speed and the torque values. Calculated horsepower value was specified using the user interface to activate the proposed algorithm and to run engine with the algorithm identified engine speed. Fuel consumption (18), torque produced (20), and engine speed(16C) readings were captured again. The power demand (kW) is calculated based on the measured engine speed and torque for both the options. These readings have the columns of power (kW) and fuel consumption for with and without the proposed algorithm. The readings were plotted as shown in Fig. 42, the graph 1 with the proposed algorithm is better than the graph 2 without the proposed algorithm. Hence there is energy savings.

## 5.8 Conclusion

This chapter described the proposed MASCF approach for saving energy in stationary Army ground vehicles while conducting normal surveillance mission. The application of the MASCF to the ECUs makes engines more efficient than just being a fuel burning machine. The MASCF approach meets the electrical demands of the CV that are within the maximum capacity of the engine and the alternator without stalling the engine. Based on the experiment results, fusing multiple efficiency maps of the engine and alternator using a soft computing approach is beneficial for optimization of engine operations. The results show that the MASCF method consumed 0 - 4.9% less fuel than the CVs with fixed RPM increments for the tested power demands of 44 - 69 kW. However, the results depend on the constraints, namely, fuel type, fuel temperature, and engine failures. Additional research is in progress to address these concepts. Chapter 6.3 describes the future work in this area. The next chapter concludes this dissertation research.

## 5.9 Disclaimer

Disclaimer: Reference herein to any specific commercial company, product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the Department of the Army (DoA). The opinions of the authors- expressed herein do not necessarily state or reflect those of the United States Government or the DoA, and shall not be used for advertising or product endorsement purposes.

# CHAPTER 6 SUMMARY AND CONCLUSION

The previous chapters described the author's work in detail. This chapter summarizes, proposes additional future work, and then concludes this dissertation research.

## 6.1 Introduction

The author of this dissertation research proposed mission aware energy saving strategies for Army ground vehicles. The author also proposed FIA algorithm and fuzzy models to represent engine and alternator performance data. In addition to this, the author also proposed collaborated system model to understand the surveillance mission activities. Section 6.2 summarizes this dissertation and Section 6.3 proposes future work for the proposed solutions.

## 6.2 Summary

Chapter 1 described the detailed background for the proposed dissertation research and the need for saving energy in stationary Army ground vehicles. Army ground vehicles carry several electronic systems to conduct military missions. These systems demand electricity to operate and to conduct mission operations. The demand for the energy varies between 1 to 32 kW. As the electrical energy demand increases, fuel consumption of the vehicle increases. Army surveillance missions and training exercises use ground vehicles for major portions of their operations. Energy saving is very important for the Army to achieve successful missions and to minimize cost. Therefore, to address this need and to provide a solution to save energy, the author of this dissertation research explored the energy saving strategies for stationary Army ground vehicles. The goal was to save energy and to balance the electrical needs of the vehicle.

Chapter 2 described the review of related work in energy saving solutions in networked and distributed systems, and automotive ground vehicles. The approaches in distributed and networked systems do not consider collaborated functions of the systems to minimize energy consumption. Therefore, applying mission aware solutions to them are very difficult and expensive. Energy consumption depends on mission conditions. However, no solution exists in the literature to address mission aware strategies. Existing proposals in the literature address additional power generation solutions than minimizing energy consumption in automotive ground vehicles. Most of the energy saving strategies are applied to moving vehicles rather than stationary vehicles. The approaches lack techniques to handle Army ground vehicle's large power demand variations. These methods may trigger engine stalls if the engine cannot handle the demand. Moreover, most of the existing techniques require altering the physical properties of the vehicle. The proposed solutions in this dissertation have addressed these gaps and introduced the concept of mission aware energy saving strategies for stationary Army ground vehicles.

Chapter 3 described the theory and its associated models to represent surveillance mission operations. Surveillance missions are complex and random. To address the mission aware energy saving strategies for Army ground vehicles, this dissertation research has proposed novel theoretical models namely, surveillance, collaborated system, systems usage algorithm, and surveillance energy consumption models. These models can be applied to any collaborated systems such as sensor networks, data centers, and event driven systems.

Chapter 4 and 4.4 described proposed mission aware energy saving strategy for silent surveillance missions of a stationary Army ground vehicle and FIA, respectively. The strategy minimizes battery discharges based on mission conditions without degrading the performance of the mission. The minimized battery discharge extends the duration of a mission. The computer simulations and a battery test show that the proposed approach minimizes battery discharge based on the needs of a mission without affecting the operational performance of the systems. Therefore, it extends the duration of a silent surveillance mission that results in a successful mission. The proposed energy saving strategy applies the surveillance mission models and the proposed FIA.

Chapter 5 described the energy saving strategy for normal surveillance missions. The proposed energy saving strategy for normal surveillance missions saves fuel energy in stationary Army vehicles. The application of this approach runs the engines efficiently during normal stationary surveillance missions. The approach balances energy demands of the vehicle without stalling the engine. The rule-based fuzzy efficiency maps of the engine and alternator is beneficial for the optimization of engine operations. Performance of the proposed approach depends on the constraints namely, fuel type, fuel temperature, and engine failures.

Several approaches such as fuzzy logic, adaptive neuro fuzzy, neural network, and factor analysis were studied and analyzed for the proposed solutions. However, complications and limitations of several approaches hinder their application to the mission aware energy saving strategies of Army ground vehicles. The simple fuzzy logic based solution perform better than other complicated and time consuming approaches.

## 6.3 Future Work

The previous chapters described the proposed energy saving strategies for stationary Army ground vehicles. This section describes the possible future work to enhance the applicability of the proposed solutions.

### Electro-chemical Properties and Energy Savings

This section describes the future work to understand the impacts of electro-chemical properties of a battery on energy savings. Chapter 3 and Chapter 4 introduced the concept of mission awareness and its application to an energy saving strategy for silent surveillance missions. This dissertation research studied the application of the proposed strategy for two common silent surveillance mission scenarios. For each scenario, the study used a lead acid type of battery. The performance of different battery chemistries vary. Future work related to this topic can be to conduct experimentation for multiple electro-chemical batteries. In addition, the future work can understand the energy savings behavior in multiple different silent surveillance mission scenarios. The information can be used to optimize the proposed strategy to handle any battery type. The energy saving strategy for silent surveillance mission is validated using a simulation setup and a battery laboratory. The future work can be to implement it on a mock up of real vehicle setup including the software controlled power distribution system.

## Battery Temperature and Energy Savings

This section describes the future work to understand the impacts of temperature of a battery on energy savings. Chapter 4 introduced the energy saving strategy for silent surveillance missions. This dissertation research studied the application of the proposed strategy for two common silent surveillance mission scenarios. For each scenario, the study used three temperature ranges i.e., 25, 40, -10 $^{o}$ Centigrade. The performance of different battery chemistries can vary depending on temperature variations. Battery performance degrades in cold temperatures and it can be dangerous at high temperatures. Both the chemical property and the temperature are very important factors that can significantly change energy consumption behaviors of a battery. Future work related to this topic can be to conduct experimentation for multiple temperature ranges. In addition, the future work can understand the energy savings behavior in multiple different silent surveillance mission scenarios. The information can be used to optimize the proposed strategy to handle any temperature ranges. The energy saving strategy for silent surveillance mission is validated using a simulation setup and a battery laboratory. The future work can be to implement it on a mock up of real vehicle setup including the software controlled power distribution system.

## Power Budgets and Energy Savings

In Army ground vehicles, electronic systems use electrical power to operate. The power budgets for different surveillance mission scenarios must be developed. For the budget for each scenario, the overall power consumption will consist of peak, average, and low power cycles. Each storage media will exhibit different properties in meeting a power budget scenario. Some electro-chemical property of a battery has great energy density but its voltage supply rapidly falls off at certain points of the battery being drained, other electro-chemistries behave differently in those scenarios. Some rechargeable electro-chemistries perform better than others when they are placed under high power loads. In applications and scenarios where there is a limited amount of stored energy and priorities need to be placed on maintaining a reserve of energy stored for emergency situations, Energy Management Systems must take into consideration both the energy source properties of the energy storage device as well as the consumption properties of the various loads. In future work, the energy strategy implementation can include the various available electro-chemistries as a parameter to manage the behavior of the battery to the various power budget scenarios. The implementation of this approach has challenges in the electrical distribution system. Therefore, the future work must understand the electrical infrastructure before implementing it on any platforms.

## Fuel Type and Temperature and Energy Savings

Chapter 5 introduced the concept of using alternator and engine performance map to develop fuzzy models to propose an energy saving strategy for normal surveillance missions. The current work was validated using an engine-dynamometer setup. The future work in this area can be to apply the results of the experiment and implement it on a real vehicle setup using an intelligent implementation architecture and an electronic chip that represents the solution. Chapter 5 also introduced the concept of mission aware energy saving. However, the proposed solution for the normal surveillance mission has a major dependency on fuel type, fuel temperature, and engine failures. In this dissertation, these items were not addressed in detail. The future work in this area can be to investigate and resolve the impacts of these elements on the real implementation of the vehicles. The future work can also leverage the results of the proposed solutions to extend them to different engine or alternator types. Additionally, the future work can understand the implications of extending this research to police cruisers and other vehicle platforms where multiple systems are operated while the vehicle is stationary.

## Mission Planning

Chapter 3 introduced the collaborated system model and other related theoretical models of surveillance missions. Chapter 4 discussed the application of these models to energy saving strategies. Future work in this area can extend the results to optimize other functionalities of the Army ground vehicles namely, mission planning, mission performance, and workflow management. This dissertation research addresses energy saving algorithms for stationary Army ground vehicles during surveillance missions. However, the future work could provide features to allow mission planners to simulate possible mission scenarios before the actual missions and provide soldiers training to handle unexpected situations under power constraint.

## Pipelined Fuzzy Controller

Chapter 4 and Chapter 5 proposed energy saving strategies using a normal fuzzy controller. In the future, it can be extended to develop pipelined fuzzy controller. Pipeline approach reduces the execution time and increases the performance of the proposed algorithms. However, it complicates the controller design due to timing and interrupt constraints of the CAN bus. The vehicle architecture has to consider all the possible constraints of the pipelined approach and develop solutions to handle them.

## Power - Fuel Consumption - Emissions Metric

Development of energy efficient automotive products such as alternators and batteries are challenged due to the lack of published engine metrics. To obtain the necessary performance information, the vendors perform their own experiments of the engine. However, the Power-Fuel Consumption-Emissions (PFE) of an engine varies from one RPM to the other. In addition, at a given RPM, the PFE of an engine varies from one manufacturer to the other. Therefore, a single measure is required to represent the engine PFE at various RPMs. To address this shortfall, the future work performs research related to relative engine PFE metric. The PFE metric can leverage the algorithms defined in [105, 106, 107]. Engine experiments provide a data set for defining the metric. However, the data is multidimensional due to multiple sensor inputs. A statistical approach such as factor analysis can be used to derive interrelationship between the sensor data to a common set of factors to develop relative engine PFE metric. Chapter 2.4 introduced the concept of factor analysis. The metric can represent a common measurement for engine performance. This information can be used to compare multiple engines at a given RPM or performance of an engine at different RPMs. For example, for a given RPM X, assume an engine A has a -10 relative engine PFE metric value and engine B has -5. Engine A seems to have less negative impact on the overall engine PFE. Therefore, between the two, engine A is a better choice than engine B at RPM X. The metric enables the comparison of multiple engines at a given RPM. This aids the designers to choose appropriate efficient RPMs or the engines while developing fuel efficient products. The concept of relative PFE metric is to provide a single measure of PFE values of an engine. The relative PFE metric arranges the PFE values all RPMs or engines in the increased PFE impact in relation to each other. For a given RPM, if the relative PFE value is greater than any other RPM, the overall engine PFE increases at that RPM. This metric can be used as a tool early in the product design phase to understand the impact of each RPM or the engine on the product's fuel efficiency.

### Non Stationary Vehicle and Energy Savings

The proposed strategies are currently studied for stationary vehicles. Similar approaches can be easily extended to a moving vehicle also. However, there are additional constraints hinder the application of this approach to a mobile vehicle. The future work can address those challenges and develop an universal algorithm to handle both stationary and non stationary vehicles. When the vehicle is moving, the size and weight of the vehicle significantly affect the energy consumption of the vehicle. The size and weight of the vehicle should be included in the future algorithms to handle a moving vehicle's energy savings. The size and weight are very important factors that can significantly change energy consumption of a vehicle. In addition to size and weight constraints, the approach should take into account of transmission impacts.

## 6.4 Conclusion

In conclusion, the silent surveillance mission aware energy saving strategy for Army ground vehicles saves 3% energy in comparision to the baseline approach for one type of mission scenario and 1.8% for the second type of mission scenario. Similarly, the normal surveillance mission aware energy saving strategy saves fuel energy in the range of 0 - 4.9% when compared with the baseline approach. The work described in this dissertation has proposed several future problems to enhance the proposed solutions.

# APPENDIX A

## Fuzzy Logic

The figures below show some of the snapshot of the fuzzy systems proposed in this dissertation. Fig. 52 and Fig. 53 shows the fuzzy inference model of the alternator efficiency and engine efficiency, respectively. Input and output membership variables are shown in the pictures.

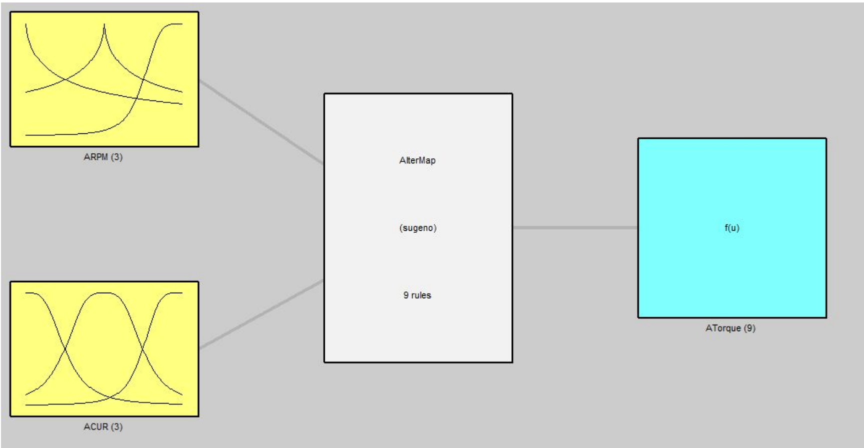


Fig. 52. Fuzzy inference system for alternator efficiency.

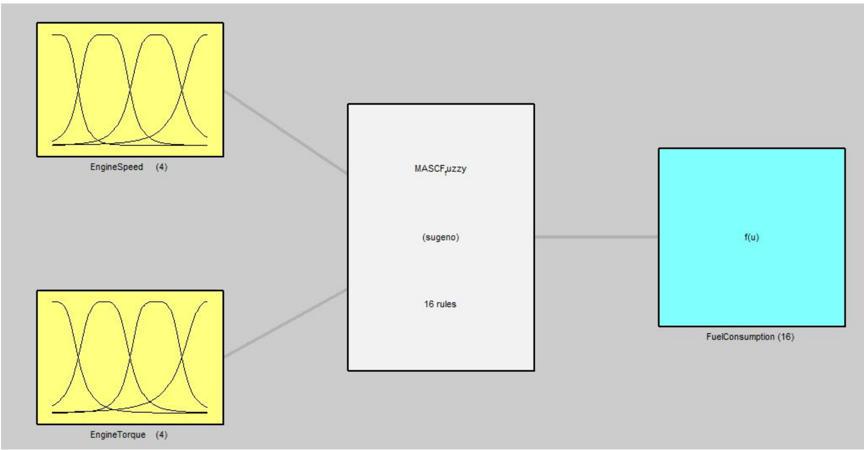


Fig. 53. Fuzzy inference system for engine efficiency.

Fig. 54, Fig. 55, Fig. 56 shows the fuzzy inference process for a sample input for alternator efficiency, engine efficiency, and engine maximum torque fuzzy models, respectively.

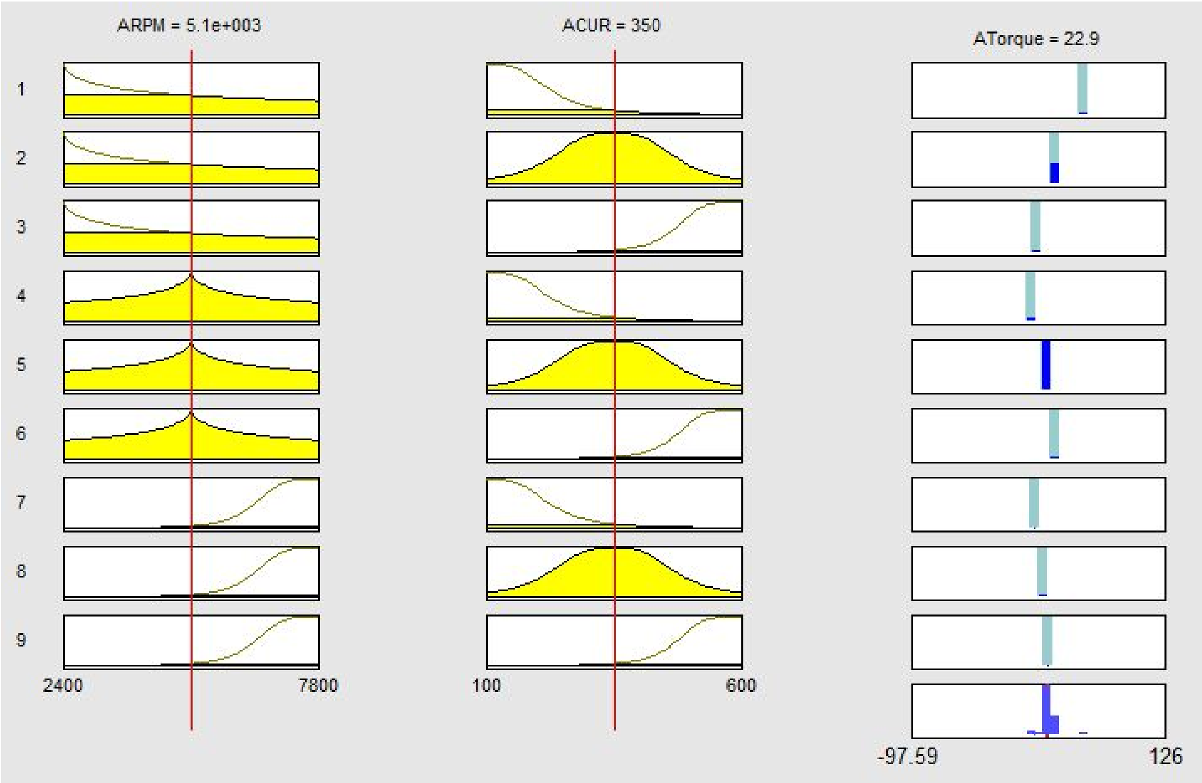


Fig. 54. Fuzzy inference for alternator efficiency.

Fig. 57 and Fig. 58 shows the fuzzy surface view for maximum engine torque, and maximum alternator current, respectively.

## MASCF Matlab Code

function readFuzzyEngines()

Location of all the fuzzy inference engines

fuzpath = './FuzzyEngines/';

global AMap MASCF MXTrq MxCur;

Read the fuzzy inferences. This will be stored as global variables so that the GUI can use


Fig. 55. Fuzzy inference for engine efficiency.

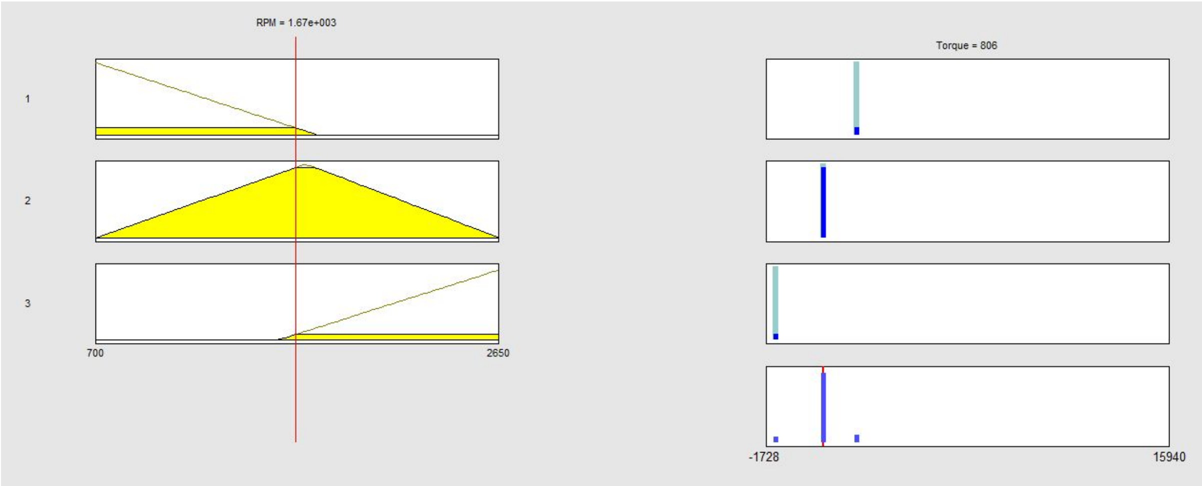


Fig. 56. Fuzzy inference for maximum engine torque.

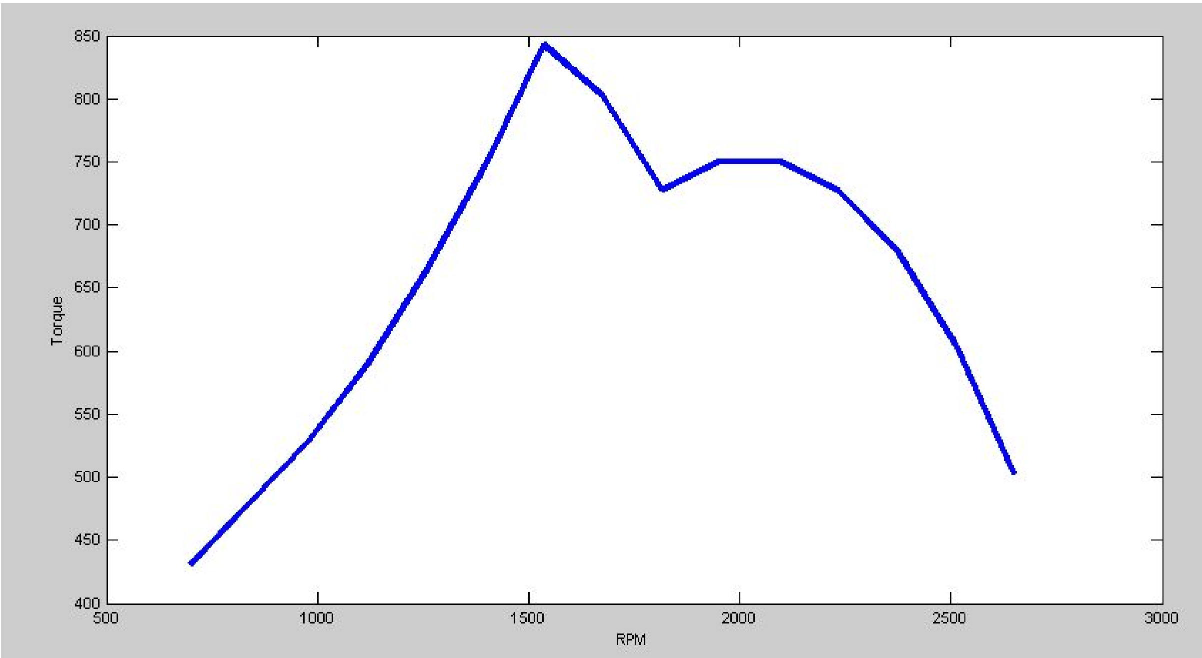


Fig. 57. Surface viewer for the fuzzy max engine torque.

it without reading the files frequently.

AMap = readfis(strcat(fuzpath,'AlterMap'));

MASCF= readfis(strcat(fuzpath,'MASCFFuzzy'));

MXTrq=readfis(strcat(fuzpath,'MaxTorqueRPM'));

MxCur=readfis(strcat(fuzpath,'MaxCurrentARPM'));

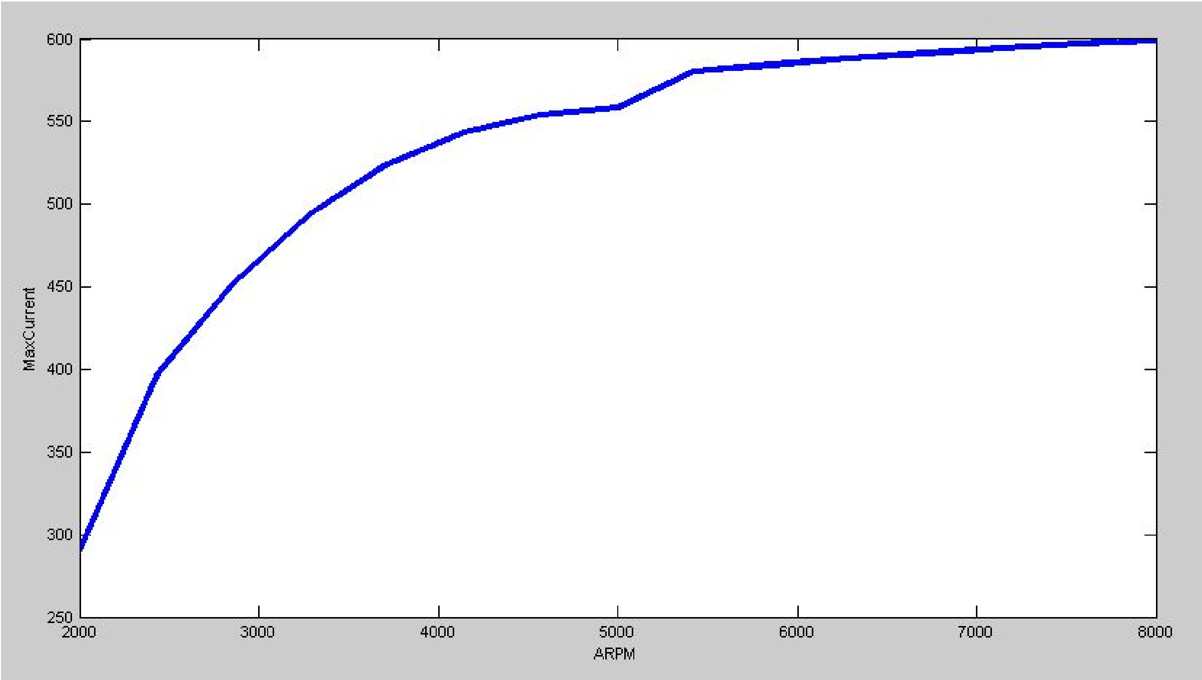


Fig. 58. Surface viewer for the fuzzy max alternator current.

return;

function findFuelEfficientRPM(handles)

global Espeed Efuelcon ETorque;

global AMap MASCF MXTrq MxCur;

global Hauto Rmin Rmax Rinc Is Teng;

engSpeed=0;

F=0;

Hauto = str2num(whatsThePopupValue(handles.Autohppopup));

Rmin = str2num(whatsThePopupValue(handles.MinRPMpopup));

Rmax = str2num(whatsThePopupValue(handles.MaxRPMpopup));

Rinc = str2num(whatsThePopupValue(handles.RPMIncpopup));

Is = str2num(whatsThePopupValue(handles.Demandpopup));

Iter = Rmin;

if strcmp(get(get(handles.uipanel4,'SelectedObject'),'Tag'),'rdodataacq')

Hauto = str2num(get(handles.edtHorsepower,'string'));

Is = str2num(get(handles.edtDemand,'string'));

end

while(Iter<=Rmax)

validate if the input is beyond range end beyond range Engine torque calculation

Talt = (evalfis([Iter*3, Is],AMap))/1.356;

if Talt <0

Talt = Talt*(-1);

end Approximate Talt using FETE (Is; w13);

Tauto = (Hauto * 5252)/Iter;

Teng = 3.2*(Talt) + 1.2*(Tauto);

Fuel consumption calculation. Determine if a given rpm can handle Teng

Imax = evalfis(Iter*3,MxCur);

if Imax > Is

Tmax = evalfis(Iter,MXTrq);

if Teng<=Tmax

Fc = evalfis([Iter Teng], MASCF);

if F==0 || Fc <=F

F = Fc;

engSpeed = Iter;

```
etoruq = Teng;
end
end
end
Iter = Iter + Rinc;
end
Espeed = engSpeed;
Efuelcon = F;
ETorque = etoruq;
```

## Adaptive Neuro Fuzzy Inference System (ANFIS)

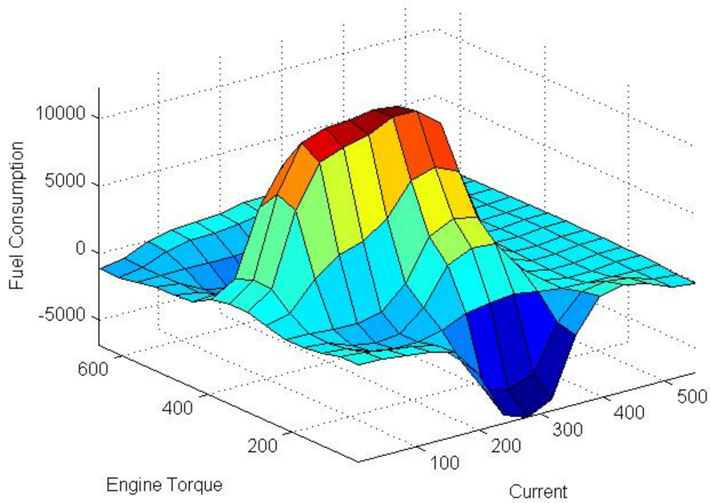


Fig. 59. ANFIS approach: fuzzy consumption distribution.

## ANFIS Matlab Code

This code is used to develop an ANFIS model to determine the fuel effficient engine speed using ANFIS.

TABLE X
ANFIS: ENGINE SPEEDS AND FUEL CONSUMPTION

| Current Draw (Amperes) | MASCF (RPM) | MASCF (lb/hr) | Baseline Engine (RPM) | Baseline Engine (lb/hr) | High-idle RPM Increments | High-idle RPM Increments (lb/hr) |
|---|---|---|---|---|---|---|
| 350 | 800 | 16.6 | 800 | 24.87 | 800 | 24.87 |
| 400 | 850 | 17.7 | 800 (stalls) | (stalls) | 1200 | 36.12 |
| 450 | 950 | 18.5 | 800 (stalls) | (stalls) | 1200 | 33.29 |
| 500 | 1150 | 20 | 800 (stalls) | (stalls) | 1200 | 30.43 |

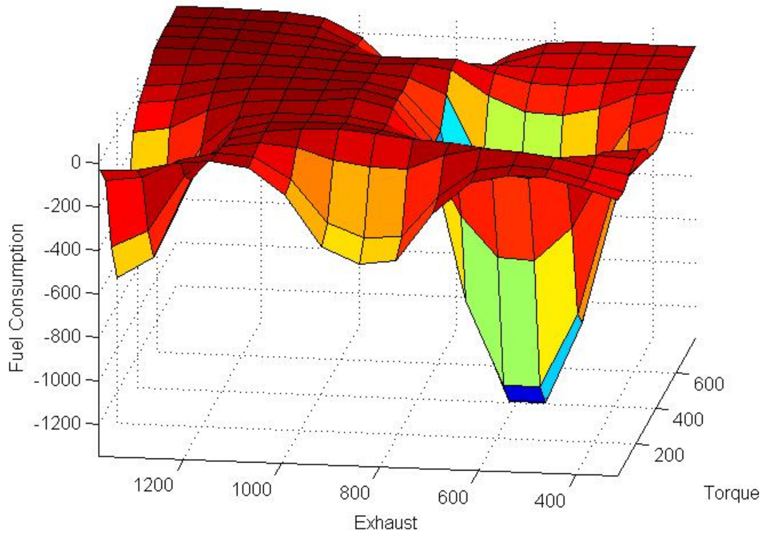


Fig. 60. ANFIS approach: fuel consumption distributionI.

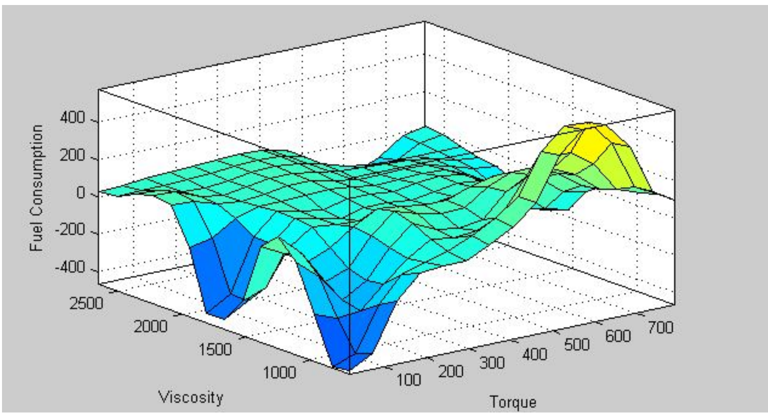


Fig. 61. ANFIS approach: fuel consumption distributionII.

List of all the data used for the ANFIS modeling. The last column is the output.
anfisdatanames = str2mat('Current','Alternator Torque','Automotive Torque','Engine Torque','Engine Speed','Fuel Consumption');

Load the data used for the modelling.
load MASCFNeuroFuzzy.mat;
database = MASCFNeuroFuzzy;

Separate the training and check data from the main data set
trainingdata = database(1:2:end,:);
checkingdata = database(2:2:end, :);

start with three inputs
inputindex = [1 4 5];
newtrndata = trainingdata(:, [inputindex, size(trainingdata,2)]);
newchkdata = checkingdata(:, [inputindex, size(checkingdata,2)]);

Create the Fuzzy Inference System
firstfis = genfis1(newtrndata, 5, 'gbellmf'); [firstfistrainout trnerror stepsize finalfirstis chkerror] = anfis(newtrndata, firstfis, [100 nan 0.01 0.5 1.5], [1,1,1,1], newchkdata, 1);

[a, b] = min(chkerror);
plot(1:100, trnerror, 'g-', 1:100, chkerror, 'r-', b, a, 'ko');
title('Training (green) and checking (red) error curve');
xlabel('Epoch numbers');

ylabel('RMS errors');

Analyzing the ANFIS Model

a = getfis(finalfirstis,'Numinputs')

for i=1:a

finalfirstis = setfis(finalfirstis, 'input', i, 'name', anfisdatanames(inputindex(i),:));

end

finalfirstis = setfis(finalfirstis, 'output', 1, 'name', anfisdatanames(end,:));

gensurf(finalfirstis);

## Factor Analysis

The engine experimental data set had 10 sensor input values. A statistical factor analysis approach was used to reduce the data set to seek the minimum number of underlying correlated factors. Factor loadings in 62 - 63 show how much a particular variable contributes to the extracted factor. If the contribution of variable towards a factor is more influential, the loadings value will be high. If it is less influential then the value will be small. Based on the loadings factors can be labelled.

| Variable | Factor1 | Factor2 | Factor3 | Communality |
|---|---|---|---|---|
| Torques | 0.826 | 0.212 | -0.510 | 0.988 |
| fuel con | 0.973 | -0.134 | -0.087 | 0.972 |
| manifoldd | 0.966 | -0.135 | -0.060 | 0.954 |
| exhausts | 0.825 | 0.270 | -0.432 | 0.941 |
| compresss | 0.882 | -0.339 | 0.233 | 0.948 |
| throttle | 0.784 | -0.329 | 0.044 | 0.725 |
| pressure | -0.488 | -0.775 | -0.326 | 0.945 |
| viscos | -0.540 | -0.722 | -0.369 | 0.948 |
| Speed | 0.714 | -0.487 | 0.452 | 0.951 |
| Variance | 5.6739 | 1.7369 | 0.9610 | 8.3718 |
| % Var | 0.630 | 0.193 | 0.107 | 0.930 |

Fig. 62. Unrotated factor loadings and communalities

Based on the factor analysis, five factors seem to cover 98.2 % of the covariances. How-

| Variable | Factor1 | Factor2 | Factor3 | Communality |
|---|---|---|---|---|
| Torques | 0.242 | -0.942 | 0.205 | 0.988 |
| fuel con | 0.723 | -0.646 | 0.180 | 0.972 |
| manifoldd | 0.731 | -0.620 | 0.189 | 0.954 |
| exhausts | 0.243 | -0.893 | 0.289 | 0.941 |
| compresss | 0.914 | -0.306 | 0.138 | 0.948 |
| throttle | 0.756 | -0.390 | 0.021 | 0.725 |
| pressure | -0.054 | 0.206 | -0.949 | 0.945 |
| viscos | -0.139 | 0.195 | -0.944 | 0.948 |
| Speed | 0.973 | -0.007 | 0.067 | 0.951 |
| Variance | 3.5496 | 2.8143 | 2.0078 | 8.3718 |
| % Var | 0.394 | 0.313 | 0.223 | 0.930 |

Fig. 63. Rotated factor loadings and communalities- Varimax rotation

| Variable | Factor1 | Factor2 | Factor3 | Factor4 | Factor5 | Communality |
|---|---|---|---|---|---|---|
| Torques | 0.199 | -0.935 | 0.207 | 0.138 | 0.127 | 0.993 |
| fuel con | 0.698 | -0.654 | 0.173 | 0.166 | 0.143 | 0.994 |
| manifoldd | 0.716 | -0.634 | 0.180 | 0.133 | 0.132 | 0.982 |
| exhausts | 0.199 | -0.905 | 0.287 | 0.153 | -0.173 | 0.994 |
| compresss | 0.905 | -0.324 | 0.126 | 0.153 | 0.133 | 0.982 |
| throttle | 0.553 | -0.340 | 0.048 | 0.759 | 0.003 | 0.999 |
| pressure | -0.047 | 0.197 | -0.952 | -0.044 | -0.050 | 0.952 |
| viscos | -0.146 | 0.200 | -0.941 | -0.015 | 0.040 | 0.949 |
| Speed | 0.954 | -0.040 | 0.052 | 0.210 | -0.174 | 0.990 |
| Variance | 3.1400 | 2.8244 | 2.0008 | 0.7334 | 0.1358 | 8.8345 |
| % Var | 0.349 | 0.314 | 0.222 | 0.081 | 0.015 | 0.982 |

Fig. 64. Rotated five factor loadings and communalities- Varimax rotation

ever, it did not choose torque as one of the variables with high influence. Without a torque, it is not possible to determine the speed.

Another factor analysis algorithm was used to determining three factors to represent the engine data:

- In a given engine and dynomometer setup, run the engine at several RPMs in increments of 100 starting from an idle RPM until engine's maximum speed. At each RPM,measure the maximum horsepower the engine generated, fuel consumption, and emissions data.
- Populate the measured data in an input file $I_f$.
- Read the input file $I_f$ and perform factor analysis using Kaiser's Varimax rotation and principle component extraction method and determine the rotated factor loadings ($R_{fl}$), variance ($V_f$), and inverse of correlation ($C_{inv}$) matrices for three factors. Name the three factors as horsepower , fuel consumption, and emission. Define a matrix consisting

of Varimax rotated factor loadings.

- Based on the inverse of correlation matrix $C_{inv}$ and factor loadings matrix compute a transformation matrix $T_m$ based the equation 6.1

$$T_m = C_{inv} * R_{fl} \tag{6.1}$$

- Compute a normalized matrix $N_{in}$ of the input file $I_f$

The algorithm was leveraging the work performed by [105, 106, 107]. The algorithm starts with collecting engine experiment data and applying factor analysis process to find the most three factors that represent the underlying structure of the entire dataset. The Table XIV shows the first output of the factor analysis in terms of correlation coefficients to represent the bivariate relationship between different sensor data values of engine RPMs. The factor analysis with principle component extraction and Varimax rotation produced three distinct factors to represent data from the six sensors. Table XIII shows the three factors along with its rotational loading. The three factors used were the horsepower, fuel consumption, and emissions. Factor one consists of engine RPM and torque, factor two consists of fuel consumption, and factor three consists of emission sensor data. With the factor analyzed data, there was no easy way to determine fuel efficient engine speed based on inputs.

## Artificial Neural Network (ANN)

## Fuzzy System as a Communication Network

Fuzzy modeling is based on human expertise of the system behavior using rule based techniques. There are a lot of fuzzy modeling methods exists in the literature. They are very successful in applying to the modern control applications. However, they require precise understanding of the subject matter for modeling the systems efficiently. To gain such expertise, many researchers perform several iterations of trial and error methods to understand

TABLE XI
NORMALIZED INPUT DATA

| RPM | Torque | Fuel Consumption | Emission1 | Emission2 | Emission3 |
|---|---|---|---|---|---|
| 0.265 | 0.545 | 0.187 | 0.831 | 1.000 | 1.000 |
| 0.302 | 0.593 | 0.221 | 1.000 | 0.989 | 0.991 |
| 0.340 | 0.631 | 0.260 | 1.000 | 0.989 | 0.991 |
| 0.378 | 0.673 | 0.306 | 1.000 | 0.989 | 0.991 |
| 0.415 | 0.700 | 0.383 | 0.781 | 0.989 | 0.991 |
| 0.453 | 0.773 | 0.456 | 0.717 | 0.989 | 0.993 |
| 0.491 | 0.853 | 0.525 | 1.000 | 0.989 | 0.996 |
| 0.529 | 1.000 | 0.622 | 1.000 | 0.990 | 0.991 |
| 0.566 | 0.999 | 0.656 | 1.000 | 0.990 | 0.990 |
| 0.604 | 0.994 | 0.695 | 1.000 | 0.990 | 0.990 |
| 0.642 | 0.989 | 0.727 | 1.000 | 0.990 | 0.991 |
| 0.679 | 0.968 | 0.764 | 1.000 | 0.990 | 0.991 |
| 0.717 | 0.958 | 0.799 | 1.000 | 0.990 | 0.991 |
| 0.755 | 0.928 | 0.818 | 1.000 | 0.990 | 0.992 |
| 0.793 | 0.915 | 0.851 | 1.000 | 0.986 | 0.989 |
| 0.830 | 0.887 | 0.872 | 1.000 | 0.986 | 0.991 |
| 0.868 | 0.872 | 0.911 | 1.000 | 0.990 | 0.989 |
| 0.906 | 0.866 | 0.944 | 1.000 | 0.990 | 0.990 |
| 0.981 | 0.781 | 1.000 | 1.000 | 0.990 | 0.993 |
| 1.000 | 0.599 | 0.831 | 1.000 | 0.993 | 0.989 |

TABLE XII
EIGENVALUES

| var | Eigenvalue |
|---|---|
| 1 | 3.371168117 |
| 2 | 1.038246862 |
| 3 | 0.685012571 |
| 4 | 0.616937539 |
| 5 | 0.286626525 |
| 6 | 0.002008386 |

the different rules that exhibit the behavior of producing the required outputs. This is a time consuming process. Moreover, if the rules need to be changed or added, then the whole system has to be revisited. Retrofitting the model may become complex.

Machine learning techniques such as neural network and ANFIS perform several iterations of learning the input and output data in various forms and generate a model. This model can be used to populate the output based on the inputs. Although this method is quite popular,

TABLE XIII
VARIMAX ROTATATION LOADINGS THREE FACTORS

| **Horsepower** | **Fuel Consumption** | **Emission** |
|---|---|---|
| 0.89965 | 0.06679 | 0.32771 |
| 0.57437 | 0.61431 | -0.07030 |
| 0.94299 | 0.22514 | 0.22559 |
| 0.24966 | 0.16863 | 0.87113 |
| -0.05128 | -0.91610 | -0.17758 |
| -0.25689 | -0.65817 | -0.49794 |

TABLE XIV
CORRELATION MATRIX AND EIGENVALUES

| **corr1** | **corr2** | **corr3** | **corr4** | **corr5** | **corr6** |
|---|---|---|---|---|---|
| 1 | 0.385465199 | 0.958822846 | 0.428832457 | -0.231654889 | -0.493846274 |
| 0.385465199 | 1 | 0.62184277 | 0.368903276 | -0.460463005 | -0.396964303 |
| 0.958822846 | 0.62184277 | 1 | 0.451486502 | -0.324474362 | -0.500071296 |
| 0.428832457 | 0.368903276 | 0.451486502 | 1 | -0.297033205 | -0.449819239 |
| -0.231654889 | -0.460463005 | -0.324474362 | -0.297033205 | 1 | 0.629170858 |
| -0.493846274 | -0.396964303 | -0.500071296 | -0.449819239 | 0.629170858 | 1 |

TABLE XV
EIGENVECTOR MATRIX WITH THREE LOADINGS

| **evec1** | **evec2** | **evec3** | **evec4** | **evec5** | **evec6** |
|---|---|---|---|---|---|
| 0.443656 | -0.498002 | -0.016187 | 0.333202 | -0.181667 | -0.640995 |
| 0.390365 | 0.106211 | -0.522200 | -0.651790 | 0.298745 | -0.222627 |
| 0.484058 | -0.408302 | -0.201507 | 0.077899 | -0.123506 | 0.732838 |
| 0.355028 | 0.001777 | 0.787407 | -0.484738 | -0.137265 | 0.011390 |
| -0.340665 | -0.668771 | 0.161267 | -0.164845 | 0.619003 | 0.018598 |
| -0.417582 | -0.356012 | -0.201056 | -0.442643 | -0.678593 | -0.045126 |

the learning aspect of the process is very time consuming and the model output is purely dependent on the availability and fidelity of the data used for the learning.

Irrespective of the technique used, all models developed from the experimented data will have some inputs, calculations, and outputs to predict or determine the behavior of a system it represents. To the best knowledge of the authors, none of the techniques in the literature describe the system as a model of communication network of inputs, outputs, and calculations. This type of representation assists researchers to understand and analyze

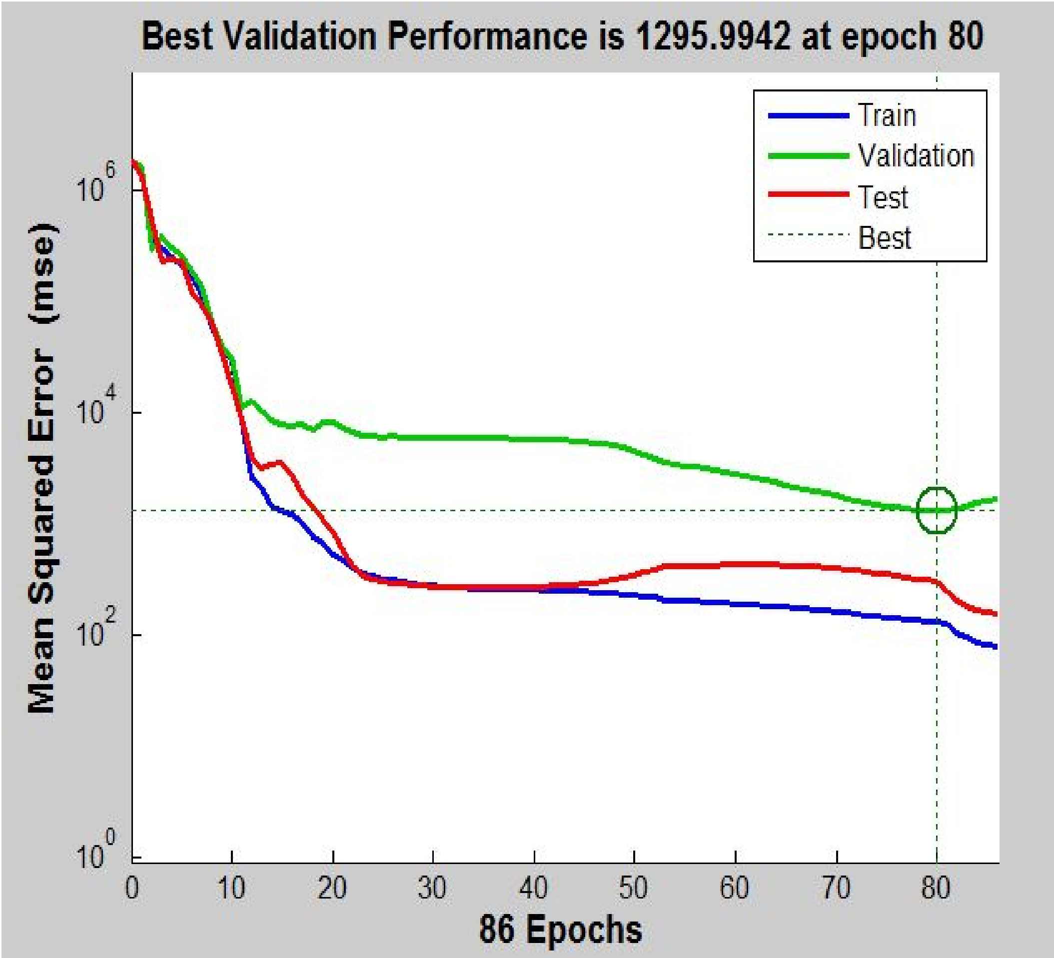


Fig. 65. ANN approach: ANN model validation.

the model for further optimization. Existing models generated from the previously discussed methods cannot be visualized for understanding its properties without going through complex analysis. Moreover, it requires complete knowledge of the data and the methods used to generate that model. Therefore, this section propose a novel method of representing the system model as a communication network using fuzzy set theory.

Fig. 69 shows the proposed fuzzy system as a network. The steps below describes the process of creating one. A fuzzy system can be represented as a communication networ. However, after analysis, this approach seem to be ineffective to represent bigger fuzzy problem. Therefore, no further development were performed.

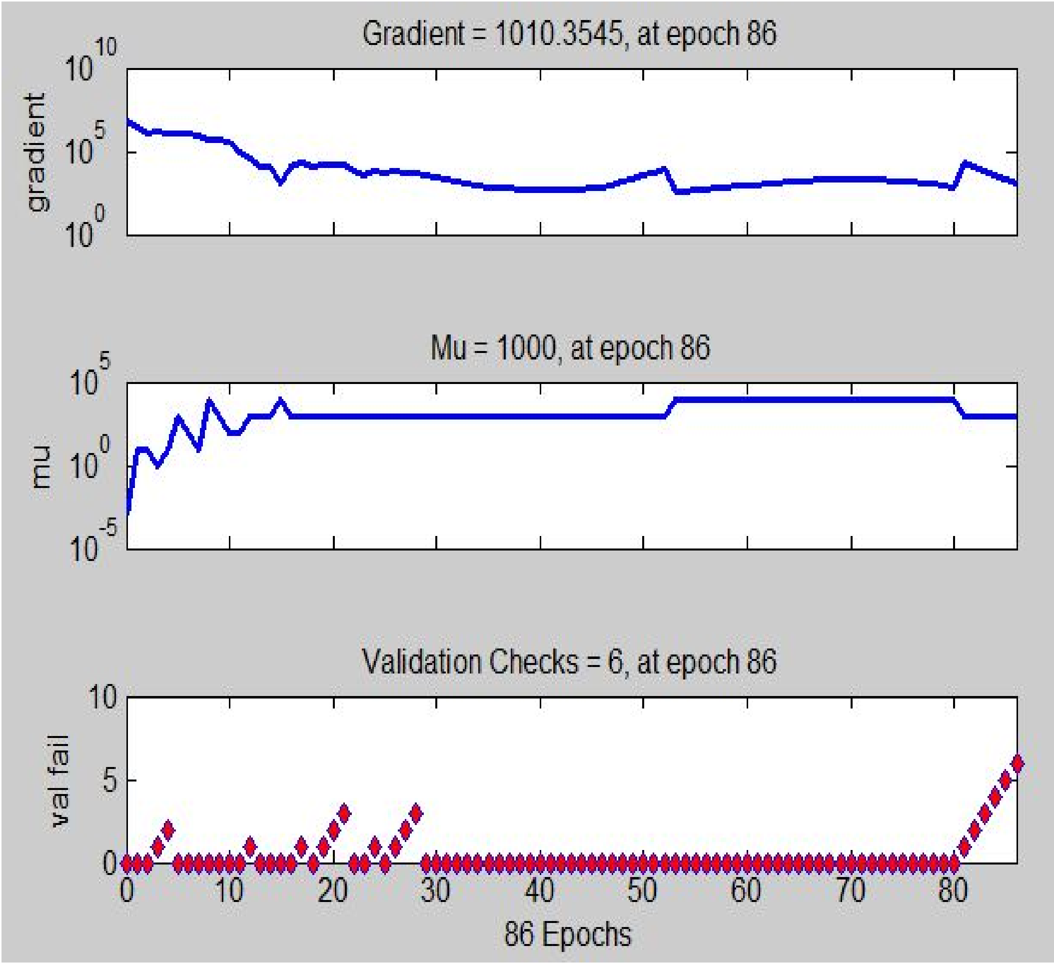


Fig. 66. ANN approach: ANN model training.

- Let S be a system represented as a communication network N of y nodes.
- Let N has a source and a destination node that represent the fuzzy function of a system as a series of possible communication paths between them. A communication path is the path between the source and the destination nodes of a network. A path can have one - many intermediate nodes known as hop points. The communication between two hop points is a hop communication.
- Let N has Hi communication paths between the source and the destination nodes, where i = 1 to p paths.
- Let X1, X2,...Xn are the inputs of S that represent the hop communications in N.

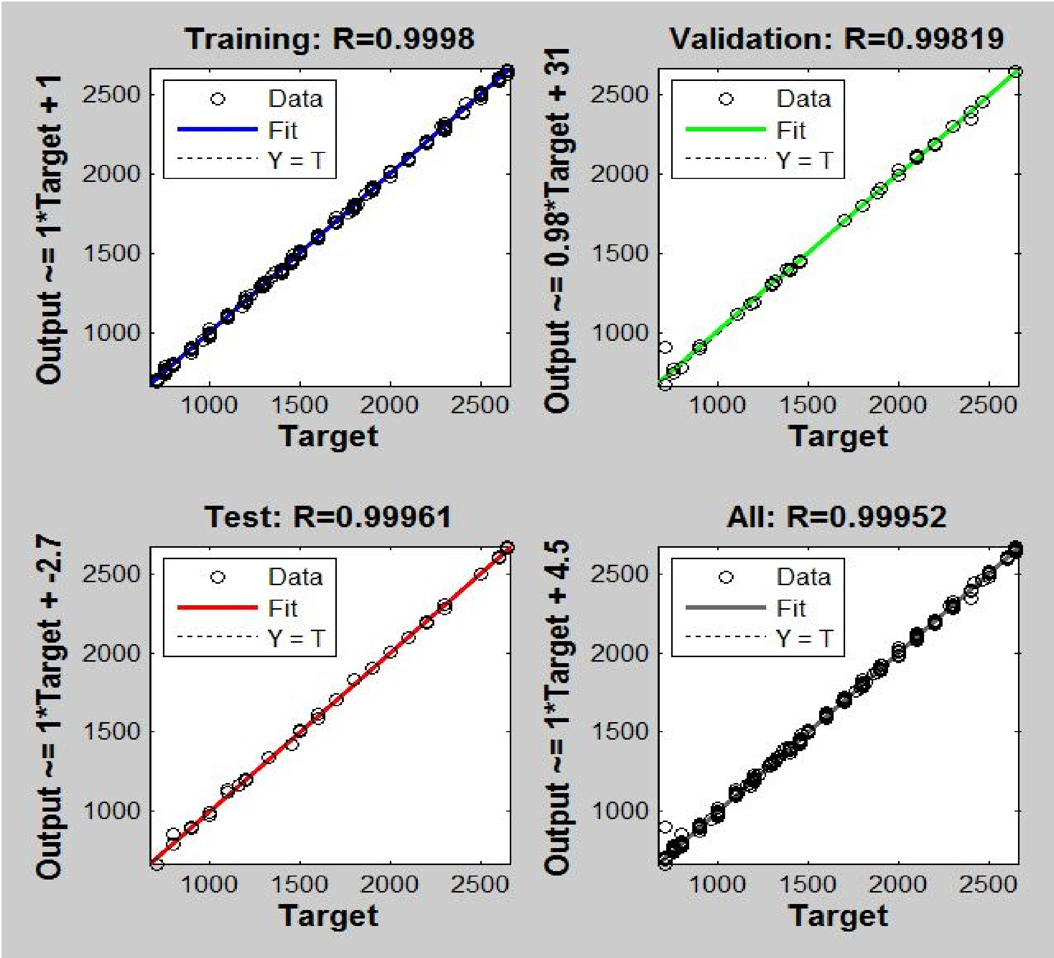


Fig. 67. ANN approach: ANN model regression testing

- Let Mij represents the jth fuzzy membership function of an ith hop communication, where i=1...n hop communications and j=1 to m membership functions of an ith hop communication.
- Let $\mu_{ij}$ represent the fuzzy membership value of an ith hop communication and jth membership function. The membership value depends on the type of jth membership function. A typical membership function can be a Triangular, Gaussian, or Bell shaped curve.
- Each hop communication between the two hop points of N represents a fuzzy hop max function. Let Hfi be the fuzzy hop max function of all the membership values of an

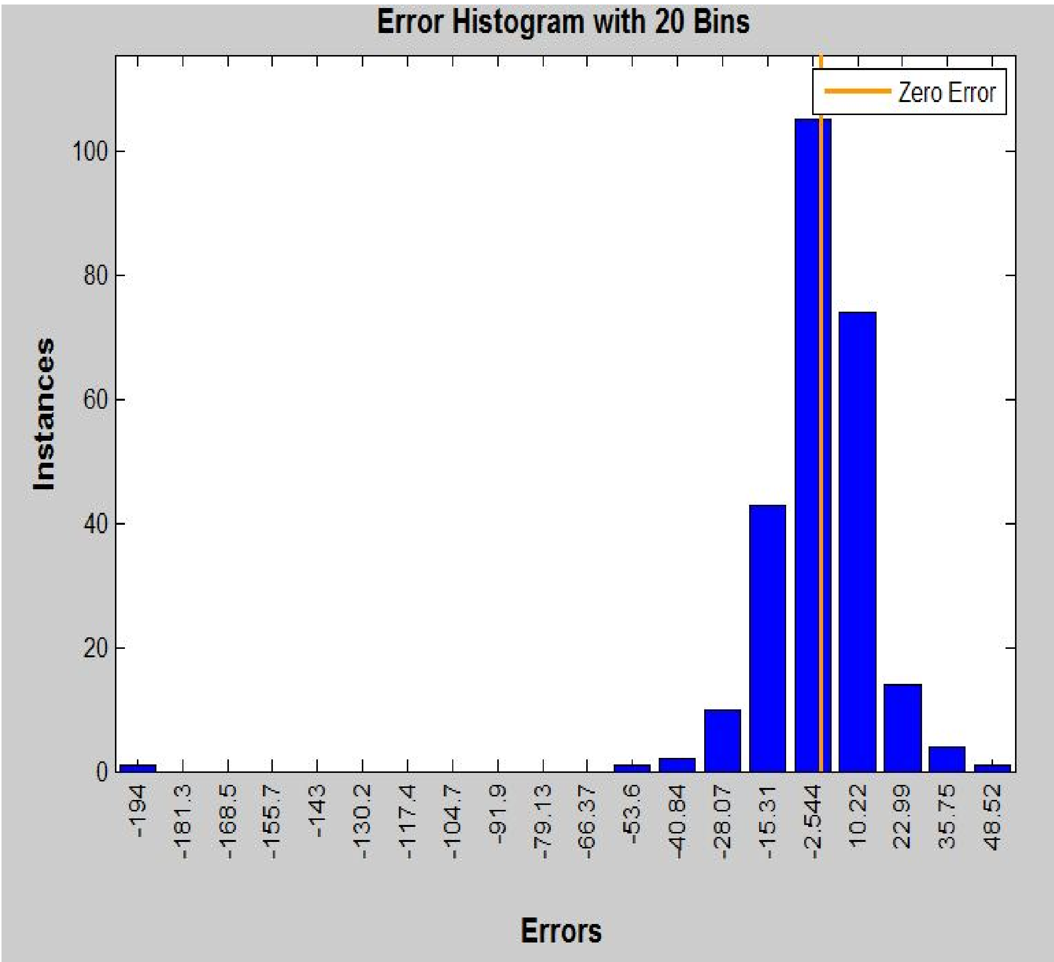


Fig. 68. ANN approach: ANN model error

ith hop communication i.e., Hfi = max ($\mu_{ij}$) where i=1...n and j=1 to m membership functions of an ith hop communication. For example, if a hop communication X1 has three membership functions M11, M12, and M13, then Hf1 = max ($\mu_{11}$, $\mu_{12}$, $\mu_{13}$).

- Each communication path between the source and the destination nodes of N represents a fuzzy path min function. Let Pfi be the fuzzy path min function of all hop max functions of an ith communication path i.e., Pfi = min (Hfi) where i=1...n hop communications. For example, if a communication path Pf1 has two hop communications then Pf1 = min (Hf1, Hf2)
- Let FN represents the Fuzzy network function of system S. It can be expressed as follows:

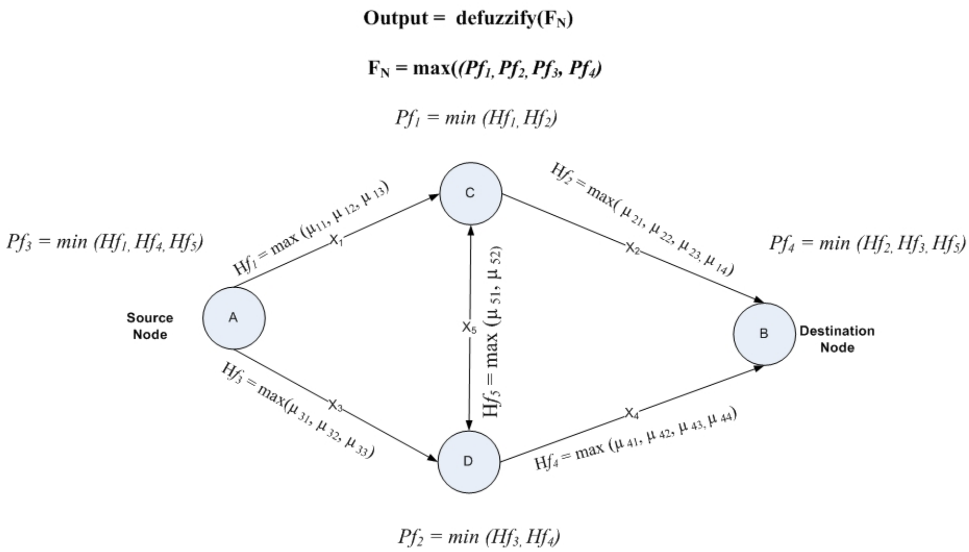


Fig. 69. A fuzzy system as a communication network

  - FN = max (Pfi) where i=1 to p communication paths. For example, if a network has three communication paths, then FN = max (Pf1, Pf2, Pf3).
- The output of FN can be obtained using the defuzzification method (yet to be identified).

## Fuzzy State Space

A fuzzy system can be represented as a state space expression. However, in this section, only a tipper type of problem has been investigated. This can be easily extended to the problem described in this dissertation. However, after analysis, this approach seem to be ineffective to represent bigger fuzzy problem. Therefore, no further development were performed.

$$x = AX(t) + BU(t) \tag{6.2}$$

$$y = CX(t) + DU(t) \tag{6.3}$$

where X(t) is a n by 1 matrix representing the $n$ states, U(t) represents the $m$ inputs matrix, and y represents the output matrix. The matrices A (n by n), B (n by 1), and C (1 by n) determine the relationships between the state and input and output variables. D matrix is the feedback and assumed to be zero matrix for fuzzy problems.

The fuzzy state space model of tipper problem has three outputs, B and D matrices are 0:

$$Cheap\_tip = PoorService\ OR\ RancidFood \tag{6.4}$$

$$Average\_tip = GoodService \tag{6.5}$$

$$Generous\_tip = ExcellentService\ OR\ DeliciousFood \tag{6.6}$$

Based on the above three outputs, the state vectors can be extracted as shown in (6.7), the output matrix y is as shown in (6.8).

$$X = \begin{matrix} Service\_rend \\ Food\_qual \\ Restaurant\_location \end{matrix} \tag{6.7}$$

$$y = \begin{bmatrix} Cheap\_Tip \\ Average\_Tip \\ Generous\_Tip \end{bmatrix} \tag{6.8}$$

For the fuzzy problem of tipper, the matrix A can be extracted based on the equations (6.4) - (6.8).

$$A = \begin{bmatrix} Poor\ OR\ Good\ OR\ Excellent & 0 & 0 \\ Rancid\ OR\ Delicious & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{6.9}$$

For the fuzzy problem of tipper, the matrix C can be extracted based on the equations (6.4) - (6.8).

$$C = \begin{bmatrix} Poor & Rancid & 0 \\ Good & 0 & 0 \\ Excellent & Delicious & 0 \end{bmatrix} \tag{6.10}$$

The state equation (6.2) is rewritten based on the equations (6.4) - (6.8) in in (6.12)

$$\begin{bmatrix} Service \\ Food \\ location \end{bmatrix} = \begin{bmatrix} Poor\ OR\ Good\ OR\ Excellent & 0 & 0 \\ Rancid\ OR\ Delicious & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} Service\_rend \\ Food\_qual \\ Restaurant\_location \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} \tag{6.11}$$

The output equation (6.3) is rewritten based on the equations (6.4) - (6.8) in (6.12)

$$\begin{bmatrix} CheapTip \\ AverageTip \\ GenerousTip \end{bmatrix} = \begin{bmatrix} Poor & Rancid & 0 \\ Good & 0 & 0 \\ Excellent & Delicious & 0 \end{bmatrix} \begin{bmatrix} Service\_rend \\ Food\_qual \\ Restaurant\_location \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} \tag{6.12}$$

# APPENDIX B

## Materials and Methods

## Source of Materials

The author collected the background data for this research by conducting extensive literature review of published papers in Defense Advanced Research Projects Agency (DARPA), Army Research Laboratories (ARL), Defense Technical Interchange Center (DTIC), Army Research Institute (ARI), IEEE, ACM, and SAE journals.

## Method

Fig. 70 describes the methodology used for the research. The figure explains in various steps of conducting and validating research. The numbers on the figure shows the order of execution. In step 1 through 7, the author collected the materials required for the research and developed algorithms. In Step 8 through 14, the author conducted and validated the research proposal and results. The author worked in a loop in steps 1 through 4a until the document findings were sufficient to conduct research and to propose new approaches. In steps 8 through 14, the author again worked in a loop until the proposed approaches are valid and verified. In step 10, the author worked on labs with pertinent instrumentation for conducting experiments and acquiring the raw data. Chapter 4 and Chapter 5 describes the related lab setup. In this step, the author also built analytical models to validate the results theoretically. In step 11, the author conducted experiments, and in step 13 and 14, the author analyzed the results and revised the proposed approaches.

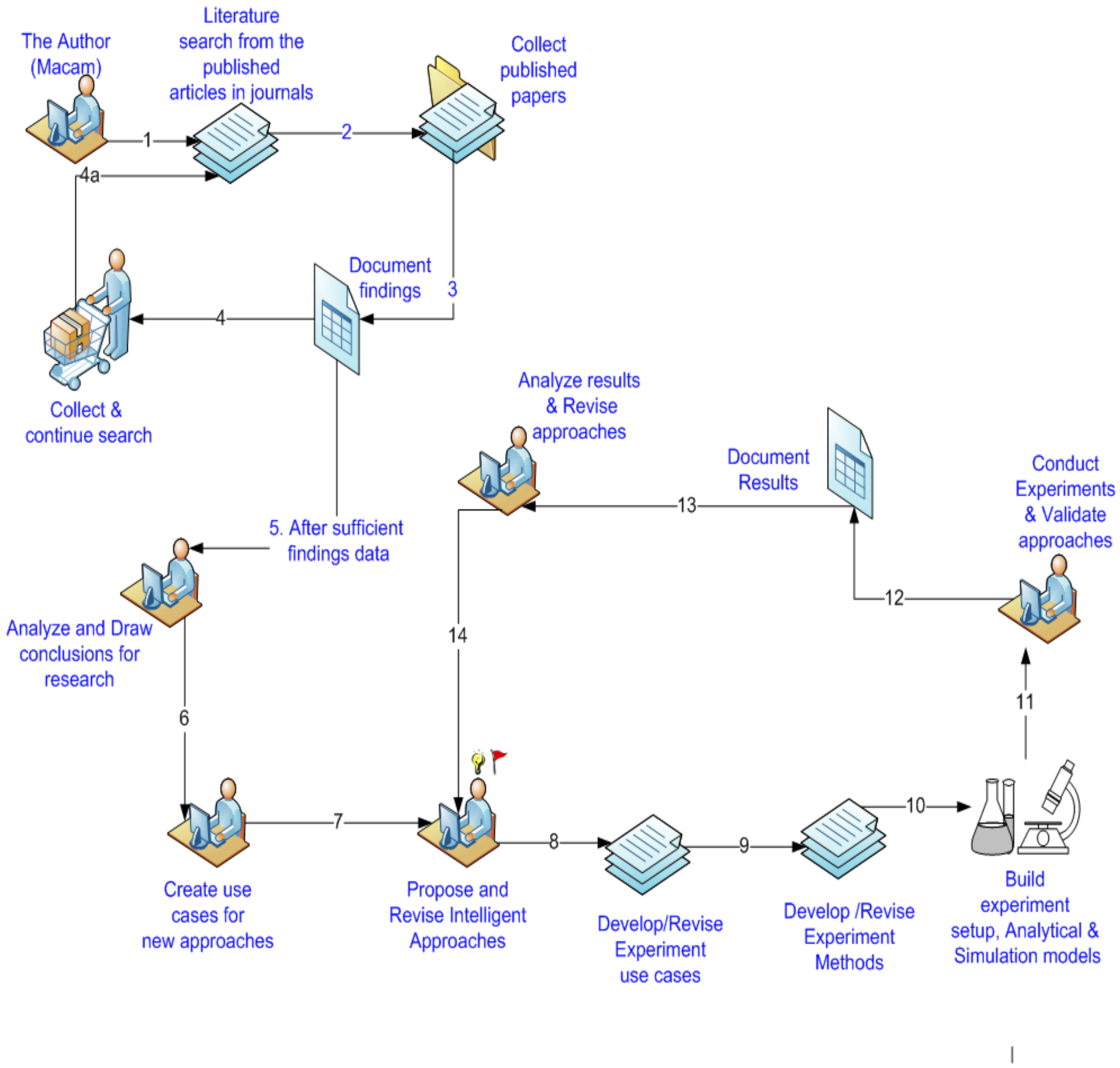


Fig. 70. Research methodology of this dissertation

# APPENDIX C

## Journal Publications:

- M. S. Dattathreya, H. Singh, T. Meitzler, "Detection and elimination of potential fire in engine and battery compartments of hybrid electric vehicles," *Advances in fuzzy systems*, vol. 2012.
- M. S. Dattathreya, H. Singh, "Mission aware energy efficiency in stationary combat vehicles," *Pending decision from the IEEE Trans. Aerospace and Electronic systems*, 2012.
- M. S. Dattathreya, H. Singh, "Silent-watch and energy management strategy in combat vehicles," *Pending decision from the IEEE Trans. Aerospace and Electronic systems*, 2012.

## Conference Publications and Presentations:

- M. S. Dattathreya, H. Singh, "A novel approach for combat vehicle mobility definition and assessment," *SAE 2012 conference publication and presentation*, 2012
- M. S. Dattathreya, "Intelligent approaches in improving in-vehicle network architecture and minimizing power consumption in combat vehicles," *Wayne State Seminar*,2012
- M. S. Dattathreya, H. Singh, "A survey of intelligent computing techniques for energy management in automobiles," *ASCOT 2012 Internal Conference*,2012
- M. S. Dattathreya, H. Singh, "Software reliability prediction for army vehicle," *2011 GVSETS Conference*, 2011
- M. S. Dattathreya, H. Singh, "Army vehicle software complexity prediction metric-five factors," *2010 WorldCom Conference*, 2010

## Patents:

- M. S. Dattathreya, US Patent 8,112,323, "Procurement requisition processing method and system," 2012
- K. S. Champlain, M. S. Dattathreya, US Patent 7,890,872, "Method and system for reviewing a component requirements document and for recording approvals thereof," 2011
- M. S. Dattathreya, US Patent 7,493,334, "System and method for handling invalid condition of a data element," 2009
- M. S. Dattathreya, US Patent 7,493,334, "System and method for validating data record," 2012
- M. S. Dattathreya, US Patent App. 12/130,178, "Profile management and creation method and apparatus in a catalog procurement system," 2008
- A. Coleman, M. S. Dattathreya, US Patent App. 12/327,478, "Method and system for processing requisitions," 2008
- M. S. Dattathreya, W. P. Shaouy, R. T. White, US Patent App. 12/017,075, "System and method for verifying an attribute in records for procurement application," 2008
- M. S. Dattathreya, H. Singh, T. Meitzler, "Detection and elimination of potential fire in engine and battery compartments of hybrid electric vehicles,", 2012 (pending submission to US patents office.)

## Poster Display and Presentation:

- M. S. Dattathreya, H. Singh, "Mission aware energy saving strategy for stationary combat vehicles," *2013 Wayne State Graduate Exhibition*, $3^{rd}$ prize winner.

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# ABSTRACT


## MISSION AWARE ENERGY SAVING STRATEGIES FOR ARMY GROUND VEHICLES

by

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Major: Computer Engineering

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Fuel energy is a basic necessity for this planet and the modern technology to perform many activities on earth. On the other hand, quadrupled automotive vehicle usage by the commercial industry and military has increased fuel consumption. Military readiness of Army ground vehicles is very important for a country to protect its people and resources. Fuel energy is a major requirement for Army ground vehicles. According to a report, a department of defense has spent nearly $13.6 billion on fuel and electricity to conduct ground missions. On the contrary, energy availability on this plant is slowly decreasing. Therefore, saving energy in Army ground vehicles is very important.

Army ground vehicles are embedded with numerous electronic systems to conduct missions such as silent and normal stationary surveillance missions. Increasing electrical energy consumption of these systems is influencing higher fuel consumption of the vehicle. To save energy, the vehicles can use any of the existing techniques, but they require complex, expensive, and time consuming implementations. Therefore, cheaper and simpler approaches are required. In addition, the solutions have to save energy according to mission needs and also overcome size and weight constraints of the vehicle. Existing research in the current literature do not have any mission aware approaches to save energy.

This dissertation research proposes mission aware online energy saving strategies for stationary Army ground vehicles to save energy as well as to meet the electrical needs of the vehicle during surveillance missions. The research also proposes theoretical models of surveillance missions, fuzzy logic models of engine and alternator efficiency data, and fuzzy logic algorithms. Based on these models, two energy saving strategies are proposed for silent and normal surveillance type of missions. During silent mission, the engine is off and batteries power the systems. During normal surveillance mission, the engine is on, gear is on neutral position, the vehicle is stationary, and the alternator powers the systems.

The proposed energy saving strategy for silent surveillance mission minimizes unnecessary battery discharges by controlling the power states of systems according to the mission needs and available battery capacity. Initial experiments show that the proposed approach saves 3% energy when compared with the baseline strategy for one scenario and 1.8% for the second scenario. The proposed energy saving strategy for normal surveillance mission operates the engine at fuel-efficient speeds to meet vehicle demand and to save fuel. The experiment and simulation uses a computerized vehicle model and a test bench to validate the approach. In comparison to vehicles with fixed high-idle engine speed increments, experiments show that the proposed strategy saves fuel energy in the range of 0-4.9% for the tested power demand range of 44-69 kW. It is hoped to implement the proposed strategies on a real Army ground vehicle to start realizing the energy savings.

# AUTOBIOGRAPHICAL STATEMENT

I am a result oriented and a highly motivated individual with 20 years of proven record of accomplishment of practising multi-disciplinary engineering fields, namely, Industrial and Production Engineering, Computer Engineering, Systems Engineering, and Software Engineering. Moreover, I have eight US patents. I also have published four technical papers in journals, and four conference proceedings. I have received academic grants and scholarships for my excellence in education. I have served in review and evaluation boards. I have a Master's degree in Computer Engineering (1999, Wayne State University), and a Bachelor's degree in Industrial and Production Engineering (1994, Mysore University, India).

I have exposure into multiple facets of engineering fields, which enabled me to research various aspects of energy consumption scenarios of systems. I have performed as a chief enterprise and application architect for IBM, and have designed, and led multiple medium to large-scale SOA implementation projects. I have been the core member of Architecture Excellence Review Board and Model Driven Business Transformation Center of Excellence, and Invention Evaluation Committees.

## Education:

- Level III certified Systems Performance Research and Development Engineer (2010)
- Systems engineer and architect training(2005)
- MS in computer engineering (1999)
- BE in industrial and production engineering (1994)

## Hands on significant specialized expertise:

- Six years: IBM Chief Architect for globalized 60 personnel located in five different countries
- 10 years: Lead globalized software and strategy development projects
- 19 years: Develop performance specifications
- 19 years: Design system and application architectures
- 16 years: Implement and customize systems engineering processes
- 14 years: Design software, network, and enterprise architectures
- 17 years: Design and develop software applications
- 15 years: Design and develop security engineering and IA processes
- six years: Design and develop model driven business transformation software applications
- Three years: Research on Energy Saving Strategies for ground combat vehicles(PhD)

## Awards/Recognition:

- Three: Special Act Award (2009-2012)
- One: IBM Outstanding Technical Achievement Award (2008)
- Three: IBM Service Excellence Awards (2006-2009)
- Seven: IBM Invention Achievement Awards (2006-2009)