IMPACT OF INFORMATION FUSION IN COMPLEX DECISION MAKING

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IMPACT OF INFORMATION FUSION IN COMPLEX DECISION MAKING

Submitted by TARIQ AZIZ to the University of Skövde as a dissertation towards the degree of Master in Informatics by examination and dissertation in the School of Humanities and Informatics

I hereby certify that all material in this dissertation which is not my own work has been identified and that no work is included for which a degree has already been conferred on me.

Signature: ________________
Date: ________________
DEDICATED

To

My Parents, wife, kids and all who’ve given me their support during the development of this thesis and for Giving Good Ideas To Prove me as an Intellectual In Front Of my Respected Teachers.
ACKNOWLEDGEMENT

With the humblest and sincerest words I thank almighty Allah, the most merciful and compassionate who is entire source of all knowledge and wisdom of mankind. I bow my head in gratitude to almighty Allah, who gave me the potential and ability to complete this research thesis.

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ABSTRACT

In military battlefield domain, decision making plays a very important part because safety and protection depends upon the accurate decisions made by the commanders in complex situations. In military and defense applications, there is a need of such technology that helps leaders to take good decisions in the critical situations with information overload. With the help of multi-sensor information fusion, the amount of information can be reduced as well as uncertainties in the information in the decision making of identifying and tracking targets in the military area.

Information fusion refers to the process of getting information from different sources and fusing this information, to supply an enhanced decision support. Decision making is the very core and a vital part in the field of information fusion and better decisions can be obtained by understanding how situation awareness can be enhanced. Situation awareness is about understanding the elements of the situation i.e. circumstances of the surrounding environment, their relations and their future impacts, for better decision making. Efficient situation awareness can be achieved with the effective use of the sensors. Sensors play a very useful role in the multi-sensor fusion technology to collect the data about, for instance, the enemy regarding their movements across the border and finding relationships between different objects in the battlefield that helps the decision makers to enhance situation awareness.

The purpose of this thesis is to understand and analyze the critical issue of uncertainties that results information in overload in military battlefield domain and benefits of using multi-sensor information fusion technology to reduce uncertainties by comparing uncertainty management methods of Bayesian and Dempster Shafer theories to enhance decision making and situation awareness for identifying the targets in battlefield domain.

KEYWORDS

Information Fusion, Situation Awareness, Decision Making, Information Overload, Multi-Sensor Information Fusion, Military Battlefield, Bayesian and Dempster Shafer Theories, Uncertainty Management Methods
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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>DSS</td>
<td>Decision Support Systems</td>
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<tr>
<td>HCI</td>
<td>Human Computer Interaction</td>
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<tr>
<td>ECG</td>
<td>Electrocardiogram</td>
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<td>JDL</td>
<td>Joint Director of Laboratories</td>
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<tr>
<td>OODA</td>
<td>Observe, Orient, Decide, Act</td>
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<tr>
<td>TRIP</td>
<td>Transformation of Requirements for the Information Process</td>
</tr>
<tr>
<td>IFF</td>
<td>Identification Friend or Foe</td>
</tr>
<tr>
<td>C2</td>
<td>Command and Control</td>
</tr>
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<td>SONAR</td>
<td>Sound Navigation and Ranging</td>
</tr>
<tr>
<td>DM</td>
<td>Decision Making</td>
</tr>
<tr>
<td>DOODA</td>
<td>Dynamic-Observe, Orient, Decide, Act</td>
</tr>
<tr>
<td>MDMP</td>
<td>Military Decision Making Process</td>
</tr>
<tr>
<td>COA</td>
<td>Course of Actions</td>
</tr>
<tr>
<td>SAW</td>
<td>Situation Awareness</td>
</tr>
<tr>
<td>SA</td>
<td>Situation Analysis</td>
</tr>
<tr>
<td>RADAR</td>
<td>RAdio Detection And Ranging</td>
</tr>
<tr>
<td>FLIR</td>
<td>Forward Looking Infrared</td>
</tr>
<tr>
<td>UMM</td>
<td>Uncertainty Management Method</td>
</tr>
<tr>
<td>DAG</td>
<td>Directed Acyclic Graph</td>
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<tr>
<td>CPT</td>
<td>Conditional Probability Table</td>
</tr>
<tr>
<td>BN</td>
<td>Bayesian Network</td>
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<tr>
<td>TIR</td>
<td>Thermal Infrared</td>
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1.1 INTRODUCTION

Now a day’s world becomes a global village due to the Internet and there is a tremendous increase and advancement in the field of computing and information systems. So in this respect, to handle complex situations and bulk amount of data and to take informed decisions, there is a need of technology for the decision makers that is helpful to make better decisions. This can potentially be done with the proper decision making support through the use of multi-sensor information fusion technology. Decision making is a very important part in the success of any field. It could be the military domain, manufacturing domain, medical domain, transportation domain etc. The top level management of every business always desires to take accurate decisions and have an aim to be successful in their area for longer period of time.

Information fusion techniques play a very important role in the context of military and defense domain. These techniques are widely used in many military applications for detecting and tracking aircraft, radars and missiles, for determining threats, risks and enemy actions (see, for example Martel and Sudano [1]; Banerjee [2]). They described the role of decision making to reduce the human errors through applying different techniques of Bayesian and Dempster-shafer theories within the information fusion along with the impact of multi-sensor information fusion technology to increase the situation awareness with the help of different sensors.

Decision making is a very complex activity in the military battlefield domain because there is high information load on the commanders and they have to take accurate decisions, often under severe time pressure, for the safety and success of the missions. The commander has to take better decisions regarding deployment of different sensors and movement of the troops. For achieving better coordination with the sub-ordinates and accomplishment of the operations the problem of information overload can be reduced through the
development of decision support systems and also by implementing the technology of multi-sensor information fusion.

Information overload is an aspect of an excessive amount of information which is beyond the cognitive abilities of a human being to control. Information overload is normally concerned with the factors like time pressure, massive amount of information flow and filtering of important information from the stream of unreliable and conflicting information. To improve the performance and effectiveness of the commander’s decision making in military battlefield domain, the issue of information overload should be reduced in order to minimize the pressure of handling huge amount of information.

Complexity is the condition of the situation that is associated with too many elements. The information overload is a big problem in military battlefield activities for better decision making. There are many factors for the information overload e.g. uncertainties, ambiguities etc. These factors indicate the conflicts in the data which leaves the commander in a very complex situation of handing and sorting out the relevant information under severe time pressure from the bulk quantity for decision making along with performing other tasks at the same time.

Information fusion techniques provide decision support through decision support systems (DSS). Decision support systems are the computer based information systems which supports a process of decision making in a good manner. There is a relationship between information fusion and DSS (see, for example Nilsson and Ziemke [3]). According to Nilsson and Ziemke, information fusion and DSS has many common features like containing knowledge about the environment, coordinating and facilitating interactions among multiple decision makers etc. Accurate and consistent information can be supplied through information fusion techniques to make the efficient DSS.

This thesis will discuss the benefits of multi-sensor information fusion for decision making in the military domain of battlefield under information overload. It focuses on information fusion support for reducing the
information overload, i.e., that the availability of so much information that
decision making in fact gets difficult (for a detailed description of this concept
see for instance (Maas et al [20]). They described an information filtering and
control system to improve the decision making process within future
command information centers to handle the problem of information overload.
They described the causes of information overload with the help of a model.
Detailed review and analysis of the affects and advantages of information
fusion technology in the military environment for decision making under the
vital issue of information overload will be presented in this thesis.

1.2 RESEARCH AREA

Information fusion is becoming more and more popular due to the
development of new sensors. There is a need of multi-sensor fusion
technology due to the great increase in data now a day’s. This technology
allows decision maker to take effective decisions. Multi-sensor information
fusion technology supports decision making e.g. the readings of pulsed radar
and imaging sensor are fused to determine the range and angular direction of a
detected aircraft. This helps the air traffic controller (decision maker) to know
the exact position of the aircraft. In this case, one sensor cannot give the
detailed information and there is a need of the readings of the two sensors on
which decision will be made.

Decision making in the military battlefield domain includes the assessment
and evaluation of important activities e.g. handling risks and threats in the
mission, proper usage of the resources required in battlefield, managing sensor
deployment issues, monitoring the position of the enemy across the borders.
The information overload affects the decision making process of all these
activities due to incomplete and conflicting results in the information.
Handling a large amount of information by reducing uncertainties and
summarizing the important information to command and control the battlefield
activities is a time consuming and complex activity that should be automated
in order to perform the battlefield activities in a better manner. So, in this
thesis the vital issue of information overload will be addressed in the
battlefield domain along with the solution through the use of multisensor information fusion technology.

The domain of military decision making is very complex and often characterized by information overload. In this specific domain, the role of the commander regarding decision making is very important, because survival and success of the mission depends upon the decision made by the commander. Information fusion techniques are used in this domain for merging information from different sources and presenting an efficient and reliable form of information to the commander.

Some work has already been done in the military domain to reduce the information overload (see Martel and Sudano [1], Louvieris et al [8], Qureshi and Urlings [6]). They pointed out the issue of information overload in the military domain and addressed the usage of multi-sensor information fusion techniques to reduce this vital issue through making flexible automation systems and developing different approaches to decision support systems.

1.3 PROBLEM STATEMENT

There are many issues (see Nilsson, Riveiro and Ziemke [5]) that need to be investigated within information fusion in decision making context. Nilsson et al [5] pointed out the factors of time pressure, high stress, inconsistencies in the data, incomplete and uncertainty in the information, trust and attention and complexity of data mining techniques.

Many areas are facing the situation of information overload, similar to military decision making (see Qureshi and Urlings [6]), e.g., manufacturing domain (see Li, Wang and Chen [7]). In these situations decision makers have to take accurate and prompt decisions regarding their important matters. The research problem addressed in this thesis is how multi-sensor information fusion technology be used to help commanders to make effective decisions in military battlefield domain under information overload? It means how the vital issue of information overload can be reduced in the military battlefield domain.
through the use of information fusion technology in order to increase the situation awareness and decision making capabilities of the commander?

1.4 AIM

To evaluate the benefits of multi-sensor information fusion technology for better decision making under complex situations of high information overload in the military battlefield domain.

1.5 OBJECTIVES

The objectives of this thesis are as follows.

- Investigate and explain the important concepts of information fusion technology, situation awareness, decision making and information overload in military battlefield domain.

- Analyse how multi-sensor fusion technology is helpful for improving the performance of commanders in critical situations of information overload in military battlefield domain?

- Comparison of information fusion methods used for reducing the information overload, thereby improving the decision making capabilities and increasing situation awareness of the commander.

1.6 RESEARCH METHODOLOGY

A detailed and comprehensive study is required about the military battlefield situations of information overload and benefits of multi-sensor fusion technology in this domain. In this thesis, a qualitative approach of research has been selected. Qualitative approach is an inductive approach involving the complete and in depth knowledge about the problem domain by exploring the related literature. This approach also includes the methods of in-depth interviews and focus groups in which group of the people give their findings and comments about an idea. It is an approach of defining problem and building concepts and theories from the predefined procedures. Quantitative
research includes the statistical analysis and this research is descriptive rather than exploratory. It includes the testing of hypothesis and it is concerned with the methods of surveys where people are asked the closed end questions. The analysis mode of quantitative research is deductive in which models are applied to analyze and test the hypothesis (see Creswell for further descriptions of these and their differences [4]).

Qualitative approach will be used in this thesis to achieve the objectives. Firstly the literature studies and research articles will be explored with the help of keywords to investigate and describe the information fusion technology, situation awareness and decision making models and processes in the battlefield along with the reasons and impacts of information overload. After that, use of the sensors in battlefield domain will be provided by identifying and analyzing the requirements of the battlefield with the help of analyzing the work of other researchers in the field of information fusion technology. At last, a comparison will be presented, describing the information fusion methods used in the battlefield to overcome the issue of information overload by studying and summarizing the relevant research topics and literature material in this field.
The military domain is normally concerned with the issues of time pressure, information overload and risks. That is why decision making in the military environment is a very complex task. For improving the commander’s performance under information overload in military battlefield domain, it is necessary to present some basic and important concepts about the information fusion research technology along with decision making, situation awareness and an issue of information overload in the military battlefield domain.

2.1 INFORMATION FUSION

In the process of decision making, firstly humans investigate and examine the analysis of the requirements of the environment. They gather multiple pieces of information regarding the situation and analyze the necessary requirements needed to perform course of actions for the accomplishment of the tasks, but the success of the decision making process depends upon the cognitive capacity and skills of the human. Humans have extraordinary skills but they can work up to some extent. With the development of new technologies into the market, the process of decision making became very complex and many challenges arises e.g. how to handle large amount of information in an efficient manner, how the necessary and required information can be extracted from the entire group of information, how decision can be made under the issues of time pressure and information overload?

Information fusion can be the solution of the above mentioned questions in which information is gathered from multiple sources in order to increase the situational awareness and cognitive abilities of the humans. According to (Hall and Llinas [9]), information fusion is the process of combining data or information to estimate or predict entity states. It is a process of gathering information from multiple sources in order to achieve the accurate estimation and prediction of
situations, threats, positions and continuous improvement of the estimations for obtaining the good results.

Information fusion involves the collection of information from different sources like sensors, databases, humans, simulations and to fuse this information in order to get the better understanding and knowledge about the object of the environment to support decision making. The field of information fusion is not new. According to (Hall and Llinas [10]), “even humans and animals have evolved the capability to use multiple senses to improve their ability to survive. It may not be possible to assess the quality of an edible substance based solely on the sense of vision or touch, but evaluation of edibility may be achieved using a combination of sight, touch, smell and taste”.

The main purpose of information fusion technology is to fuse the information from different sources and merge all information into a single accurate result that is helpful for the better decision making in complex situations of different fields. The role of information fusion technology is described in detail in the next sections of this thesis.

2.1.1 INFORMATION FUSION MODELS

In order to understand the information fusion technology, it is necessary to describe some models that have been developed to solve the problems of different domains. Models are the structures that show the relationships and guidelines for the improvement of the results. There are many models in the area of information fusion technology. Some models are as follows.

2.1.1.1 JDL (JOINT DIRECTOR OF LABORATORIES) MODEL

The most famous model in the technology of information fusion is probably the JDL model (Joint Director of Laboratories) (see Hall and Llinas [10]) that was developed in 1980 within US department of defense by the American government committee. This model is the first one that was developed within the information fusion community and it was developed for the military and defense applications. According to (Hall and Llinas [9]), JDL model is referred to as functional model that defines the functions of the data fusion system rather than a process model.
that indicates the flow of the fusion process by performing level 1 first, then level 2 and so on. It has been revised many times. The revised JDL model having all levels is as follows.

**Figure 1** The JDL fusion model adapted from (Hall & McMullen 2004) [16]

JDL model takes input from different sources like sensors, databases, human and simulations, performs the fusion from starting level to end level and finally gives the output to the user through the physical interface. The description of all levels of JDL is as follows.

**Level 0  **  **Signal Assessment**

It is the process of preprocessing data in the sensors and estimation and prediction of the signals. Before starting the fusion process, data is preprocessed with other data. It includes functions like image processing, signal processing, data alignment and filtering.

**Level 1  **  **Object Assessment**

It is the process of extracting and combining data from different sources in order to estimate or predict the entity attributes like speed, velocity, direction, location and it is used for target tracking.

**Level 2  **  **Situation Assessment**

It is the process of describing the relationships among the entities/objects and relationships between the entity and the environment. The techniques of automated reasoning and artificial intelligence are used in this level.
**Level 3**  
**Impact Assessment**

It is the process of estimating and predicting the future affects and consequences of the current situations. Threats, risks and impacts are measured in this level. This level deals with the question that what will happen if I did this?

**Level 4**  
**Process Refinement**

It is the process of refining and monitoring the overall process of the information fusion. This level of JDL model is used for the improvement of identification and tracking of objects and assessment of threats by examining the information sources.

**Level 5**  
**Cognitive Refinement**

This level presents the fused and meaningful information to the user through interface. It focuses on “interaction between the data fusion system and a human decision maker to improve the interpretation of results and decision making process (Hall and McMullen [16])”.

The first two levels of signal and object assessment represent low level fusion where main focus is on the extraction of data from multiple sources and preprocessing data to make compatible for fusion to detect and estimate the object states. Low level fusion is sometime called data fusion and it is normally used for target tracking through applying different filtering techniques. The other two levels of situation and impact assessment represent high level fusion where the main focus is on defining the relationships among objects and between objects and environment instead of representing attributes of objects. It also concerns the future impact of performed actions including risks and threats. “These two levels are normally called information fusion rather than data fusion (Niklasson et al [17])”.


2.1.1.2 **DASARATHY FUNCTIONAL MODEL**

This model was developed in 1994 and it shows categorization of different data fusion functions. Dasarathy used abbreviations to represent the processes in a matrix form dividing the input and output data fusion in three different forms of data, features and decisions (see Hall and McMullen [16]). According to Hall and McMullen [16], Steinberg and Bowman have provided a link between the Dasarathy and JDL model. The following table shows the levels of the Dasarathy functional model.

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
<th>Notation</th>
<th>Analogues</th>
</tr>
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<tbody>
<tr>
<td>Data</td>
<td>Data</td>
<td>DAI-DAO</td>
<td>Data-level fusion</td>
</tr>
<tr>
<td>Data</td>
<td>Features</td>
<td>DAI-FEO</td>
<td>Feature selection and feature extraction</td>
</tr>
<tr>
<td>Features</td>
<td>Features</td>
<td>FEI-FEO</td>
<td>Feature-level fusion</td>
</tr>
<tr>
<td>Features</td>
<td>Decisions</td>
<td>FEI-DEO</td>
<td>Pattern recognition and pattern processing</td>
</tr>
<tr>
<td>Decisions</td>
<td>Decisions</td>
<td>DEI-DEO</td>
<td>Decision-level fusion</td>
</tr>
</tbody>
</table>

**Table 1** Levels of Dasarathy functional model adapted from (Bedworth and O’Brien) [22]

2.1.1.3 **WATERFALL MODEL**

The waterfall model has three levels from the bottom level of data to the top level of decision. In the first level data is collected from the sensors and preprocessed to provide the information about environment. The second level is about the feature extraction and pattern processing and it is used to fuse the features. The third level indicates the interpretation of the objects to achieve better decision making. There is also an element of feedback that informs the multi-sensor system for the reconfigurations of the levels in order to achieve better decision making through correct assessment of the situation (see Esteban et al [21]).
2.1.1.4 TRIP MODEL

As mentioned by Hall and McMullen [16], Kessler and Fabian (2001) has developed the most recent model for the data fusion process named as TRIP (Transformation of Requirements for the Information Process) model which combines the information requirements of humans with the data collection. This model is based on the hierarchical levels of stages containing human information requirements, objective, situation, information, object, collection, collection evaluation and observable world. The main focus of TRIP model is to have knowledge and understanding about the requirements of the specific domain regarding the sensor resources management. The diagram of the TRIP model has been shown by Hall and McMullen [16, page 70].

2.1.1.5 OMNIBUS PROCESS MODEL

Bedworth and O’Brien [22] have developed an omnibus process model which is a combination of the different models of Dasarathy, JDL, Waterfall and decision making model OODA (Observe, Orient, Decide, Act). This model is an intelligence cycle in nature containing the list of tasks in an ordered form and feedback loops are also acknowledged in this model. According to Bedworth and O’Brien, this model can be used in two ways. Firstly, the structure is divided into...
different parts to perform ordered list of tasks and secondly same structure can be used to describe the objectives of the each task.

**Figure 3** The Omnibus Model adapted from (Bedworth and O’Brien [22])

Bedworth and O’Brien [22] also described the comparison between different models related to the information fusion which is as follows.

**Figure 4** The Comparison of different information fusion related models adapted from (Bedworth and O’Brien [22])

The comparison of four models of the information fusion have been described in the above figure showing the relationship between all the stages of different models along with the activities performed in each level.
2.1.2 APPLICATION AREAS

Information fusion technology plays a very important role in different application areas and is used in many fields. An overview of the use of information fusion technology is given below by taking examples of some different domains.

2.1.2.1 EXAMPLES FROM THE OTHER DOMAINS

Network Security

Information fusion technology is used in the field of network security for the purpose of risk evaluation, intrusion detection, and alert correlation (see Chang, Yu and Pei [11]). In this area, an information fusion based automated decision support system helps the management to raise alarm in case of any intrusion. Organizations can protect their network and secure losses through utilization of information fusion.

Robotics

Information fusion technology is used in robots that are equipped with many sensors for taking information about the objects e.g. thousands of meters under water to find the black boxes of crashed aircrafts with the help of robotic machines (see, for example Hollinger et al [25]). Robots are used with multi-sensor fusion capabilities in many applications in nuclear industry, railways, under water equipments, highways, aircraft servicing and manufacturing industries (cf. Parker and Draper [12]). Robots are used to work continuously without any break, to speed up the work in order to save time and it is also helpful for achieving accuracy in the work. According to (Luo, Yih and Lan Su [13]), automatic vehicle controlling and position location are the necessary functions of robot.

Banks & Credit Card Companies

Information fusion technology is used for the anomalies detection in banks and credit card companies in order to monitor criminal activities. Anomaly detection is the process of finding the unexpected behavior from the data. Some techniques to
handle the issues of fraud and theft are presented in the anomaly detection survey (see Chandola, Banerjee and Kumar [14]).

**Medical**

The technology of information fusion is used in the medical field for identifying and analyzing diseases and abnormalities in data (see Toure et al [15]) through latest machines like X-ray, ECG etc.

**Transportation**

Information fusion technology is used in the transportation systems for automatic controlling, detecting and tracking of vehicles, trains and aircraft (cf. Luo, Yih and Su [12]).

### 2.1.3 SUMMARY OF BENEFITS AND LIMITATIONS

The concept of information fusion technology along with models and usage of this technology in different application areas has been described earlier in this thesis. The importance, usage and benefits of information fusion technology in different domains can easily be estimated from the previous section.

In brief, information fusion is used to improve and increase accuracy, reliability, situation awareness, robustness and to reduce ambiguity for effective decision making. In information fusion, information is gathered from different sources. Precision can be obtained through fusing information from many sources because one source might not give the complete and comprehensive understanding about an object of the environment. This technology helps decision makers to understand the concept of situation awareness for taking better and prompt decisions.

Information fusion has also some limitations or challenges along with the benefits. The system becomes more complex due to the fact that information is coming from different sensors (sources). There may be an issue of the coordination and conflicts between sensors. There is also a need of compatibility of different information coming from heterogeneous sensors before fusion process. Although
there are some challenges in this technology, information fusion is still very accepted and popular technology.

2.2 **MILITARY DOMAIN**

The military domain is about supporting C2 (Command and Control). The command refers to the expertise and skills (cognitive abilities) of the commander in order to lead the group for the accomplishment of the mission whereas control means the overall monitoring and analyzing the tactical activities regarding the current situation of the battlefield. The management of the military makes plans about the attacks, assesses the resources needed in terms of human strength and equipments and finally executes the action. Commander leads the force in the battle and controls the military operation activities according to his prior knowledge and experience (Headquarters department of the Army Washington [29]) by reducing the threats and risks in order to achieve success in the mission.

2.2.1 **CATEGORIZATION OF MILITARY DOMAIN**

Military domain can be divided into air defense, ocean surveillance and battlefield surveillance. Information fusion techniques are used in all the categories to improve and enhance situation awareness and decision making capabilities of the leaders to take important decisions regarding crucial aspects. The domain of battlefield surveillance is described in detail in the next section along with an overview of the air defense and ocean surveillance domain.

2.2.1.1 **AIR DEFENSE**

In this category, a fighter pilot has to perform the following activities continuously in a very quick time before the enemy action in order to achieve success in the mission.

- Observing and gathering the requirements of the current situation of the environment.
- Assessment and detection of the position of the other fighter planes.
- Judging the plane as friend or hostile based on the readings from the different sensors within the system.
• Deciding and implementing the action based on the available information (shoot or not).

The pilot cannot perform all the above mentioned activities by using only his own thinking. He needs some decision support on which he decides what to do next. In this case information fusion based decision support systems help the fighter pilot to reach at better decision for performing the above mentioned activities. Multi-sensor fusion technology plays an important role in the air defense domain (see, for example Kouemou, Neumann and Opitz [19]).

2.2.1.2 OCEAN SURVEILLANCE

Hall and Llinas [9] explained the ocean surveillance domain through the following figure.

![Diagram of ocean surveillance system](image)

**Figure 5** An example of an ocean surveillance system adapted from (Hall and Llinas [9])

Aircraft, ship and the submarine are detecting each other signals with the help of different sensors. Ship and aircraft receives the signals from the radar about the presence of the under water submarine, whereas the submarine uses sonar (Sound navigation and ranging) technology. Sonar technology uses sound for navigating
and communicating the submarine with other vessels. Information fusion techniques are used in the ocean surveillance domain for detecting and tracking of ocean based targets e.g. submarines, ships, aircrafts etc and many other purposes (see, for example Zhu et al [23]).

2.2.1.3 BATTLEFIELD SURVEILLANCE

The battlefield domain is about commanding and controlling the battle process which is very complex, unpredictable and often affected by rapidly changing factors of the environment. In the battlefield domain a commander takes orders from his superiors and implements the orders within his group to support and lead the troop for performing the command and control activities in order to achieve success in the mission. The command hierarchy of the military battlefield domain is as follows.

![Battlefield Command Hierarchy](image)

Figure 6   Battlefield Command Hierarchy adapted from (Horn and Baxter [24])

The human strength is divided into many troops in battlefield domain. Every troop has a commander to lead the group in the tactical environment. For the success of the mission it is necessary to divide the tasks in different groups e.g. one troop is allocated for the supervision of the safety of the heavy machinery and equipments, other may be involved to handle and control the fire hazard in case of emergency, but there will be another group which is involved in attacking the enemy. All commanders of different troops coordinate with each other and deliver the current
status of the situation to the squadron commander. The detailed information about
the battlefield surveillance domain is presented in the next section.

2.2.2 BATTLEFIELD SURVEILLANCE DOMAIN

In order to understand the battlefield domain, it is necessary to describe some
important concepts about the battlefield procedure, role of the commander,
situation awareness and process of decision making along with the factor of
information overload.

2.2.3.1 BATTLEFIELD PROCEDURE

The battlefield procedure is about performing different activities of planning,
preparing, assessing and executing the actions. According to Authority of the
Chief of Land Staff [26], the battlefield procedure is a continuous process of the
following four levels.

![Figure 7](image)

**Figure 7** The Battle Procedure Model adapted from (Authority of the Chief
of Land Staff [26])

**Planning**

Planning is a procedure of making strategies to perform the course of actions for
the successful accomplishment of the tasks. A commander takes decisions in favor
of the mission in order to achieve better results and his correct decision depends
upon the planning phase. This phase is continues process of developing the
policies before staring the battle and also modification of the policies within the
battle. The plan structure for the battlefield contains the following information in
order to achieve the goal of the mission.
• Requirement of the assets and resources needed in terms of equipment and human strength (planning for which type of equipments needed and how many battalions required for performing the specific task).

• Management of threats associated with the battlefield (planning about assessing and organizing the risks e.g. fire, loss of equipments).

• Knowledge about the weather and land conditions of the battlefield.

• Assignment of the different tasks to various troops (planning for making different battalions for performing different activities).

• Maintenance of training activities performed by the troops (planning about the preparation of the battle).

Planning is an important part of the battlefield procedure because it helps in order to determine the weaknesses in the plan before actual starting of the battle (see, for example Allen et al [27]). Allen et al [27] developed a framework for the collaborative planning to reduce the issues relating to the military e.g. information overload, resource allocation etc.

**Preparation**

Preparation of the battlefield procedure is the second step after planning phase. According to Authority of the Chief of Land Staff [26], this phase contains the following activities.

- Participation in the rehearsals
- Inspection and preliminary movements
- Training
- Coordination

In this phase, commander prepares his soldiers for the actual battle to work on the plan by performing the above mentioned activities. Soldiers can understand the battle rhythm through rehearsals that is the process of practicing an activity in preparation for the actual performance of that activity (Authority of the Chief of
Land Staff [26]). Preliminary training, inspection and coordination help the soldiers to perform better in the battlefield because of having preliminary knowledge about the commander intentions and concept of the military operations. Training before actual execution of the battle trains the soldiers how to attack the enemy and react in case of unpredictable events. Benefits and areas of the training in the battlefield have been described in great detail by Manacapilli et al [28]. They explained the training areas of communication, medical, physical fitness, self defense techniques and weapons training.

**Assessment**

Assessment is the process of monitoring and reviewing the remaining other levels of the battlefield. It is about observing the overall current situation of the battlefield mission regarding some important issues e.g. threats, risks, type of resources needed, communication gaps, sensor management etc and scrutinizing the plans and actual training of the troops keeping in mind the success factors for the mission. This level deals with the questions like how success can be achieved in the mission by deploying different plans, what are the plans and procedures to handle critical situations, where are the loopholes in the mission?

This level has a great impact and importance in the procedure of the battlefield, because preparation and analyses of the answers to the above mentioned questions helps commander in the battlefield position for judging the unpredicted type of threats (relating to the mission that will lead to the failure) e.g. sudden movement of the enemy troops to some different location, external factors of weather etc.

**Execution**

Execution is about the actual implementation of the command and control actions in the military battlefield. It is the process of attacking the enemy with by using machinery and fighting equipments for the accomplishment of the mission. A commander actually executes the plans and takes crucial decisions based on the previously constructed plans in this phase.

**2.2.2.2 ACTIVITIES OF THE COMMANDER**

Information fusion technology helps commanders to identify targets and threats in the battlefield for successful accomplishment of the tasks. The commander
performs the command function by directing the force towards the accomplishment of the mission according to his prior knowledge and experience (Headquarters department of the Army Washington [29]). The role of the operational commander in the battlefield is very important because the overall success of the mission wholly depends on his decisions and actions. He has to perform the following activities in the battlefield surveillance.

- Understanding and correct assessment of the current situation of the environment.
- Judging and analyzing the position and movements of the enemy troops on the borders.
- Correct deployment of the sensors keeping in mind the knowledge about sensors regarding position, type, reliability and accuracy.
- Estimating the threats and risks (e.g. fire hazards, bad weather conditions) involved in case of the battle, because risks leads to the failure of the mission.
- Supervision of the current and future usage of resources of the battlefield e.g. machinery, fighting equipments, radars, missiles etc.
- Evaluating enemy objectives and future actions.
- Managing coordination and providing information about the current status of the battlefield to superiors.
- Taking good and prompt decisions that maximize the success ratio of the mission and minimizes threats and risks.

The responsibilities of the commander in his unit are very crucial for the successful accomplishment of the tasks. Loh [30] has provided some principles of the good leadership that commander should have in the form of positive vision, capability of distinguishing between mistakes and intended actions, understating the concepts of discipline and trust on the entire unit and ability of applying the discipline fairly regardless of friendship and rank.

2.2.3.3 INFORMATION OVERLOAD IN BATTLEFIELD SURVEILLANCE

Information overload is the condition in which the information processing requirements exceed the information processing mechanisms available, so that the
organization is unable to process the information adequately (Tushman and Nadler, 1978 [77] as mentioned in Maas et al [20]). Information overload has been shown to impact decision performance by affecting the decision making to alter his decision making strategy (Newell and Simon 1972 [78], as mentioned by Williams et al [31]).

Battlefield surveillance is an unpredictable field and often affected by many factors which cause the failure in the success of the mission. Information overload is one of the main factors in the battlefield domain that becomes the reason for the poor performance in execution of the mission. According to Freeman, Cohen and Serfaty [32] the increased flow of the information in battles is not risk free, as flow increases, staff may drown in data while the commanders thirst for the information. There is a need for accurate information in the modern battlefield today to make better decisions. The volume of the information in battlefield is quite high and the main issue in this case for the commander is how to extract the meaningful information from the bulk quantity without losing the important information? Some times the requirements exceed the cognitive abilities of the commander to handle the situations that lead to the issue of information overload.

The environment of the battlefield domain is very complex in which commander occasionally has to make accurate decision within limited time because of rapid change in the situation (sudden movement of the troops across the border). There are many factors for the information overload in the battlefield surveillance domain. Some of the factors are described by Maas et al [20] which are as follows.

2.2.3.3.1 FACTORS OF INFORMATION OVERLOAD

**Uncertainty**

Uncertainty refers to the lack of the sufficient information about the state of the environment. According to Foody and Atkinson, 2002 [79] (as mentioned by Riveiro [33]), uncertainty is “quantitative statement about the probability of error”, where inaccurate measurements, estimates or predictions are associated with uncertainties. In the battlefield domain a commander needs proper
information in order to make the better decisions. There are two issues relating to the uncertainty factor which are as follows.

- The first one is about that the extracted information from different sources is too much as compared to the needed information. In this case the problem for the commander is how he will manage bulk of information and extract only the relevant information?

- The second case about uncertainty is that the information received is too low as compared to the needed information. In this case commander has to extract more information from the sources in order to meet the requirements of the tasks.

Both cases of uncertainty represent high and low quantity of the information that lead to the information overload. If the quantity of the information is too high then it will require more time to extract meaningful data from the database whereas low quantity can ignore the important data. The process of information gathering from different sources takes too much time whereas the time to assess and process the information to take better decision is short in the battlefield domain. A commander has to perform many tasks simultaneously in the complex and tactical environment of the battlefield. Uncertainties can be managed through different information fusion methods and can be visualized with some visualization techniques described by Riveiro [33]. These techniques help commander to make the better decision under the situation of information overload.

In the battlefield domain the commander coordinates with the soldiers and superiors about the current situation of the battle by sending messages with the help of different communication channels. There are many factors that affect the communication between the commanders e.g. weather conditions, external noise, land condition etc. These factors are the sources that cause uncertainty in the battlefield domain. Many sensors are deployed in the battlefield to receive the information but the external conditions of the weather can disturb the signals of the sensors.

**Conflicts**

Conflicts mean inconsistencies in the information which are due to the different reasons e.g. faulty sensor and object models. Many sensors in the battlefield
domain are used to detect enemy activities but there may be a risk that different sensors conflict each other signals and give wrong results or mismatch information to the commander.

Conflicting information causes stress for the commander. In this situation commander may make the wrong decision in a battlefield environment to identify enemy positions across the border due to the contradicting results by the sources. According to Maas et al [20], the operator has to perform many tasks simultaneously in the battlefield environment e.g. dealing with information displayed on the screen, communication with the commanders through headphone and presentation of textual messages on paper and his mail box. In this case, if extracted information from two different sensors is conflicting, then decision making for the commander in this scenario will be very hard.

**Complexity**

Complexity relates with some specific aspects of the environment e.g. time pressure and intensity that can impact the organizations decision making process. “Complex systems are formed of multiple interacting elements whose collective actions are difficult to infer and complexity increases in military conflict as the application of effective force must be more carefully selected or more accurately targeted, and where the implications of errors in these choices become more severe” (Yam [34]). The battlefield environment is often affected by unpredictable events in form of fire emergency and rapid change in the form of sudden movements of the enemy troops which leads to the complexity. There is a need of new and more electronic fighting equipment in the military battlefield today, but complexity leads to the information overload that should be reduced along with the proper usage of resources to defeat the enemy for the successful accomplishment of the mission.

### 2.2.3 DECISION MAKING

Decision making (DM) is the process of selecting some course of actions from the given different alternatives of strategies. The process of DM is very important in every field to perform the task of activities in a better position and success can be
achieved through better DM. The decisions may be simple or complex made by single decision maker or multiple decision makers with respect to the situations of the environment. DM is the combination of all managerial functions e.g. planning (for deciding what should be done? when? how? where? by whom?) and some other functions, such as organizing, implementing, and controlling (Forman and Selly [36]).

The purpose of the decision making process is to provide help to the management for achieving goals and objectives in a better way. According to Simon [87] as mentioned in Forman and Selly [36] page 18, the decision making process consists of the following three phases.

**Intelligence**

Intelligence is the first phase of the decision making process and it involves many activities such as identifying the problems, taking feedbacks from the group of decision makers and analysis of the strengths, weaknesses and threats to the organizations.

**Design**

After identifying the problems, the next phase is about to find out the alternative solutions to fix the problems in order to perform the process of DM in a better way.

**Choice**

The last phase of the decision making process is to select the best option from different alternatives of the solutions to the problems made in the previous step by keeping in mind the pros and cons of the decision in order to meet the objectives.

2.2.3.1 **DIFFICULTY IN DECISION MAKING**

According to Clemen, 2001 [80] (as mentioned by Al-Karaeen [35]) decision making is not an easy process and he has pointed out some reasons for the difficulty of decision making which are as follows.

- The complexity of the decision is due to the availability of a large amount of information that exceeds the cognitive capabilities of the decision maker to interpret and handle.
IMPACT OF INFORMATION FUSION IN COMPLEX DECISION MAKING

- The uncertainty in the decision making situation that leads to the form of doubtful and inaccurate results.
- Difference of opinions on the same problem from different members of a group of decision makers that leads to different conclusions.

2.2.3.2 DECISION MAKING IN MILITARY BATTLEFIELD

Decision making in the tactical environment of the military battlefield is a very complex activity. DM in the military battlefield involves many aspects of C2 activities e.g. usage of weapons and other resources, estimation of risks and threats, reducing uncertainties. The most accepted model used in the information fusion technology for decision making in the command and control activities is the Boyd’s OODA (Observe-Orient-Decide-Act) loop (Boyd, 1987 as described by Osinga [37]). The OODA loop was developed by an American aviator John Boyd during the Korean War (1950) and he explained the model and its importance for defending the war successfully. The detailed explanation of the OODA loop is as follows.

2.2.3.3 DECISION MAKING (OODA LOOP) MODEL FOR MILITARY BATTLEFIELD

Boyd 1987 has described four levels of the OODA loop model that are as follows.

Observe

The first activity of the OODA loop involves gathering of observations and facts of the environment. In the original OODA loop, this activity refers to the act of detecting the enemy aircraft by the fighter pilot with the help of different sensor readings provided by the system embedded in the cockpit. In case of battlefield, this phase includes gathering information and observation of activities e.g. movements of enemy troops across the border, weather and land conditions.

Orient

The next step of orient includes interpretation and updating the observations through analyzing the information. Success can be achieved with better analysis
and interpretation that depends upon the skills, expertise and experience of the fighter pilot. In the original OODA loop, this activity refers to the act of positioning your aircraft towards opponent’s aircraft to make a base for the next step. In battlefield environment, this phase refers to the act of analyzing the observations and requirements needed to perform the task successfully.

**Decide**

This phase includes the process of plans creation to solve the problems. After that this plan makes the base for actual decision making for choosing one plan among different course of actions. In the original OODA loop, this activity refers to the act of deciding to shoot an adversarial aircraft or not. In battlefield, commander makes plan for different activities e.g. attacks, controlling hazards, monitoring proper usage of resources and makes decision to select the best and feasible plan for implementation.

**Act**

This phase is the actual execution of the plan that has been decided in the previous step. In the original OODA loop, this activity could refers to the act of pressing trigger towards the enemy aircraft and attacking the enemy in battlefield.

![Figure 8](image-url)  
**Figure 8** The OODA Loop Model (Boyd’s 1987) adapted from Osinga [37]

All the activities of the OODA loop are cyclic in nature from the first activity of observe to the last activity of act. After performing the last activity, new observations are made again and this process continues in this form. This endless loop will stop when there is nothing more to observe after the successful completion of the last activity. The main aim of the OODA loop is to go inside the
decision loop of the enemy, capture his decisions and perform this cycle in a quicker time as compared to the enemy to achieve success in the battle.

Adapted from Curts and Campbell [36]

2.2.3.4 DECISION MAKING DYNAMIC (OODA LOOP) MODEL FOR MILITARY BATTLEFIELD

The original OODA loop was developed by John Boyd for fighting between two aircrafts and it was used only in the domain of aviation but after that John Boyd has extended the original OODA loop into dynamic OODA loop to accommodate different forms of combat along with the fight between two aircrafts. The detailed description of the DOODA loop is as follows.

![Dynamic OODA Loop Model](image)

Figure 9 The Dynamic OODA Loop Model (Boyd’s 1987) adapted from (Brehmer [39])

John Boyd proposed the dynamic OODA loop in order to include the dynamic nature of the C2 activities as visualized by Brehmer [39] in figure 9. The main activities of the dynamic OODA loop model are same as of the original OODA loop but this model expresses the decision making process in great detail through showing the relationships between all the activities. This model includes the original activities of the OODA loop with decision making process, as well as the following functions of Creveld’s 1987 [81] (as mentioned in Brehmer [39]).
• Collection of information about enemy and own forces, the weather and terrain conditions.
• Finding out the ways for storing, extracting, filtering, classifying and displaying the information.
• Assessment of situation.
• Working out on alternative means to achieve the objectives.
• Deciding and planning.
• Monitoring the execution of the process through feedbacks.

The dynamic OODA loop consists of several loops instead of one loop as in the original OODA loop and it also includes the feedbacks from different processes to explain the relationship among all activities. This model shows the Observe process as data collection, Orient as situation understanding, Decide as selection of appropriate action and Act as the actual execution of the action. The description of the dynamic OODA loop activities are as follows.

• Observe is the process of extracting information by observing and interacting with the outside environment and it includes the guidance and control from the Orient process and also receives the feedback from the Decide and Act processes.
• The Orient process includes the functions of cultural traditions, genetic heritage, analysis and synthesis, new information and previous experience. These all functions represent to the fact of understanding the situation elements for better awareness through judging and analyzing the circumstances with the help of expertise and experience.
• Decide is the process of selection of appropriate action to perform the tasks. This process indicates choosing the best approach among different hypothesis to make decisions better.
• Act is the process of actual execution of the decision process or it can be called as the testing of the decision.
2.2.3.5 THE MILITARY DECISION MAKING PROCESS

According to Marr [40], “The MDMP (Military Decision Making Process) is an analytical process, employing a time-intensive, but logical sequence to analyze the situation, develop a range of options, compare these options, and then select the option that best solves the problem.” The MDMP is an approach to solve the problems that commander faces to command and control the activities of the tactical environment of the battlefield. This process helps the commander in a battlefield to reach at the better decision after performing some activities in a sequence.

The commander has to perform the activities that are mentioned in the following diagram from Receipt of Mission to Execution and Assessment to make decisions in the battlefield.

![Diagram of the Military Decision Making Process](image)

**Figure 10** The Military Decision Making Process adapted from Marr [40]

The description of all the activities of MDMP is as follows.
Receipt of Mission

The first activity of the MDMP is Receipt of Mission. High authorities in the military allocate the mission to the commander. The entire unit has to obey the order of his commander to perform the tasks. This activity includes the initial assessment to perform the tasks such as determining the staff estimates and time needed for the planning, preparing and executing the mission (Headquarters of the Army [41]). Commander has to update his higher authorities for the current situation of the battlefield. The authorities issue a warning order to the commander to implement the new plan in case of any changes in the plan.

Mission Analysis

The next step in the MDMP after receiving the mission is the Mission Analysis. In this step, mission is analyzed in order to know the intentions of the higher authorities by performing the functions such as reviewing assets, determination of the specific and essential tasks, risk management and identification of the critical facts (Headquarters of the Army [41]). This step is necessary to understand the problem and to know the clear statement of the authorities for successful accomplishment of the tasks.

Course of Action Development

After receiving and analyzing the mission, the commander develops COAs (Course of Actions) with the involvement of staff. COAs are the sequence of instructions in the form of a plan to achieve the objectives. (Headquarters of the Army [41]) has provided some qualities of the COAs such as feasibility, acceptability and completeness. These qualities show that the COAs have to support the accomplishment of the mission in the specific time and according to the resources and complete in all respects.

Course of Action Analysis

After the development of COAs, the COAs are analyzed by refining and validating the friendly options against enemy options through performing test of war gaming (Marr [40]). War gaming is the process of visualizing the flow of the
battle in order to implement the COAs. This phase helps the commander to reduce the damage to the friendly forces for maximizing the combat power against the enemy forces (Headquarters of the Army [41]).

**Course of Action Comparison**

In this phase, COAs of each unit are compared in order to know the advantages and disadvantages of the COAs. Each unit presents his COA and gives suggestions for the improvement of other COAs. The purpose of this phase is to select the most feasible COA that gives the highest probability for the success of the mission. “The selected COA poses the minimum risk to the soldiers, equipment and mission accomplishment” (Headquarters of the Army [41]).

**Course of Action Approval**

After comparison of different COAs, the commander decides and selects the best COA to fulfill the task. COAs are rejected or modified with the approval of the commander. In case of rejection, the staff has to start the whole process again and in case of modification, staff can continue their work from performing the war games. “Based on the commander’s decision, the staff immediately issues a warning order with essential information so that subordinate units can refine their plans” (Headquarters of the Army [41]).

**Orders Production**

The staff refines the COA according to the instructions of the commander and after that issues an order to implement the specific COA that shows the procedure and all necessary information relating to the mission such as risk management and resource allocation.

**Rehearsals**

Before actual execution of the mission, the soldiers perform rehearsals in the field in order to know the pros and cons of the battle. Rehearsals in the form of training provide knowledge and some skill to the soldiers for performing better in the battlefield.
**Execution and Assessment**

The last activity of the MDMP is the actual execution of the selected COA to perform the command and control activities in the battlefield.

### 2.2.4 SITUATION AWARENESS

Due to the development of the new technologies, now systems have ability of producing large amount of data in different domains. Accurate and consistent information is required to perform the decision making process in a better form but to extract the relevant and necessary information from the huge amount of data, data has to be sorted and filtered in order to get the required information. This problem of extracting relevant information from data is called information gap. This information gap is shown in the following figure.

![Image of information gap]

**Figure 11** The Information Gap adapted from (Endsley and Garland [42])

In order to increase the abilities of the decision maker, the concept of SAW (Situation awareness) has been introduced. SAW is the most commonly used term in the battlefield and in other combat systems and it makes a base for the decision making process. Many authors have defined SAW, some closely related to the aviation domain and some general. Some definitions are as follows.

“Situational awareness can be defined at a number of different levels. At a higher level, we might say that it simply means that the pilot has an integrated
understanding of factors that will contribute to the safe flying of the aircraft under normal or non-normal conditions. The broader this knowledge is, the greater the degree of situational awareness. As situational awareness increases, it is thought that the pilot is increasingly able to ‘think ahead of the aircraft,’ and that he can do this for a wider variety of situations.”

Regal, Rogers and Boucek [43]

“SAW is an abstraction that exists within our minds, describing phenomena that we observe in humans performing work in a rich and usually dynamic environment.”

Billings [44]

According to the definitions, SAW is the idea of the mind to understand and observe the situations of the environment. The concept of SAW is related with the SA (situation analysis). According to Niklasson et al [17], the iterative process of gathering and analyzing the information to provide and maintain a product i.e. the state of SAW, in order to enhance decision making is called SA whereas the SAW is the result of this process.

Klein [82] (as mentioned in Roy, Breton and Rousseau [45]) has provided some following reasons to show the importance of SAW.

- SAW appears to be linked to performance.
- Limitations in SAW may result in errors.
- SAW may be related to expertise.
- SAW is the basis of decision-making.

2.2.4.1 ENDSLEY’S SITUATION AWARENESS MODEL

Endsley has provided the following general and perhaps the most widely accepted definition of the SAW.

“SAW is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future.”

Endsley, 1988

as mentioned in Endsley and Garland [42]
Endsley expended her definition of SAW into the above mentioned cognitive model of SAW that contains three mental representations of the perception, comprehension and projection rather than functional (JDL) or process (OODA) model. The detail of three levels is as follows.

**Perception**

The first step to achieve SAW is the perception. Perception means getting awareness about the status and attributes of the elements of the environment. Without a basic perception of important information, the odds of forming an incorrect picture of the situation increase dramatically (Endsley and Garland [42]). In the aviation domain, this level refers to perceive the elements for identification of the aircrafts (friendly or enemy).

**Comprehension**

The next level is to understand the elements of the environment and interpretation of the perceived information to know the situation. This level includes how people combine, interpret, store, and retain information and the integration of multiple pieces of information and a determination of their relevance to the person’s goals (Endsley and Garland [42]).

**Projection**

The highest level of SAW is achieved through perceiving the knowledge about the status and attributes of the elements of the environment and comprehension of
these elements. This level includes the outcomes and predictions that happen in
the near future.

2.2.4.2 SITUATION AWARENESS AND DECISION MAKING

Endsley and Garland [42] explained the relationship between SAW and DM
process through the Endsley SAW model (cf. figure 12). According to Endsley
and Garland [42], SAW makes the base for the DM process on which the decision
maker decides and performs certain COAs. SAW is the pre-stage before DM
process and it is a decision maker’s internal (mental) model of the state of the
environment containing three mental levels rather than a process such as DM. The
relationship between SAW and DM process can also be viewed through following
diagram.

Figure 13 Situation Analysis, Situation Awareness and Decision Making
adapted from (Roy, Breton and Rousseau [45])

The above diagram is showing the relationship between SA, SAW and DM. The
two activities of the OODA loop (observe and orient) refers to the process of SA
for gathering and interpreting the information from the environment to achieve the
state of SAW through performing mental activities of perception, comprehension
and projection to make the decisions for performing COAs through the OODA
loop activities of Decide and Act.

Good example has been given by Niklasson et al [17] to explain the relationship
among SA, SAW and DM. While driving car, driver hears the horn sound and see
flashing lights and identify an ambulance through mirror (perception). The driver
understands that there is an emergency (comprehension) and he projects that an
ambulance cannot cross him until he moves his car to one side (projection). Now driver reached to the state of SAW through SA to take the decision to move his car.

2.2.4.3 SITUATION AWARENESS IN MILITARY BATTLEFIELD

The term of SAW is used very commonly in the military battlefield domain to enhance the decision making process for the successful accomplishment of the tasks. The SAW helps the soldiers and commanders to get the awareness of the key elements (enemy activities, their location, weapon capabilities, terrain and weather conditions) of the battlefield situation, the comprehension of the elements and their future impacts in order to achieve goals and objectives. SAW is the key for making better tactical decisions and it gives the ability to the commanders to compress the time necessary for conducting different procedures when there is limited time available for planning and preparation of an operation (Headquarters Department of Army [48]).

U.S. Army Training and Doctrine Command (as mentioned in Holmquist and Goldberg [49]) has defined the SAW as “the ability to have accurate real-time information of friendly, enemy, neutral, and non-combatant locations; a common, relevant picture of the battlefield scaled to specific levels of interest and special needs.” According to Holmquist and Goldberg [49] this definition is relevant to all soldiers on the battlefield for improving their capability to gather and understand the up-to-date information regarding enemy in order to get success in the mission.

In the dynamic tactical situations of the battlefield, soldier’s SAW is very important because it provides the basis for the MDMP and it reduces errors in this process. The overall success of the battlefield mission depends upon the MDMP activities for execution of the approved COA and to perform these activities, the mental state of SAW gives the sound foundation through performing the process of SA.

Different activities of the military battlefield are performed by different troops in order to perform their tasks separately and in a better form but the intentions of all
the troops are to achieve their goals and objectives. Endsley and Jones [47] has provided list of following some goals in the battlefield for different categories.

![Table 2 Goals in the Battlefield adapted from (Endsley and Jones [47])](image)

The above mentioned table shows different goals of the battlefield e.g. detection and identification of enemy and friendly targets, communication between the teams, improved planning and decision making and management of targeting objects and resources. All these goals relate to different groups of the military army and these can be achieved through good SAW.

Endsley’s SAW model has been described earlier in this section. She has explained the model with three levels of perception, comprehension and projection. The McGuinness and Fog [83] (as mentioned by Salerno [46]) extended the Endsley SAW model by adding the fourth level, named as Resolution which covers the process of decision making and planning that was not initially included by the Endsley. This new level of Resolution provides the awareness to choose a single COA among different actions in order to achieve the required result. According to the McGuinness and Fog [83] (as mentioned by Salerno [46]), fusion system must be resilient and dynamic to be successful in this day and age and it must also address the entire process flow from data acquisition to awareness, prediction and the ability to request elaboration or additional data.

McGuinness and Fog have explained all the levels of Endsley SAW model in the following tabular form that is helpful to explain the relationships among different levels of SAW and also to explain the different battlefield activities.
McGuinness and Fog have described the four different levels of SAW by explaining the levels in the form of corresponding contents and processes involved in these levels. According to them, these levels involve answering of some questions. Perception is about to answer the question “What are the current facts?” and it includes awareness of the necessary and relevant information from different sources by knowing the contents about states, events and objects of the environment in the form of sensing, detection and identification processes.

Comprehension is about to answer the question “What is actually going on?” and it includes the interpretation and combination of the information to know the actual meaning of the current situation. Projection is about to answer the question “What is most likely to happen?” and it includes the possible outcomes of the comprehension level through predicting the results. The last level of Resolution is about to answer the question “What exactly shall I do?” and it involves the process of decision making and planning for actual execution of the operation.

According to Cooper [76] (as mentioned by Endsley and Jones [47]) the battlefield knowledge can be achieved with the help of cognitive hierarchy and higher level of SAW can also be achieved by turning effectively data into information and information into understanding in the following form.

<table>
<thead>
<tr>
<th>SA Function</th>
<th>Contents</th>
<th>Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>PERCEPTION (What are the current facts?)</td>
<td>Provides awareness of relevant information from external sources: readouts, displays, communications, environment, and so on</td>
<td>Explicit objects, events, states, values</td>
</tr>
<tr>
<td>COMPREHENSION (What is actually going on?)</td>
<td>Provides awareness of what all this means, i.e. a more abstract understanding of the situation at hand, an appropriate schema for assimilating information.</td>
<td>Implicit meanings, situation types</td>
</tr>
<tr>
<td>PROJECTION (What is most likely to happen?)</td>
<td>Provides awareness of how this situation may develop over time by predicting or simulating possible scenarios, including one’s own actions and their dynamic effects.</td>
<td>Future scenarios, possible outcomes</td>
</tr>
<tr>
<td>RESOLUTION (What exactly shall I do?)</td>
<td>Provides awareness of the best path to follow to achieve the required outcome to the situation, drawing a single course of action from a subset of available actions.</td>
<td>Intention, courses of action</td>
</tr>
</tbody>
</table>
Figure 14 Relationship between Cognitive Hierarchy and Situation Awareness adapted from (Endsley and Jones [47])

The meaning and explanation of SAW levels in military can be viewed through following table by describing the example of battlefield.

<table>
<thead>
<tr>
<th>SAW Levels</th>
<th>Military Battlefield Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perception</td>
<td>Sensing the detection and identification of different friendly or hostile objects e.g. tanks, aircrafts, missiles on system screens through information provided by different sensors such as ground radars.</td>
</tr>
<tr>
<td>Comprehension</td>
<td>Combining data from different sensors, extracting relevant and necessary information from the data and interpretations of the resulted information by the commanders for better understanding of the exact situation e.g. hostile aircraft is in the territory and it will attack.</td>
</tr>
<tr>
<td>Projection</td>
<td>Predictions of the commander about what will happen and what will be the effects of his action in near future? e.g. in case of presence of hostile aircraft in territory, making estimates by the commander about quantity of fighting equipments in case of attacking the hostile aircraft.</td>
</tr>
<tr>
<td>Resolution</td>
<td>Planning and selection of one COA from different alternatives by the commander, keeping in mind all future impacts e.g. selection of plan to minimize casualties.</td>
</tr>
</tbody>
</table>

Table 4 Situation Awareness Levels with respect to Battlefield Activities
2.2.5 **SUMMARY**

The concepts of information fusion technology, situation awareness and decision making in the military battlefield domain have been described in this chapter along with the important factor of information overload. A very famous information fusion JDL model is widely used for estimating and predicting entity states and threats involved in the military domain. The decision making process especially in the military battlefield domain is very complex because of performing different activities by the commander in the presence of risks and threats under severe time pressure and information overload. Different factors of information overload like uncertainties and conflicts have also been explained in this chapter. The state of mind (situation awareness) can be achieved by performing the process of gathering and analyzing information (situation analysis) that makes the basis for the decision making process in the military domain.
In order to explain multi-sensor information fusion technology, it is necessary to give some information regarding sensors which are normally the sources of information in this technology.

3.1 SENSORS

Sensors are embedded in intelligent systems for automatic controlling without the involvement of the human. A sensor is an electronic device that converts the measures of a physical quantity into signals and gives the results to the human for decision making. Sensors are used in many applications e.g. home appliances, manufacturing and scientific instruments, medical, transportation, space and in defense and have many features such as lower weight, greater portability and lower manufacturing cost (Luo, Yih and Su [13]). Normally sensors are divided into active and passive sensors. Active sensors emit energy in the form of waves to detect objects in the environment whereas the passive sensors do not emit they take energy from the external sources of environment (Solanki [56]).

According to Breckenbridge and Husson [84] (as mentioned in Luo, Yih and Su [13]), smart sensor must possess the following three features.

- The ability to perform logical computable functions.
- Communicate with one or more other devices.
- Make a decision using logic or fuzzy sensor data.

3.2 MULTI SENSOR INFORMATION FUSION

The human can assess the environment with the help of different senses e.g. touch, taste, smell, hearing, sight. These senses can be seen in terms of different sensors which give the data to the human brain for integrating the different information to make better understanding of the environment. A comprehensive picture about the environment can be achieved through the use of multiple senses e.g. to identify
the facial shape and sound quality of human, sight and sound senses will work together.

The idea of Multi-sensor information fusion is similar to the idea of using different senses by the human. According to Luo, Yih and Su [13], multi-sensor information fusion refers to the process of combining sensory data from multiple sensors to provide the more reliable and accurate information. The process of multi-sensor fusion and integration can be described with the help of following figure.

![Multisensor Integration and Fusion](image)

**Figure 15** Multisensor Integration and Fusion adapted from (Luo and Kay [50])

Different sensors from (1 to n) are taking the data from the environment and are integrated to provide information to the system. The first two sensors produce the output in the form of $X_1$ and $X_2$ which are fused to the new output of $X_{1,2}$. The output from the third sensor $X_3$ fused with the output of other two sensors ($X_{1,2}$) in the next fusion node to make the output as $X_{123}$. Similarly this process continues for the $n$ sensors. Three functions of the integration process are also indicated in
the above figure in the form of sensor selection for selecting most appropriate sensor, representation of the data in the world model and transformation of the sensors before the fusion process.

3.2.1 LEVELS OF MULTISENSOR FUSION

There are some levels of representations in the multisensor integration and fusion indicating in the figure 15 from low to high. These levels are as follows.

**Data Level Fusion**

The lowest level is the data level fusion which is also known as pixel/signal/measurement level fusion. It involves directly collecting and combining data of equal types from different sensors. According to Gee and Abidi [51], this fusion is suitable for real time applications and signal processing is an example of this fusion where information describes the alignment and synchronization of the sensors.

**Feature Level Fusion**

The next level is feature level fusion in which features of the data are extracted and combined. Features may be the color, size and shape of the object. This fusion is used for image recognition in which the object is identified with the help of features. Scalzo et al [52] have presented the effectiveness of feature level fusion to classify the gender through describing the algorithm and framework for feature level fusion.

**Decision Level Fusion**

Decision level is also called symbol level fusion and it is the highest level in the multisensor fusion and integration. Symbols represent the input as in the form of decisions and each source provides classification and identification of the objects of the environment. After that, information from different sources in the form of decisions is fused to identify the objects. According to Luo and Kay [50] the decision is usually made by matching features derived from the sensory information. Different information fusion techniques are used in this fusion to
identify the targets in different domains (see, for example Miguez, Bugallo and Djuric [53]).

Luo and Kay [50] have described these three abstraction levels of the multisensor fusion and integration process with the help of following example for the recognition of the tank.

![Fusion levels in Automation Recognition of a Tank](image.png)

**Figure 16** Fusion levels in Automation Recognition of a Tank adapted from (Luo and Kay [50], page 712)
3.3 MULTI SENSOR INFORMATION FUSION IN MILITARY BATTLEFIELD

The goal of this thesis is to explain the role and advantages of the multisensor information technology in the military battlefield domain to reduce the factor of information overload to enhance SAW and DM process. The functions of three sensor fusion levels in the battlefield domain can be viewed from the following figure.

![Figure 17 Inference Hierarchy adapted from (Hall and Llinas [10])](@197x478)

The process of observing the presence of the targets (aircrafts, tanks) in the battlefield through different sensors readings about their locations and speed, identification of the objects based on the previous readings and finally making decisions through performing SA and threat analysis represents the sensor fusion levels from lower level of signal fusion to the upper level of decision fusion.

Today’s military battlefield requirements have changed from the past because of the development of new technology in the form of smart sensors. Multisensor fusion technology has a very useful role for achieving the following tasks in this domain.

- Detecting (finding), tracking (continuous monitoring) and classification (fighter or civil) of aircrafts and ground targets.
- It is used for increasing situation awareness and decision making capabilities of the commanders to make better decisions.
- It is used for estimation of risks, threats and impacts regarding fulfillment of the tasks for the success of the mission.
- It is used to understand and reduce the complex issues of information overload and uncertainties in the military battlefield domain.
For a detailed discussion on the role of multi-sensor information fusion in the battlefield domain (see, for example Maas et al [20]; Martel and Sudano [1]; Banerjee [2], Yang et al [18], Fitch et al [54] and Xing et al [55]). Hall and McMullen [16] have provided a detailed survey about using multisensor fusion techniques in military applications. A very useful multisensor fusion JDL model is presented here to show the battlefield activities with respect to their levels.

### 3.3.1 JDL LEVELS WITH RESPECT TO MILITARY BATTLEFIELD DOMAIN

Many models have been developed but a very famous sensor fusion model JDL was firstly developed for the military applications. JDL information fusion model is a very useful in the military applications for performing the vital activities. All levels of JDL model corresponds some actions of the military domain. The importance of usage of multisensor fusion technique in the military domain is presented here through displaying the relation between the JDL model and the military activities.

<table>
<thead>
<tr>
<th>JDL Levels (0-5)</th>
<th>Military Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Assessment</td>
<td>Detection of signals by the radar sensor for target tracking.</td>
</tr>
<tr>
<td>Object Assessment</td>
<td>Identification of the aircrafts (Air defense), tanks (Battlefield surveillance) and ships (Ocean surveillance), Estimation of the location and speed of the entities (aircrafts, tanks, ships).</td>
</tr>
<tr>
<td>Situation Assessment</td>
<td>Estimation about the entities existence and type of resources (sensors, machinery, equipments and weapons) needed, Divisions of military group in platoons and battalions (to perform military activities in different groups at various locations).</td>
</tr>
<tr>
<td>Impact Assessment</td>
<td>Prediction of enemy intentions about attacks, threats, risks and impacts of the current actions.</td>
</tr>
<tr>
<td>Process Refinement</td>
<td>Sensor resource management depending upon the situation (selection of which type of sensor e.g. turning</td>
</tr>
</tbody>
</table>
on the IFF (Identification Friend or Foe) sensor to determine the aircraft identity instead of turning on other sensors).

| Cognitive Refinement | Coordination and communication between pilot and operator (air defense) or commander and operator (battlefield surveillance) through physical interface (for transmission of the messages about awareness of the situation). |

Table 5  
Relation between the JDL model and the military activities

3.3.2 MULTISENSOR FUSION TO REDUCE INFORMATION OVERLOAD

The factor of information overload has been described in detail along with their factors in the Background section. A commander has to manage many activities in the battlefield e.g. communication with the soldiers to know the current situation of the battlefield and with high authorities to inform them the present position, managing resources needed for battlefield, estimation of threats and implementation of the decisions.

The success of the mission depends upon the decision of the commander whereas his decision depends upon the experience, expertise and also on the knowledge about the information provided by the sources (sensors), but there may be a chance that the information provided by the sensor is uncertain and conflicting which increases the complexity that puts more load on the commander to make decisions.

Many issues associated with the dynamic nature of the battlefield domain in the form of communication issues, sensor management issues, target identification issues, uncertainty and conflicting issues (see, for example Horn and Baxter [24], Opitz et al [57], Zhang, Ji and Looney [58], Xiong and Svensson [59]). This thesis will present the multisensor fusion methods used for the issue of uncertainty management to identify the targets in the battlefield to reduce information overload up to some extent, but before explaining the uncertainty management.
methods, it is necessary to describe some reasons for the uncertainty in the battlefield and advantages of multisensor fusion to reduce uncertainties in the battlefield for minimizing the information overload on the commander to enhance the SAW and DM with the help of some examples.

3.3.2.1 REASONS OF UNCERTAINTIES

Zhang, Ji and Looney [58] and Xiong and Svensson [59] have provided some reasons for the uncertainties which are as follows.

- Sensor failure.
- Noise.
- Obstacles in the battlefield.
- Weather conditions.
- Improper sensor management.

All the above causes of uncertainties are related to the multisensor environment in which normally the source of information is sensor. It is obvious that in case of sensor failure, sensors cannot give the exact readings. Sensors transmit signals in the form of waves to detect the targets, but for instance obstacles and bad weather conditions disturb the signal of the sensors which lead to the inaccurate information. The last reason of improper sensor management has been described in detail by Xiong and Svensson [59].

According to Xiong and Svensson [59], sensor management is the process of managing or coordinating the use of the multiple sensors to improve the measurements i.e. selection of right sensors to perform the right service on the right object at the right time. Improper sensor management relates to the issues of sensor deployment (when, where and how many sensors required) and sensor selection issues (which sensor required).

Various types of sensors used in the battlefield to provide different information e.g. classification, identification of friend or foe, range and direction. One sensor cannot provide all information regarding one object in the battlefield because different sensors are of different capabilities in form of coverage, weather
sensitivity and maximum ranges e.g. Hall and Llinas [10] have given the example of fusing two different types of information provided by two different sensors such as RADAR (RAdio Detection And Ranging) for providing only the factor of range and FLIR (Forward Looking Infrared) for providing the other factor of angular direction to determine the exact position of the target in the air. Keeping in mind the separate and individual capabilities of the sensor, sensor deployment and sensor selection should be managed to reduce the issue of uncertainty.

3.3.2.2 BENEFITS OF MULTISENSOR FUSION

Esteban et al [21], Hall and Llinas [9], Luo and Kay [50], Varshney [61] have defined many benefits of using multisensor fusion technology which are as follows.

- Estimation of the target position and velocity can be improved with the help of two different readings provided by two identical sensors (RADAR) regarding same attribute (range).

- Errors about finding the exact location of the target can be reduced with the help of two sensors, providing two different types of attributes e.g. range and angular direction of the target.

- In case of failure of one sensor, the operation of other sensors helps to improve the reliability and robustness of the system.

- Coverage of the region for detecting the targets can be increased with the help of multiple sensors.

- Performance and confidence of the system can be increased with multiple sensors that enhance the SAW and DM.

- More data can be collected in less time with the help of multiple sensors instead of one sensor that helps to take out more information from excessive amount of data.
- Display resolution can be improved with the use of multiple sensors having different resolutions in order to identify the image of the target.

- Cost can be reduced with the use of multiple sensors. Normally it looks that deployment of one sensor is cheaper than the deployment of multiple sensors, but in case of any failure of one sensor in the environment of single sensor, target position of the enemy cannot be identified and enemy attack can put the huge loss in the form of causalities and amount of money.

The ultimate goal of multisensor fusion technology is to help the decision makers in complex environments to perform the right decisions in order to meet their objectives. All the above mentioned benefits of multisensor fusion technology help commanders in a battlefield to take correct decisions about the identification of the different targets to reduce the issue of information overload in the form of uncertainties.

Measurement errors represent uncertainties in the data that can cause the commander to misinterpret the current situation of the battlefield which could make the base for wrong actions that result in severe negative effects. Multisensor fusion plays very important role to reduce these uncertainties. Although there are some issues relating to multisensor fusion that Xiong and Svensson [59] has mentioned in the form of sensor placement and sensor coordination, but this technology has more benefits over the use of single sensor. The effective use of this technology with the help of different sensors in a battlefield environment to reduce the information overload on the commanders to enhance SAW and DM can be visualized with the help of the following diagram.
Figure 18 Relationship of multisensor fusion technology with DM and SAW in military battlefield to reduce information overload

The overview of the use of multisensor information fusion technology along with its functions related to the process of decision making and state of situation awareness especially in the field of military battlefield to describe the reasons of the information overload that can effect the decision making capabilities of the commander has been shown in the above figure.
According to the figure, sources (sensors) capture the data from the environment and inputs data to the multisensor fusion technology that performs the following actions:

- **provides** different methods such as Bayesian and Dempster Shafer that reduce the factor of uncertainties (produce by different reasons) that causes the main factor of information overload that affects the battlefield process.

- **supplies** the activities of the sensor fusion JDL model that corresponds the battlefield activities that relate to the battlefield process and also improves the process of DM that requires the state of SAW that holds in the brain of the commander and ultimately enhances the battlefield process.

- **reflects** levels of the multisensor fusion that indicates the battlefield activities from low level data fusion (detection of signals by the sensors) to the high level decision fusion (threat assessment).
The issue of uncertainty along with its causes and impacts on the process of decision making in military battlefield has already been described in the earlier sections of this thesis. According to Bloch and Hunter et al [85] (as mentioned in Karlsson [62]) defined the term of uncertainty as follows.

"Uncertainty refers to lack of sufficient information about the state of the world, for determining whether a Boolean statement (which can only be true or false) is indeed true or false."

Uncertain information from the sensors can cause losses in the military battlefield in the form of wrong decisions made by the commander. The incorrect decision about identification of enemy targets in a battlefield and erroneous actions can put more pressure on the commander. Multisensor fusion technology helps commanders to take right decisions regarding battlefield activities through reducing the uncertainties in the information. The detail of two Uncertainty Management Methods (UMMs) of Bayesian theory and Dempster Shafer theory is presented in the next section to show how these methods reduce the uncertainty in identification of targets in a multisensor environment.

4.1 BAYESIAN THEORY

Bayesian theory is one of the UMMs used in information fusion technology. According to Karlsson [62], this theory is an approach of calculating probabilities of the belief. In this approach the random variables are joined with the direct edges to describe the concept of conditional probabilities. Assume that $A$ and $B$ denotes two random variables, then the joint probability distribution for all possible values of $A$ and $B$ can be defined with the help of following Bayes formula.

$$P(A|B)=\frac{P(B|A)P(A)}{P(B)}$$
Before explaining this rule, it is necessary to describe some important terms used in the Bayesian theory.

4.1.1 **PROBABILITY**

Probability is the measurement of the degree of the belief that an event will occur. This term is related with the following two terms.

4.1.2 **PRIOR AND POSTERIOR PROBABILITY**

According to the Luger [60],

“Prior probability often called the unconditional probability, of an event is the probability assigned to an event in the absence of knowledge, that is, the probability of the event prior to any evidence”

and

“The posterior probability, often called conditional probability, of an event is the probability of an event given some evidence”

To explain these two concepts of probabilities, one example has been taken from the Triola [63]. The task of one organization is to select the adult for the survey about usage of credit card in America. In order to find the probability that the selected adult is male, rough idea can be made that half of Americans are male and half are female then in this case the probability will be the prior probability expressed in the form of \( P(M) = 0.5 \). After selection of the adult, it was noticed that the adult was smoking during the time of interview, now in this case to find the probability of adult is male, the prior probability is revised into the posterior probability showing that normally 85% smokers are male and it can be expressed as \( P(M|S) = 0.85 \).

4.1.3 **BAYESIAN NETWORK**

According to Jensen [86] (as mentioned in Laskey [64]), BN (Bayesian network) consists of the following things.

- A set of random variables representing the nodes.
- A set of directed edges between variables showing the dependencies between the nodes.
The random variables together with the directed edges form a DAG (Directed Acyclic Graph).

- CPTs (Conditional Probability Tables) that show the probability values of parent and child nodes.

The following snapshot has been taken from the Johansson [65] in order to explain the Bayesian network with the help of example in more detail.

**Figure 19** The Example of Bayesian Network adapted from Johansson [65]

The above diagram shows a Bayesian network DAG having four random variables of Cloudy, Sprinkler, Rain and WetGrass indicated by characters of C, S, R and W respectively in the CPTs. The probabilities mentioned in the CPT of Cloudy are prior probabilities having equal ratio of 0.5 in each case of C=T and C=F, whereas the other probabilities mentioned in other CPTs of Sprinkler, Rain and WetGrass are posterior probabilities. If the weather is cloudy then it is obvious that there can be only 10% (0.1) chance of using Sprinkler and 90% (0.9) chance of not using the Sprinkler, but if the weather is not cloudy then in this case the chances of using Sprinkler are 50% (0.5). Similarly if the weather is cloudy then it has more chances of rain i.e. 80% (0.8) and 20% (0.2) chance of not raining. If Sprinkler used along with the Rain then it has the highest probability of WetGrass i.e. 99% (0.99) and only a very little chance of 0.1% (0.01) that the grass is not wet. In any case of using Sprinkler with Rain, there will be the probability of 0.9 (90%) for WetGrass and probability of 0.1 (10%) for no WetGrass. Finally, if no Sprinkler is
used and there is no Rain then it’s not possible that the grass is wet i.e. 0.0% and 100% chance that grass is not wet.

The joint probability distribution having all combinations of the probabilities of all variables used in the above example can be written as,

\[ P(C,S,R,W) = P(C) \cdot P(S|C) \cdot P(R|C) \cdot P(W|S,R) \]

**4.1.4 CHAIN RULE**

Chain rule is used to calculate the joint probability distributions. According to Kjaerulff and Madsen [66], to calculate the P(X) for a set of variables \( X = \{X_1, \ldots, X_n\} \), the chain rule is,

\[
P(X) = P(X_1 | X_2, \ldots, X_n) \cdot P(X_2, \ldots, X_n) \\
= P(X_1 | X_2, \ldots, X_n) \cdot P(X_2 | X_3, \ldots, X_n) \cdots P(X_{n-1} | X_n) \cdot P(X_n)
\]

\[
= \prod_{i=1}^{n} P(X_i | X_{i+1}, \ldots, X_n)
\]

In order to understand the working of chain rule and BN, suppose the problem is to find out the joint probability distribution from figure 19 that the grass is not wet (W=F) given the conditions of cloudy weather (C=T), raining (R=T) and no sprinkler is used (S=F), then this joint probability distribution can be calculated in the following way.

\[
P(W=F|C=T,R=T,S=F) = ?
\]

\[
= \frac{P(W=F,C=T,R=T,S=F)}{P(C=T,R=T,S=F)} \quad \text{Bayes Theorem}
\]

\[
= \frac{P(C=T)*P(S=F|C=T)*P(R=T|C=T)*P(W=F|S=F,R=T)}{\sum P(C=T)*P(S=F|C=T)*P(R=T|C=T)*P(W|S=F,R=T)} \quad \text{Chain Rule}
\]

\[
= \frac{0.5*0.9*0.8*0.1}{0.5*0.9*0.8*0.1 + 0.5*0.9*0.8*0.9}
\]

\[
= \frac{0.036}{0.036 + 0.324}
\]

\[
= \frac{0.036}{0.36}
\]

\[
= 0.1
\]
From the answer it is clear that if the weather is cloudy outside along with raining and sprinkler is not used then it is obvious that there should be minimum chances of not wetting the grass i.e. 10% (0.1) and more chances of wetting the grass i.e. 90% (can easily be calculated by following the above calculations).

### 4.1.5 Conditional Independence

The concept of conditional independencies is used in the BN and to show these independencies, the concept of d-separation is used in BN. According to Johansson [65], two variables in a BN are d-separated means conditional independent if, for all the paths between two variables.

1) "There is an intermediate variable V such that either the connection is serial or diverging and the state of V is known”
2) “The connection is converging and we have no knowledge of V and its descendants.”

The different kinds of connections from figure 19 are as follows.

#### Serial Connections

- Cloudy → Sprinkler → WetGrass
- Cloudy → Rain → WetGrass

If there is hard evidence about Rain and the usage of Sprinkler (means value of intermediate variable is known) then these serial connections are conditional independent which means that evidence on Cloudy weather will not affect the belief about the state of the WetGrass and vice versa or Cloudy weather does not make any influence on the WetGrass. There may be a chance that no evidence found about the usage of Sprinkler, in this case the evidence of Cloudy weather will affect the state of WetGrass and vice versa means not conditional independent.

#### Diverging Connections

- Sprinkler → Cloudy → Rain
If there is hard evidence about Cloudy weather then the above mentioned diverging connection is conditional independent which means that evidence of the usage of Sprinkler will not affect the belief about the state of the Rain and vice versa.

**Converging Connections**

Sprinkler → WetGrass → Rain

If there is no hard evidence about WetGrass and its descendents then this converging connection is conditional independent which means that evidence of the usage of Sprinkler will not affect the belief about the state of the Rain and vice versa.

### 4.1.6 TARGET IDENTIFICATION THROUGH BAYESIAN NETWORK

Target identification is one of the issues of the battlefield domain. A commander has to take decisions about the correct identification of the targets and his decisions normally based on the readings of the sensors. The uncertainty issue arises here when extracting the information from different sensors because of many reasons (cf. section 3.3.2.1 page 49). Uncertainties can be removed with the help of BN that helps commander to take decision about the accurate identification of the targets. Following example will show the effectiveness of the Bayesian approach in uncertainties.

![Bayesian Network for Identification of Targets](image)

**Figure 20** Bayesian Network for Identification of Targets adapted from Bladon, Hall and Wright [67]
This example has been taken from Bladon, Hall and Wright [67] to explain the working of Bayesian theory in uncertainties. Two sensors $S1$ and $S2$ are detecting the type of Aircraft variable that has two attributes of friend ($f$) and enemy ($e$) along with the two conditions of the weather ($norain$ and $rain$) in the above diagram. The CPTs of the above diagram are as follows.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$</td>
<td>0.7</td>
</tr>
<tr>
<td>$e$</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Table 6 (a) CPT for Aircraft**

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>$f$</th>
<th>$e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$norain$</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>$rain$</td>
<td>0.1</td>
<td>0.9</td>
</tr>
</tbody>
</table>

**Table 6 (b) CPT for Weather**

The table 6 (a) presents the prior probability distributions of different types of aircrafts ($friend$ and $enemy$) having the probabilities of 0.7 and 0.3 respectively. The table 6 (b) is the CPT for the values of the Weather having probability of 0.9 for $norain$ and 0.1 for $rain$. The table 6 (c) is the CPT for the values of sensor1 given Aircraft and Weather, and the table 6 (d) is the CPT for the values of sensor2 given Aircraft and Weather.

Some calculations are performed now along with the results of GeNIe software in order to show the effectiveness of the Bayesian theory to reduce uncertainties in target identification. Suppose Sensor 1 and Sensor 2 are providing same
information that the aircraft is friendly and weather is clear (norain) then in this case the probability of the Aircraft for friend can be calculated in the following way from the tables 6 (a-d).

Abbreviations used for calculation:
Aircraft = A, Weather = W, Friend = F, Enemy = E, Sensor1 = S1, Sensor2 = S2

\[
P(A=F|S1=F, S2=F, W=norain) = \frac{P(A=F, S1=F, S2=F, W=norain)}{P(S1=F, S2=F, W=norain)}
\]

\[
= \frac{P(A=F)*P(W=norain)*P(S1=F|A=F, W=norain)*P(S2=F|A=F, W=norain)}{\sum P(A)*P(W=norain)*P(S1=F|A, W=norain) * P(S2=F|A, W=norain)} 
\]

\[
= \frac{0.7*0.9*0.9*0.6}{0.7*0.9*0.9*0.6 + 0.3*0.9*0.1*0.4}
\]

\[
= 0.969 
\]

**Figure 21** Probability of Aircraft (same information from both sensors under clear weather conditions)

The formulas of Bayesian and chain rule are used to calculate the above mentioned probability. From the calculation it is clear that if both sensors provide same information about Aircraft identification i.e. friendly in this case then there are more chances (0.969) of that Aircraft for which both sensors are providing
same information. The result is verified by the above diagram (produced in GenIe) and similarly probability for the enemy Aircraft can also be calculated in the same way.

Suppose Sensor 2 is providing information that the aircraft is friendly with clear (norain) weather conditions but Sensor 1 is not providing any information. A commander has to take decision about the accurate type of aircraft, but in this case one sensor is identifying and the other is not which means information is incomplete that lead to the uncertainty. In the case of incomplete information, the probability of the Aircraft for friend can be calculated in the following way from the tables 6 (a-d).

\[
P(A=F|S2=F, W=norain) = \frac{P(A=F, S2=F, W=norain)}{P(S2=F, W=norain)} = \frac{P(A=F) \cdot P(W=norain) \cdot P(S2=F|A=F, W=norain)}{\sum P(A) \cdot P(W=norain) \cdot P(S2=F|A, W=norain)}
\]

\[
= \frac{0.7 \cdot 0.9 \cdot 0.6}{0.7 \cdot 0.9 \cdot 0.6 + 0.3 \cdot 0.9 \cdot 0.4}
\]

\[
= \frac{0.378}{0.378 + 0.108}
\]

\[
= 0.778
\]

Figure 22 Probability of Aircraft (incomplete information under clear weather conditions)
According to the above calculation and figure, the probability of the Aircraft as *friend* has decreased now from the previous value of 0.969 (cf. figure 21) to the value of 0.778. It is because of the reason that now one sensor is providing information instead of both sensors but the overall results did not change and showing that there are more chances of *friendly* Aircraft instead of *enemy* in both the cases of same information from both sensors and incomplete information. The probability of *friendly* aircraft (0.969) is greater than the probability of *enemy* aircraft (0.031) in figure 21 and similarly in the figure 22 (0.778>0.222).

Suppose Sensor 2 is providing information that the aircraft is *friendly* and now weather is not clear (*rain*) then the probability of the Aircraft for *friend* can be calculated in the following way from the tables 6 (a-d).

\[
P(A=F|S2=F, W=\text{rain}) = \frac{P(A=F, S2=F, W=\text{rain})}{P(S2=F, W=\text{rain})} \\
= \frac{P(A=F) \times P(W=\text{rain}) \times P(S2=F|A=F, W=\text{rain})}{\sum P(A) \times P(W=\text{rain}) \times P(S2=F|A, W=\text{rain})} \\
= \frac{0.7 \times 0.1 \times 0.9}{0.7 \times 0.1 \times 0.9 + 0.3 \times 0.1 \times 0.1} \\
= \frac{0.063}{0.063 + 0.003} \\
= \frac{0.063}{0.066} = 0.955
\]

*Figure 23* Probability of Aircraft (incomplete information under bad weather conditions)
According to the above calculation and figure, the probability of the Aircraft as friend has increased now from the previous value of 0.778 (cf. figure 22) to the value of 0.955 (cf. figure 23). The main difference in both cases (figure 22 and 23) is weather conditions. Sensor 2 has more capability of working in the bad weather conditions i.e. rain instead of clear weather as compared to the Sensor1 (cf. values of Table 6 c, d). The weather is not clear in this case so that the probability for friendly aircraft is increased from previous value. There are some sensors that work better at night and in bad weather conditions like TIR (Thermal Infrared).

Suppose Sensor 1 is showing that the Aircraft is enemy and Sensor 2 is showing the conflicting information that the aircraft is friendly along with clear weather conditions (norain) then the probability of the Aircraft for friend can be calculated in the following way from the tables 6 (a-d).

\[
P(A=F|S1=E, S2=F, W=norain) = \frac{P(A=F) \cdot P(W=norain) \cdot P(S1=E|A=F, W=norain) \cdot P(S2=F|A=F, W=norain)}{\sum P(A) \cdot P(W=norain) \cdot P(S1=E|A, W=norain) \cdot P(S2=F|A, W=norain)}
\]

\[
= \frac{0.7 \cdot 0.9 \cdot 0.1 \cdot 0.6}{0.7 \cdot 0.9 \cdot 0.1 \cdot 0.6 + 0.3 \cdot 0.9 \cdot 0.9 \cdot 0.4}
\]

\[
= 0.0378
\]

\[
= 0.0378 + 0.0972
\]

\[
= 0.28
\]

Figure 24 Probability of Aircraft (conflicting information under clear weather conditions)
Now the result from the above figure is very different with the previous result of figure 22. Weather conditions are clear (norain) in both cases (figure 22 and figure 24) but one case relates to incomplete information and the other one relates to conflicting information. According to figure 24, the probability of the enemy aircraft (0.72) is higher than the probability of the friendly aircraft (0.28) which is quite opposite to the previous result of figure 22 that is showing more probability to friendly aircraft as compared to the enemy aircraft. This result showing aircraft as enemy because Sensor 1 is indicating aircraft as enemy and weather conditions are clear so that the probability of the enemy aircraft is increased by neglecting the information of Sensor 2 i.e. friendly aircraft because Sensor 2 is less reliable in clear weather as compared to the Sensor 1.

Suppose Sensor 1 is showing that the Aircraft is enemy and Sensor 2 is showing the conflicting information that the aircraft is friendly but weather is not clear (rain) now then the probability of the Aircraft for friend can be calculated in the following way from the tables 6 (a-d).

\[
P(A=F|S1=E, S2=F, W=\text{rain}) = \frac{P(A=F, S1=E, S2=F, W=\text{rain})}{P(S1=E, S2=F, W=\text{rain})} \]

\[
= \frac{P(A=F)P(W=\text{rain})P(S1=E|A=F, W=\text{rain})P(S2=F|A=F, W=\text{rain})}{\sum P(A)P(W=\text{rain})P(S1=E|A, W=\text{rain}) P(S2=F|A, W=\text{rain})} \]

\[
= 0.7*0.1*0.3*0.9 \quad \frac{0.7*0.1*0.3*0.9 + 0.3*0.1*0.7*0.1}{0.7*0.1*0.3*0.9 + 0.3*0.1*0.7*0.1} \]

\[
= 0.0189 \quad \frac{0.0189+0.0021}{0.0189+0.0021} \]

\[
= 0.0189 \quad \frac{0.021}{0.021} \]

\[
= 0.9
\]
According to figure 25, the probability of the friendly aircraft (0.9) is higher than the probability of the enemy aircraft (0.1) which is opposite to the previous result of figure 24 that is showing more probability to enemy aircraft as compared to the friendly aircraft. This is because of the reason that Sensor 2 is indicating aircraft as friend and weather conditions are not clear so that the probability of the friendly aircraft is increased by neglecting the information of Sensor 1 i.e. enemy aircraft because Sensor 1 is less reliable in bad weather as compared to the Sensor 2.

4.2 DEMPSTER SHAFER THEORY

DST (Dempster Shafer Theory) is proposed by Shafer in 1976 in his book named “A Mathematical Theory of Evidence”. DST is a mathematical theory that is used to manage the uncertainty issue and it is about building beliefs about the exact state of the environment from different evidences (Sentz and Ferson [68]). DST is a numerical model that is used as an alternative to the BN. DST provides graphical description of the knowledge through explaining relationships between different variables and also provides numerical explanation by assigning basic probability assignments to all the subsets of the variables (Cobb and Shenoy [69]).

\( \Theta \) symbol represents frame of discernment that is the set of all possible values. There are some assumptions about frame of discernment in the DST, the first one is that the elements of the \( \Theta \) are mutually exclusive (only one state can be true)
and second one is that elements are exhaustive (true state will be in the Θ) Karlsson [70].

Let \( m_1 \) and \( m_2 \) are two mass functions in the frame of discernment \( U \) then Dempster rule of combination is as follows.

\[
m(A) = \sum_{B \cap C = A} m_1(B) m_2(C) \]

\[
1 - \sum_{B \cap C \neq \emptyset} m_1(B) m_2(C)
\]

In order to understand the working of DST, it is necessary to describe some functions of this theory.

### 4.2.1 FUNCTIONS OF DEMPSTER-SHAFER THEORY

The three functions used in the DST are as follows.

#### 4.2.1.1 MASS FUNCTION

Basic probability assignment function is denoted by \( m \). “Mass function of a given set \( A \) represented by \( m(A) \) expresses the proportion of all relevant and available evidence that a particular element of \( X \) (the universal set) belongs to the set \( A \) but to no particular subset of \( A \)” (Sentz and Ferson [68]).

In DST, each mass function can be represented through following three equations.

1) \( m: 2^\Theta \rightarrow [0,1] \) (Mass function should be between 0 and 1)

2) \( m(\emptyset) = 0 \) (Mass function of the empty set is 0)

3) \( \sum_{A \subseteq \Theta} m(A) = 1 \) (Sum of all mass functions is 1)

#### 4.2.1.2 BELIEF FUNCTION

The belief function \( Bel \) is the sum of all the basic probability assignments over all subsets (Nazarko [71]) and it can be presented through following equation.

\[
Bel(A) = \sum_{B \subseteq A} m(B)
\]

#### 4.2.1.3 PLAUSIBILITY FUNCTION

Plausibility \( Pl \) is the sum of all the basic probability assignments of the sets that intersect with the set \( A \) (Sentz and Ferson [68]) and it can be presented through following equation.
\[ Pl(A) = \sum_{B \cap A \neq \emptyset} m(B) \]

4.2.2 **EXAMPLE OF DEMPSTER SHAFER THEORY**

An example has been taken from Smets [72] to show the working of DST for understanding the functions of belief and plausibility. The example is about to find the person that murder John. Better estimates about the murderer can be obtained by combining all evidences and calculating beliefs and plausibility’s by performing following calculations of the DST.

Who murdered John?

*(Frame of discernment)*

\( \Theta = \{\text{Henry, Tom, Sarah, Peter}\} \)

*(Evidences from witness 1)*

\( m_1(\{\text{Henry, Peter, Sarah}\}) = 0.7, \quad m_1(\{\text{Sarah}\}) = 0.3 \)

*(Evidences from witness 2)*

\( m_2(\{\text{Henry, Sarah}\}) = 0.4, \quad m_2(\{\text{Tom, Peter, Henry}\}) = 0.6 \)

All the possible persons involved in the murder of John are mentioned in the *frame of discernment* along with the evidences of two witnesses’. According to witness 1, there is a chance of 70% that any one of among Henry, Peter and Sarah murdered John and only 30% chance that Sarah murdered John. Similarly witness 2 reported that there is a chance of 40% that any one of between Henry and Sarah murdered John and 60% possibility of among Tom, Peter and Henry.

<table>
<thead>
<tr>
<th>( m_1 )</th>
<th>( m_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>{Henry, Sarah}/0.4</td>
<td>{Tom, Peter, Henry}/0.6</td>
</tr>
<tr>
<td>{Henry, Peter, Sarah}/0.7</td>
<td>{Henry, Sarah}/0.28</td>
</tr>
<tr>
<td>{Sarah}/0.3</td>
<td>{Sarah}/0.12</td>
</tr>
</tbody>
</table>

**Table 7 Mass Calculations**

*Mass Calculations*

\[ m_{12} \{\emptyset\} = 0.18 \]

\[ m_{12} \{\text{Henry, Sarah}\} = m_{12} \{\text{Henry, Sarah}\}/0.28 = 0.34 \]

\[ 1- m_{12} \{\emptyset\}/1-0.18 = 3.4 \]
The mass functions of the first witness are in the left column of the above table whereas the mass functions of other witness are in the right column. The method of representing mass functions in a table is to find the common values between the two sets of different evidences; multiply the values of the denominator and put this multiplication result under the set of common values. After making the table, the next step is to take all common values (4 in this case) and divide these values by the subtracted result of mass function of empty set by 1. From the results it is concluded that there is a higher possibility of 51% that any one of between Henry and Peter has murdered John instead of other persons.

**Belief Calculations**

\[
\begin{align*}
Bel_{12} \{\text{Henry, Sarah}\} &= m_{12} \{\text{Henry, Sarah}\} + m_{12} \{\text{Sarah}\} \\
&= 0.34 + 0.15 \\
&= 0.49 \\
Bel_{12} \{\text{Henry, Peter}\} &= m_{12} \{\text{Henry, Peter}\} \\
&= 0.51 \\
Bel_{12} \{\text{Sarah}\} &= m_{12} \{\text{Sarah}\} \\
&= 0.15
\end{align*}
\]

Belief function is a lower degree of belief in DST. The method of calculating belief is to add that masses from the result of mass calculations which are subsets of the belief set e.g. to calculate the belief of Henry and Sarah (\(Bel_{12} \{\text{Henry, Sarah}\}\)), there are only two subsets of this set from the resulted mass calculations i.e. \(m_{12} \{\text{Henry, Sarah}\}\) and \(m_{12} \{\text{Sarah}\}\). The belief about Henry and Sarah has increased in this case from 0.34 to 0.49 but the overall result is still showing that any one of between Henry and Peter has murdered.

**Plausibility Calculations**

\[
\begin{align*}
Pl_{12} \{\text{Henry, Sarah}\} &= m_{12} \{\text{Henry, Sarah}\} + m_{12} \{\text{Henry, Peter}\} + m_{12} \{\text{Sarah}\} \\
&= 0.34 + 0.51 + 0.15
\end{align*}
\]
IMPACT OF INFORMATION FUSION IN COMPLEX DECISION MAKING

\begin{align*}
P_{l_12} \{\text{Henry, Peter}\} & = m_{l_2} \{\text{Henry, Peter}\} + m_{l_2} \{\text{Henry, Sarah}\} \\
& = 0.51 + 0.34 \\
& = 0.85
\end{align*}

\begin{align*}
P_{l_12} \{\text{Sarah}\} & = m_{l_2} \{\text{Sarah}\} + m_{l_2} \{\text{Henry, Sarah}\} \\
& = 0.15 + 0.34 \\
& = 0.49
\end{align*}

Plausibility function is a higher degree of belief in DST. The method of calculating plausibility is to add all masses from the result of mass calculations that have at least one common value e.g. to calculate the plausibility of Henry and Sarah \(P_{l_12} \{\text{Henry, Sarah}\}\), there are three sets now that have at least one common value with this set i.e. \(m_{l_2} \{\text{Henry, Sarah}\}, m_{l_2} \{\text{Henry, Peter}\}\) and \(m_{l_2} \{\text{Sarah}\}\). The result is showing that any one of between Henry and Sarah has murdered John (the other two persons did not murder).

4.3 TARGET IDENTIFICATION THROUGH DEMPSTER SHAFER THEORY

Same example has been taken from Bladon, Hall and Wright [67] to show the working of DST now instead of Bayesian theory for target identification. There are two sensors which are observing the type of aircrafts as friend or enemy and the problem is to find the correct estimate of the single aircraft. There are also two weather conditions (rain and norain). The frame of discernment and the readings of two sensors in clear (norain) and bad (rain) weather conditions are as follows.

\(\Theta = \{\text{F, E}\}\) (F for friend and E for enemy)

Sensor 1 readings are,

\(m_1(\{\text{F}\}) = .9, m_1(\{\text{E}\}) = .1\) (clear weather) and \(m_1(\{\text{F}\}) = .7, m_1(\{\text{E}\}) = .3\) (bad weather)

Sensor 2 readings are,

\(m_2(\{\text{F}\}) = .6, m_2(\{\text{E}\}) = .4\) (clear weather) and \(m_2(\{\text{F}\}) = .9, m_2(\{\text{E}\}) = .1\) (bad weather)

\[
\begin{array}{c|c|c}
\text{m}_1 & \text{m}_2 \\
\hline
\{\text{F}\}/.6 & \{\text{E}\}/.4 \\
\{\text{F}\}/.9 & \{\text{F}\}/.54 & \emptyset)/.36 \\
\{\text{E}\}/.1 & \emptyset)/.06 & \{\text{E}\}/.04 \\
\hline
\end{array}
\]

Table 8 Mass Calculations for Identifying Aircrafts (same information from both sensors under same weather conditions)
It is clear from the above calculations that the aircraft is friendly having highest mass of 0.931 instead of enemy having less mass of 0.069. This is because of the reason that both sensors have initially given evidences in the form of highest masses of 0.9 and 0.6 to the friendly aircraft as compared to the enemy aircraft.

Suppose weather is not clear (rain) and Sensor 1 is providing higher evidence to the friendly aircraft whereas Sensor 2 is providing higher evidence to the enemy aircraft. The working of DST in case of conflicting information between two sensors is as follows.

Sensor 1 readings are,
$m_1(\{F\}) = .7, m_1(\{E\}) = .3$
Sensor 2 readings are,
$m_2(\{F\}) = .2, m_2(\{E\}) = .8$

<table>
<thead>
<tr>
<th>$m_1$</th>
<th>$m_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>${F}/.2$</td>
<td>${E}/.8$</td>
</tr>
<tr>
<td>${F}/.7$</td>
<td>${F}/.14$</td>
</tr>
<tr>
<td>${E}/.3$</td>
<td>${\emptyset}/.06$</td>
</tr>
</tbody>
</table>

**Table 9** Mass Calculations for Identifying Aircrafts (conflicting information from both sensors under bad weather conditions)

$m_{12}\{\emptyset\} = m_1\{F\}m_2\{E\} + m_1\{E\}m_2\{F\}$
$m_{12}\{\emptyset\} = .56+.06$
$= 0.62$
$m_{12}\{F\}=(.14)/1–0.62 = .14/0.38 = 0.368$
$m_{12}\{E\}=(.24)/1–0.62 = .24/0.38 = 0.632$
Now results are very different as compared to the results derived from Table 8. It is clear from the above calculations that the aircraft is *enemy* instead of *friendly* because of highest mass of 0.632 as compared to 0.368 whereas the resulting calculations from Table 8 are showing that the aircraft is *friendly* not *enemy*. This is because of the reason that Sensor 2 is more capable of identifying targets in bad weather conditions as compared to Sensor 1, so the answer goes to the higher evidence of Sensor 2 i.e. *enemy* by neglecting the higher evidence of Sensor 1 for *friend*.

Suppose weather is clear (*norain*) now and Sensor 1 is providing higher evidence to the *friendly* aircraft whereas Sensor 2 is providing higher evidence to the *enemy* aircraft. The working of DST in this case of conflicting information between two sensors is as follows.

Sensor 1 readings are,
\[ m_1(F) = .9, \quad m_1(E) = .1 \]

Sensor 2 readings are,
\[ m_2(F) = .2, \quad m_2(E) = .8 \]

\[
\begin{array}{c|c|c|c}
{m_1} & {m_2} & \{\emptyset\} & \{E\} \\
\hline
\{F\}/.2 & {E}/.8 & \{\emptyset\}/.72 & \{E\}/.02 \\
\{F\}/.9 & {F}/.18 & \{\emptyset\}/.02 & \{E\}/.08 \\
\{E\}/.1 & \{\emptyset\}/.02 & \{E\}/.08 \\
\end{array}
\]

**Table 10** Mass Calculations for Identifying Aircrafts (conflicting information from both sensors under clear weather conditions)

\[
m_{12}\{\emptyset\} = m_1(F)m_2(E) + m_1(E)m_2(F) \\
m_{12}\{\emptyset\} = 0.72 + 0.02 \\
= 0.74
\]

\[
m_{12}\{F\} = (0.18)/(1-0.74) = 0.18/0.26 = 0.692 \\
m_{12}\{E\} = (0.08)/(1-0.74) = 0.08/0.26 = 0.308
\]

It is clear from the above calculations that the aircraft is *friendly* instead of *enemy* because of highest mass of 0.692 as compared to 0.308 whereas the resulting calculations from Table 9 are showing that the aircraft is *enemy* not *friendly*. Sensor 1 is more capable of identifying targets in clear weather conditions as
compared to the Sensor 2. Although Sensor 2 has provided higher evidence of 0.8 for the enemy aircraft but the final result is converted into the favour of Sensor 1 because of clear weather conditions.

4.3 **COMPARISON BETWEEN BAYESIAN AND DEMPSTER-SHAFER THEORY**

Both methods are used for decision making under uncertainty and have some similarities and differences. Both theories need prior requirements in the form of masses and probabilities. There is a need of prior probabilities in Bayesian theory which are assigned by experts whereas the masses are assigned in the DST that shows different evidences obtained by multiple sources. The Bayesian theory represents beliefs through probabilities whereas the DST represents beliefs by using mass functions instead of probabilities that show evidences of the measurements. Belief and plausibility functions are used in DST to represent lower and higher degree of belief for making more accurate assessment of the target in military domain whereas these functions are not used in the Bayesian theory.

From the previous explanations about calculated results of both theories for target identification, it is clear that both theories enhance the state of SAW and DM process by producing strong results about correct identification of the aircraft in the military domain in case of uncertain information from sensors. The method of DST is used in that situations when there is low conflict between different measurements of multiple sensors. If two sensors are highly conflicting each other then DST produces very illogical results.

Zadeh’s example (Haenni [73]) is very popular in this case in which one doctor gives 99% possibility to the disease of meningitis for a patient, only 0.1% for concussion and 0% to tumor whereas the second doctor gives 99% possibility to the disease of tumor, only 0.1% for concussion and 0% to meningitis. The opinions of two different doctors are highly conflicting each other. After combining masses with DST, the result is 100% to the concussion disease which both doctors almost ignored. Some experts have proved the Zadeh’s example wrong and reject the criticism on DST (see for example, Haenni [73]) and some
have proposed new combination methods (see for example, Wu, Ye and Chen [74]).

According to Wu et al [75], DST is more close to the human perception and reasoning processes compared to the Bayesian theory and more natural because of representing observations through evidences from multiple sources instead of the using probabilities. There is also big difference between two theories in the situation of unknown knowledge (whether true or false), Bayesian theory gives equal probabilities of 0.5 in case of no knowledge about hypotheses whereas DST gives the mass of 0 if there is no evidence. Suppose the frame of discernment (Θ) has three variables of friend, enemy and neutral, sensor is showing 60% to the friend state which means target is more likely friend. In this case Bayesian theory will assign 60% to friend and divide remaining 40% in two equal parts of 20% and allocate these probabilities to other both states of enemy and neutral whereas DST will allocate 60% to the friend and remaining 40% to the whole set of frame of discernment “Θ” instead of dividing because of the non availability of the exact evidence about the information.

Bayesian network is used to describe/represent the joint probability distributions of all the used variables (nodes) by specifying their relationships with the parent nodes through conditional probabilities whereas the DST combines evidences and calculates the joint masses (basic probability assignment) of all the variables present in the frame of discernment to achieve the belief and plausibility levels showing states of the knowledge. According to Hall and McMullen [16], DST requires more computational power in terms of memory and processing as compared to the Bayesian theory; hypothesis are used in Bayesian network whereas propositions are used in DST that contains overlapping of different combination of hypothesis. Conceptual difference between these two theories is described by Yen [88] as mentioned in Hall and McMullen [16, Page 223] with the help of figure that shows the assignment of evidence to only one hypothesis in Bayesian theory and assignment of evidence to multiple hypotheses (propositions) in DST.
This thesis is structured to fulfill the objectives gradually for accomplishment of the aim. The concepts related to the military battlefield domain are described in detail to achieve the following first objective.

- Investigate and explain the important concepts of information fusion technology, situation awareness, decision making and information overload in military battlefield domain.

Data or information is combined from different sources in information fusion technology in order to know the exact entity states of the environment to support the process of decision making. This technology is used in many applications (cf. section 2.1.2) and different models are used to implement this technology (cf. section 2.1.1). Some challenges found while investigating this technology in the form of compatibility, association, coordination and conflicts in the sensors (cf. section 2.1.3). The concept of situation awareness based on the functions of perception, comprehension, projection and resolution (cf. table 3, page 40) has also been investigated to reduce the information gap (cf. figure 11, page 34) for achieving the goals of the military battlefield (cf. table 2, page 39) by showing the impact and relation of this concept with the decision making process (cf. section 2.2.4.2).

The process of decision making is not easy (cf. section 2.2.3.1) because it involves many planning functions (what should be done? when? how? where? by whom?) along with the functions of organizing and controlling. The process of decision making for a commander becomes very complex in the military battlefield domain because of performing so many activities in a specific order (cf. figure 10, page 31) along with handling responsibilities of the mission (cf. 2.2.2.2) under the factor of time pressure and information overload including the presence of risks and threats involved in the form of fire, loss of equipment and causalities. Information overload is the factor in which the information processing
requirements exceed the information processing mechanisms available. Some factors have been investigated in the form of uncertainties, conflicts, complexities (cf. section 2.2.3.3.1) which represent incomplete and conflicting information that put more pressure on the commander in the form of serious disaster based on wrong decision that eventually results information overload. These uncertainties arise due to some external factors of the environment e.g. weather conditions, noises, obstacles that affect the capabilities of the sensors and some other issues e.g. sensor failure and inappropriate sensor management (cf. 3.3.2.1).

Some challenges have found while exploring and investigating the first objective such as how to handle large amount of information in an efficient manner, how the necessary and required information can be extracted without losing the important information how decision can be made under the issue of information overload? All the challenges relate to the main issue of information overload.

The identification of the information overload problem lead to the next step of finding solution of this problem for the accomplishment of following next objective.

- Analyse how multi-sensor fusion technology is helpful for improving the performance of commanders in critical situations of information overload in military battlefield domain?

In order to reduce the problem of information overload in military battlefield domain, the multisensor fusion technology has been explained and analyzed as a solution which helps the commander for better decision making. The multisensor fusion technology combines information from multiple sensors (cf. figure 15, page 43) and represents three levels of data, feature and decision (cf. section 3.2.1) which refers to the different activities of the military battlefield (cf. figure 17, page 46). This technology is used for many purposes in the military battlefield domain such as risk management, reducing information overload and detecting, tracking and classifying different targets (cf. section 3.3). The factor of information overload can be reduced through minimizing uncertainties in the data with the help of multisensor fusion technology. Some examples related to the target identification problem has been described to show the effectiveness of this.
technology for minimizing uncertainties and improving the decision making capabilities of the commander (cf. sections 4.1.6 and 4.3). The examples show the efficiency of multisensor fusion technology for producing accurate results in the cases of incomplete and conflicting information from two sensors. This technology provides many benefits such as accuracy, reliability, robustness, less cost, more coverage and minimum errors (cf. section 3.3.2.2).

There are many multi-sensor fusion techniques for reducing uncertainties that lead to the next step of explaining and comparing two techniques for fulfilling the following third and final objective of the thesis.

- Comparison of information fusion methods used for reducing the information overload, thereby improving the decision making capabilities and increasing situation awareness of the commander.

The working of two uncertainty management methods of Bayesian and Dempster Shafer theories for reducing the uncertainties in target identification problem has been described and analyzed through taking different scenarios in the form of incomplete and conflicting information along with specifying the effects of sensor capabilities under different weather conditions (cf. sections 4.1.6 and 4.3). The calculated results indicate the effectiveness of these methods for correct identification of the target in case of uncertain information even in different weather conditions. Finally these two methods were compared to describe the differences and similarities between these methods (cf. section 4.3). Both methods are effective to handle the issue of uncertainty and have some strength and weaknesses such as Dempster Shafer theory is suitable in low conflicts whereas Bayesian theory can be used in high conflicts as well, Dempster Shafer theory is more close to the human perception because of representing observations through evidences whereas Bayesian theory is not because of using probabilities.

The overall structure for achieving objectives represents the aim of the thesis in the form of explaining and analyzing the use of multisensor information fusion technology for reducing uncertainties that results information overload through uncertainty management methods that improves the decision making capabilities of the commander in a battlefield.
Qualitative research method has been selected in this thesis in order to achieve the aim. Some interesting and challenging topics were found while studying and exploring relevant literature and research articles regarding the continuation of this thesis in the future in the form of explaining more methods other than Bayesian and Dempster Shafer theories not for only the identifications of the targets in a battlefield environment but for the higher levels of battlefield relating to threat evaluation and weapon allocation. Only the problem of target identification has only been covered in this thesis but this work has improved the understanding in order to reach at the top of the ladder representing threat evaluation and weapon allocation activities through climbing from the start representing target identification.

As an extension of this thesis, the threat evaluation and weapon allocation activities of the military domain could be analyzed through studying the algorithms and different multisensor fusion methods used to understand and analyze these activities. The effectiveness of different methods and algorithms could be compared graphically and numerically and tested through performing different tests with the help of software.
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