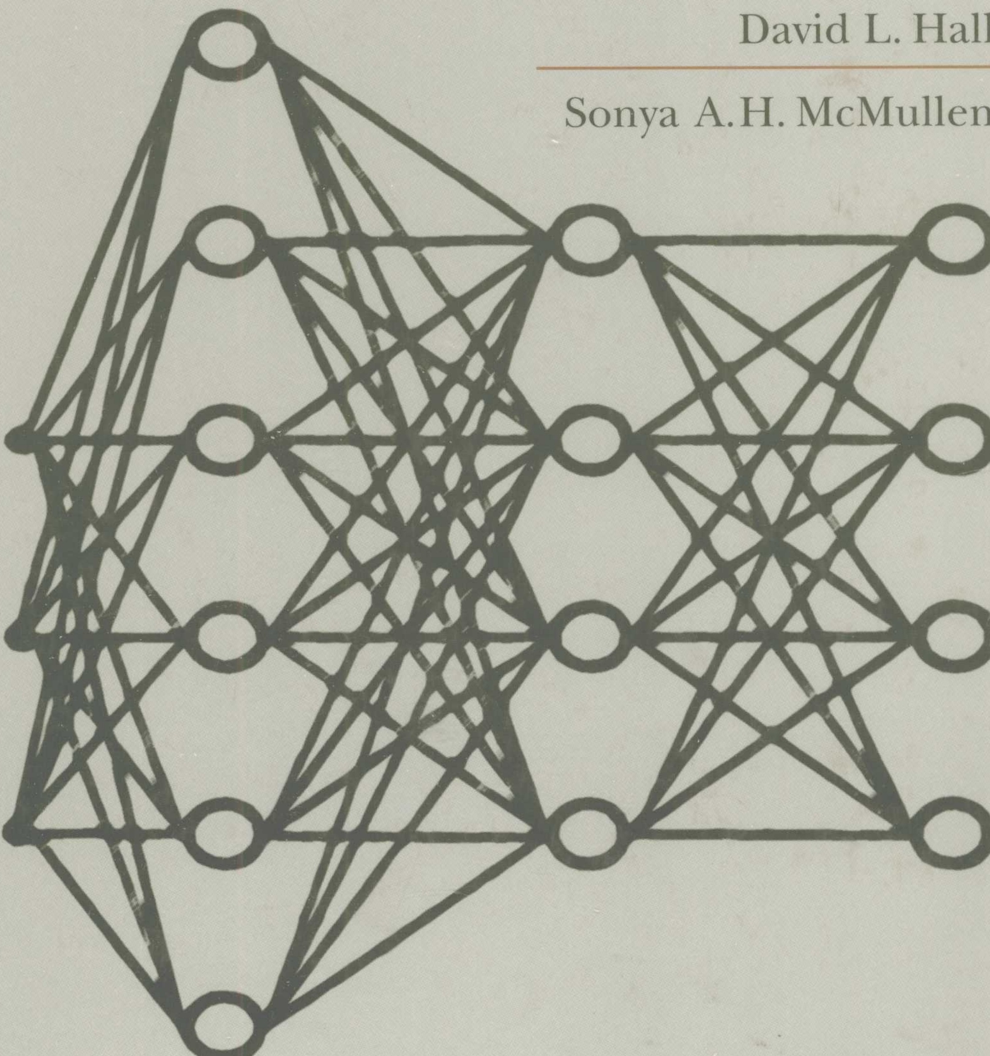
Mathematical Techniques in Multisensor Data Fusion

Second Edition



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This book is dedicated to the memory of Mary Jane M. Hall. For 31 years, she was the loving wife of David Hall. She was the mother of Sonya Anne Hall (McMullen) and Cristin Marie Hall. Her guidance and love for our family will never be forgotten.

Preface

The original edition of the book, *Mathematical Techniques in Multisensor Data Fusion* was aimed at providing students and working professionals with an overview and introduction to data fusion methods. Data fusion involves combining information from multiple sources or sensors to achieve inferences not possible using a single sensor or source. Applications of data fusion range from military applications such as battle management and target tracking to automated threat assessment. Nonmilitary applications include environmental monitoring, medical diagnosis, monitoring of complex machines, and robotics. The original text was intended to provide a "gentle" introduction to data fusion algorithms across the broad spectrum from data association and correlation to target tracking and identification, automated reasoning, and human-computer interaction. In addition, advice was provided on system implementation including systems engineering methods and utilization of commercial off-the-shelf software tools.

This second edition provides a major update to the original text. New chapters are provided on cognitive-assisted reasoning, human-computer interaction, emerging new applications, and new models for data fusion. All chapters have been upgraded to include new references, sources available on the Internet, new graphics, and new techniques such as intelligent agents, hybrid reasoning, and fuzzy logic processing. The book recognizes new advances in smart sensors, distributed computing, and increased processing capability of personal computers and new interaction devices such as 3-dimensional full-immersion displays and Haptic devices. In addition, references are provided to new research in target tracking, automated reasoning, and cognitive modeling.

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Chapter 1

Introduction to Multisensor Data Fusion

This chapter provides an introduction to the concepts and terminology of multisensor data fusion. The chapter also provides a guide to the remainder of this book.

1.1 INTRODUCTION

In the past 15 years, a discipline called multisensor data fusion or distributed sensing has been developed to solve a diverse set of problems having common characteristics. Multisensor data fusion seeks to combine data from multiple sensors to perform inferences that may not be possible from a single sensor or source alone. Applications span military problems such as automatic target recognition, analysis of battlefield situations, or threat assessments. Other applications include remote sensing problems involving the determination of the composition of ground vegetation or the location of mineral resources and industrial applications including the control of complex machinery (e.g., nuclear power plants) or automated manufacturing. Data from different sources and types of sensors are combined using techniques drawn from several disciplines: signal processing, statistical estimation, pattern recognition, artificial intelligence, cognitive psychology, and information theory. Input data from sensors may include parametric positional data, such as angular data (e.g., azimuth, elevation, and image coordinates), range or range-rate information, and data related to object identity (e.g., either actual declarations of identity from a sensor or parametric data that can be related to identity, such as radar cross section or spectral data). Input information may include information from human observers, other data fusion systems, or computational models.

Data fusion is analogous to the ongoing cognitive process used by humans to integrate data continually from their senses to make inferences about the external world. Humans receive and process sensory data–sights, sounds, smells, tastes, and touch–which are then assessed to draw conclusions about the environment and what it means. Recognition of an acquaintance whom one has not seen for a long period of time, for example, may involve assessment of factors such as general facial shape, identification of distinctive visual features (e.g., prominent nose or hair color), identification of voice tonal patterns, or even distinctive ways of walking or gesturing. Comedians mimic distinctive features of famous people to evoke recognition and to caricature others. Recognition and assessment of a situation by a human is greatly affected by training, attention, mood, physical condition, or other factors. A physician may assess a fellow human with much different perceptions than would, say, a friend or casual acquaintance. Nevertheless, humans utilize a natural fusion of sensory data for recognition of external events. Many of the techniques developed for data fusion attempt to emulate the ability of humans (or animals) to perform fusion.

This chapter provides an introduction to data fusion problems and defines the basic terminology. The Joint Directors of Laboratories (JDL) data fusion group model of data fusion [1] is introduced, along with a summary of applications, input data, outputs, types of sensors, and basic implementation issues. The first edition of this book declared that, "Data fusion is not a discipline in the same sense as more well-defined studies such as signal processing or numerical methods. Well-defined techniques, terminology, and a professional community do not yet exist." Since the first edition of this book, significant progress has been made to develop models [2], structured engineering procedures [3], and guidelines for requirements analysis [4], architecture selection [5] and algorithm selection [6, 7]. While data fusion is still not a mature technology, significant progress has been made. That progress is reflected in the updates to this second edition.

Chapter 2 presents the JDL data fusion process, which defines several levels of fusion processing including the following:

- Level 1 processing (object assessment): Fusion of multisensor data to determine the position, velocity, attributes, characteristics, and identity of an entity (such as an emitter or target);
- Level 2 processing (situation assessment): Automated reasoning to refine our estimate of a situation (including determining the relationships among observed entities, relationships between entities and the environment, and general interpretation of the meaning of the observed entities);
- Level 3 processing (impact assessment): Projection of the current situation into the future to define alternative hypotheses regarding possible threats or future conditions;
- Level 4 processing (process refinement): A meta process that monitors the ongoing data fusion process to improve the processing results (namely improved accuracy of estimated kinematics/identity of entities and improved assessment of the current situation and hypothesized threats);
- Level 5 processing (cognitive refinement): Interaction between the data fusion system and a human decision maker to improve the interpretation of results and the decision-making process.

This book is organized using the JDL model structure. Chapter 2 describes the JDL model and identifies algorithms and techniques for fusion. Chapters 3–6 cover different types of processing involved in level 1 fusion. Particular methods involve statistical estimation and pattern recognition. Chapter 7 is devoted to methods for performing level 2 and level 3 fusion. These techniques are drawn from artificial intelligence. Chapter 8 introduces the concept of level 4 fusion involving the control of sensor and information resources and the dynamic refinement of the fusion process. Chapter 9 addresses level 5 fusion. This concept was recently introduced by [8]. Chapter 10 provides a discussion of the implementation of data fusion systems; Chapter 11 presents some emerging applications; and Chapter 12 discusses automated information management.

1.2 FUSION APPLICATIONS

Data fusion applications span a wide domain including the military and nonmilitary applications summarized in Table 1.1. Military applications include ocean surveillance, air-to-air and surface-to-air defense, battlefield intelligence, surveillance and target acquisition, and strategic warning and defense. Nonmilitary applications include law enforcement, remote sensing, and automated monitoring of equipment, medical diagnosis, and robotics. A summary of these applications follows. Additional information about military applications may be found in [9-12]. Chapter 8 provides a survey of implemented data fusion systems and commercial tools related to data fusion.

Table 1.1

Examples of Multisensor Data Fusion Applications

Application	*Inferences Sought*	*Primary Observable Data*	*Surveillance Volume*	*Sensor Platforms*
Ocean surveillance	Detection, tracking and identification of targets and events	Acoustics Electromagnetic radiation Evidence of nuclear radiation	Hundreds of nautical miles Air, surface, and subsurface	Ships Aircraft Submarines Ground-based Ocean-based
Air-to-air and surface-to-air defense	Detection, tracking and identification of aircraft	Electromagnetic radiation	Hundreds of miles (strategic) Miles (tactical)	Ground-based Aircraft
Battlefield intelligence and surveillance	Detection and identification of potential ground targets	Electromagnetic radiation Acoustics	Tens to hundreds of miles about a battlefield	Ground-based Aircraft
Strategic warning and defense	Detection of indications of	Electromagnetic radiation	Global surveillance	Satellites Aircraft

Table 1.1 (continued)

Examples of Multisensor Data Fusion Applications

Application	*Inferences Sought*	*Primary Observable Data*	*Surveillance Volume*	*Sensor Platforms*
	impending strategic actions Detection and tracking of ballistic missiles and warheads	Nuclear particles		
Law enforcement	Transportation and location of drug shipments	Electromagnetic radiation Acoustics	Country and state borders	Tethered balloons Aircraft Ground-based
Remote sensing	Identification, location of mineral deposits; crop and forest conditions	Electromagnetic radiation Human reports and observations	Hundreds of miles	Aircraft Satellites Ground-based
Automated monitoring of equipment	Status and health of equipment Identification of impending fault conditions	Electromagnetic radiation Acoustic emissions Vibrations Temperature and pressure Human observations	Volume of the monitored machine or factory	Organic sensors associated with the machine or factory
Medical diagnosis	Diagnosis of disease, tumors, and physical condition	Electromagnetic radiation Nuclear magnetic resonance Chemical reactions Biological data Human observations	Volume of the human body or observed component	Sensors placed in, on, and around the body
Robotics	Identification and location of obstacles	Electromagnetic radiation Acoustics	Near-location about the robot	Robot platform

Ocean surveillance seeks to detect, track, and identify targets, events, and activities. Examples of enemy activities of interest are the launch of a torpedo from a submarine, surface broach of an underwater-launched missile, and communication of a submarine with other vehicles. The ocean surveillance area includes subsurface, surface, and airborne targets in a volume whose dimension may cover a significant portion of the Earth. Numerous ships, submarines, and aircraft may be involved in the surveillance process while also being targets of interest. Observable data spans the entire physical range: from acoustic data obtained via sono-buoys, towed acoustic arrays, and underwater arrays, through the electromagnetic spectrum, nuclear particles, and nonnuclear particles.

Air-to-air defense and surface-to-air defense seeks to detect, track, and identify aircraft at ranges that permit evasion or deployment of weapons [13]. Systems to identify a single aircraft are sometimes termed identification-friend-foe-neutral (IFFN) systems. Primary observable phenomena include electromagnetic radiation (infrared, visible, and radio frequencies) utilizing passive and active sensors such as radar, electronic support measure (ESM) receivers, infrared (IR) cameras, laser radar, and electro-optical sensors (TV). The surveillance volume ranges from hundreds of cubic miles for strategic applications such as the air defense of a country's coastline, to a few-mile radius for defense of a single tactical aircraft. A closely related nonmilitary application is the identification of incoming aircraft at commercial airports.

Battlefield intelligence is aimed at the detection and identification of potential ground targets *(movers, shooters,* or *emitters)* to infer enemy capabilities, tactics, and strategies. Electromagnetic radiation is a primary observable, including IR emission from enemy engines, RF emissions of communications radios, beacons, radars, visible photographs of an area of interest, and ESM receivers. Additional information may be gained from acoustic and chemical sensors. Battlefield intelligence seeks to develop an enemy order of battle (a database containing the accurate identification, location, and characteristics of enemy platforms, emitters, and military units) and to determine the meaning and intent of the order of battle, (i.e., the enemy situation and assessment of threat). The area of interest for battlefield intelligence ranges from tens to hundreds of square miles. The advent of modern weapons extends the tactical area of surveillance, corresponding to the increased range of new weapons.

The mission of strategic warning and defense [14] is twofold: (1) to detect indications of impending strategic actions and, in a worst case, (2) to detect and track ballistic missiles and warheads. The large-scale Strategic Defense Initiative has highlighted the difficulties of such a mission. A global sensor system is required, utilizing satellites and aircraft. Primary observable quantities are the detection of electromagnetic radiation (e.g., actual visual confirmation of launch facilities, IR emission from rocket plumes, heating of reentering warheads), and nuclear radiation. The detection of strategic indications and warnings involves observations of an enemy's military activities such as communication, force dispersion, alert status, and even nonmilitary political activities. Clearly, data fusion for this problem requires very complex observations, combinations of data, and inferences via scenarios and models.

Nonmilitary applications of fusion attack a diverse set of problems. Examples include law enforcement applications such as drug interdiction, remote sensing, medical diagnosis, automated control and monitoring of complex equipment, and robotics.

Law enforcement applications are similar to military intelligence and surveillance. Drug interdiction, for example, may involve patrol of a border to identify and locate drug shipments. Sensory data includes sensors similar to those used in military applications. A unique biological sensor, a specially trained dog, may be used to *sniff-out* the presence of drugs. As drug criminals become more sophisticated, the range of sensors required and processing required for data fusion become more extensive. Law enforcement applications have another commonality with military applications, namely, the use of countermeasures by the criminal to reduce the information content of sensors. The huge profits in drug traffic lead to the purchase of sophisticated technology by criminals to avoid detection.

Remote sensing applications [15] include the surveillance of the Earth to identify and monitor crops, weather patterns, mineral resources, environmental conditions, and threats (e.g., oil spills, and radiation leaks). Here again the entire spectrum of data may be monitored. Special sensors such as synthetic aperture radars allow active surveillance, while passive sensors may monitor visual and IR spectra. Special examples of remote sensing are NASA's use of Landsat satellites to monitor the Earth's surface and space probes to investigate the planets and solar system and the Hubble space telescope. Each of these examples involves a suite of sensors used in coordination to locate, identify, and interpret physical phenomena and events.

Fusion systems are also being developed to monitor and control complex equipment and manufacturing processes [16]. Certain systems, such as nuclear power plants and modern aircraft, require monitoring beyond the ability of a human operator. Semi-automated monitoring is required to ensure that the system continues to operate properly. Data from multiple sensors is monitored to assess the health of a system. A number of data fusion systems have also been developed for automatic fault diagnosis of complex equipment. Inferences range from the simple monitoring of equipment's function (e.g., are the output data—temperature, pressure, speed—within acceptable ranges?) to complex inferences (e.g., are there indications of an impending meltdown?) involving many possible observations and indicators.

Other examples of data fusion are the techniques employed for medical diagnosis [17]. At a basic level, to diagnose common illnesses, a physician may use touch (feeling a patient's skin, or checking the motion of a joint), sight (observing a patient's complexion, or seeking evidence of ear obstructions.) and sound (listening to breathing), as well as a patient's self-reported symptoms. More complex problems may involve obtaining data from multiple sensors (e.g., x-ray images, nuclear magnetic resonance, chemical and biological tests, and ultrasound images) and other data to determine the condition of a patient. Typically one or more