1

Concepts and Foundations Automation and Emerging Technologies

1.1 Introduction

The term "automation" generally refers to a set of automated processes on an input based on expert-inspired thinking. In a broader and more specialized field of management, the term includes automatic data retrieval (DR) and intelligent digital data processing (DP) to understand and quantify the situation. The input data to these systems are a set of numbers that are transmitted online or offline using advanced hardware and even a single image processor. Figure 1.1 shows a simple structure of an automated system for determining road conditions (at Amir Kabir University of Technology, Tehran Polytechnic), which is used for the automation in infrastructure management. Automation encompasses a range of activities from information extraction to robotic navigation, data analysis, solution presentation and knowledge discovery, and knowledge learning and self-learning.

Data on the condition of an infrastructure, such as roads, bridges, tunnels, railroad tracks, or a microscopic image of a bitumen mixture automatically with the machine, are first converted into digital format and stored as input in computer memory or transferred online to the analyzer software. These digital data can be processed or displayed and controlled simultaneously or on a high-resolution monitor. In general, the process of digitization of road infrastructure scans includes all operations of digitization, storage, processing, and display of output through the computer. The program inputs are then transferred to the processor after storage or online through the terminal. After processing the outputs through the same terminal, the data are available and usable. Figure 1.2 shows the chain of automation steps for automating typical processing.

Automated processing and automation have a wide range of applications, such as automatic assessment of road surfaces, automatic assessment of bridges and technical structures, assessment and inspection of tunnels, evaluation of pavement texture roughness, quality control of pavement markings, road safety audit, detection of signs, and classification. For this purpose, advanced devices in-line with modern technology such as remote sensing (RS), use of satellites and other spacecraft, robotics and automatic inspection, and advanced laser equipment are used. The data obtained by the multipurpose usability, such as images, are used for the simultaneous assessment of pavement distress as well as road audits.

This data may be used to isolate and monitor the health of infrastructure or to diagnose damage or other infrastructure characteristics, such as surface drainage, friction, roughness, and slope and arch determination. Images captured by automated systems are utilized as important data to detect various types of failures or to visually evaluate decisions. Figure 1.3 provides examples of several different types of images in infrastructure. Other needs and applications of automation range from robot insights for automation in aerial road imaging to the movement of ligaments on tunnel wall bodies that fall into the automation category. In other words, whenever a machine receives two- or

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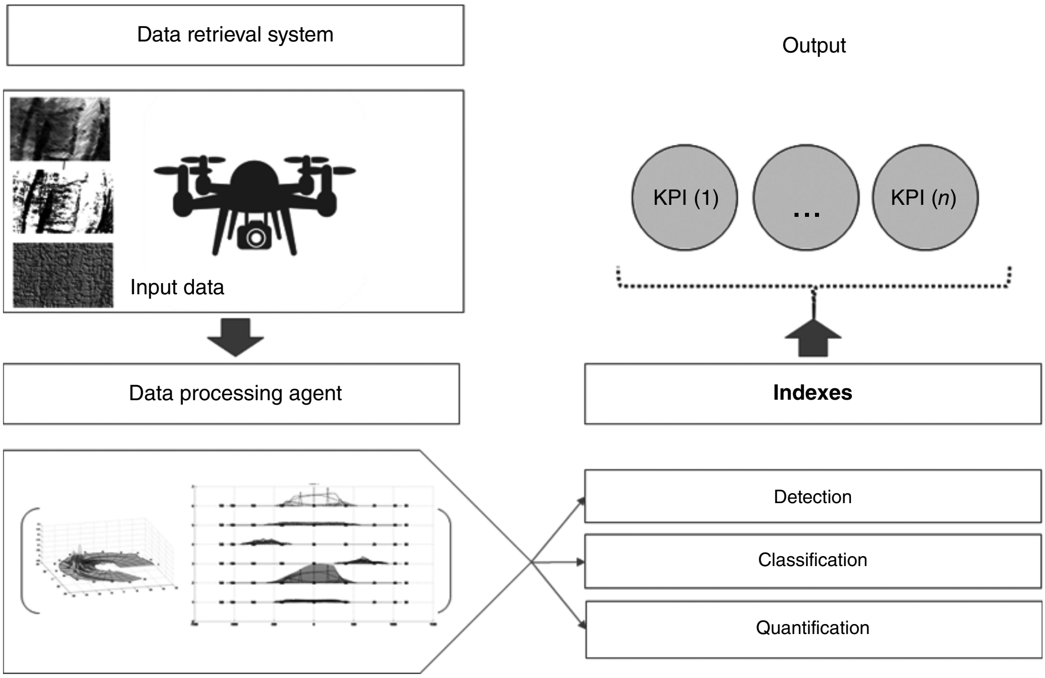

Figure 1.1 An example of a schematic automatic robotic information retrieval system for automation in infrastructure management.

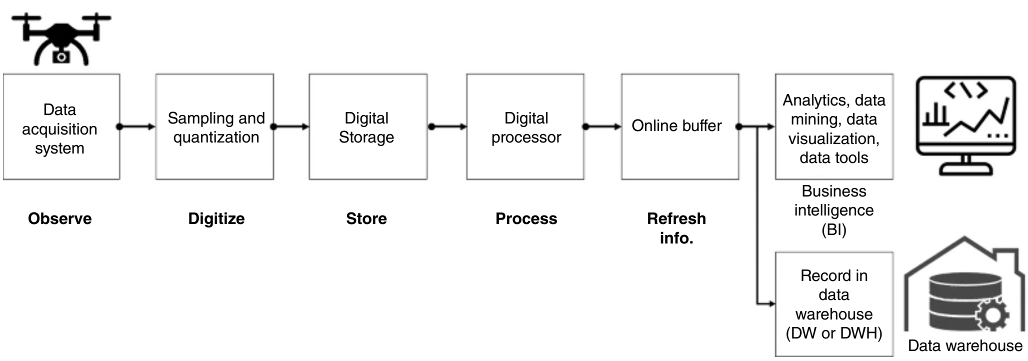

Figure 1.2 The schematic chain of automation steps for automating typical processing.

higher-dimensional data, an image is eventually processed. Although there are many methods and limitations to image processing, in this text, we will consider the following basic classes:

- Structure and framework of automation and key performance indices (KPIs)
- Advanced image processing techniques
- Fuzzy techniques and recent advances
- Automatic detection and its applications in infrastructure
- Feature extraction and fragmentation methods
- Feature prioritization and selection methods

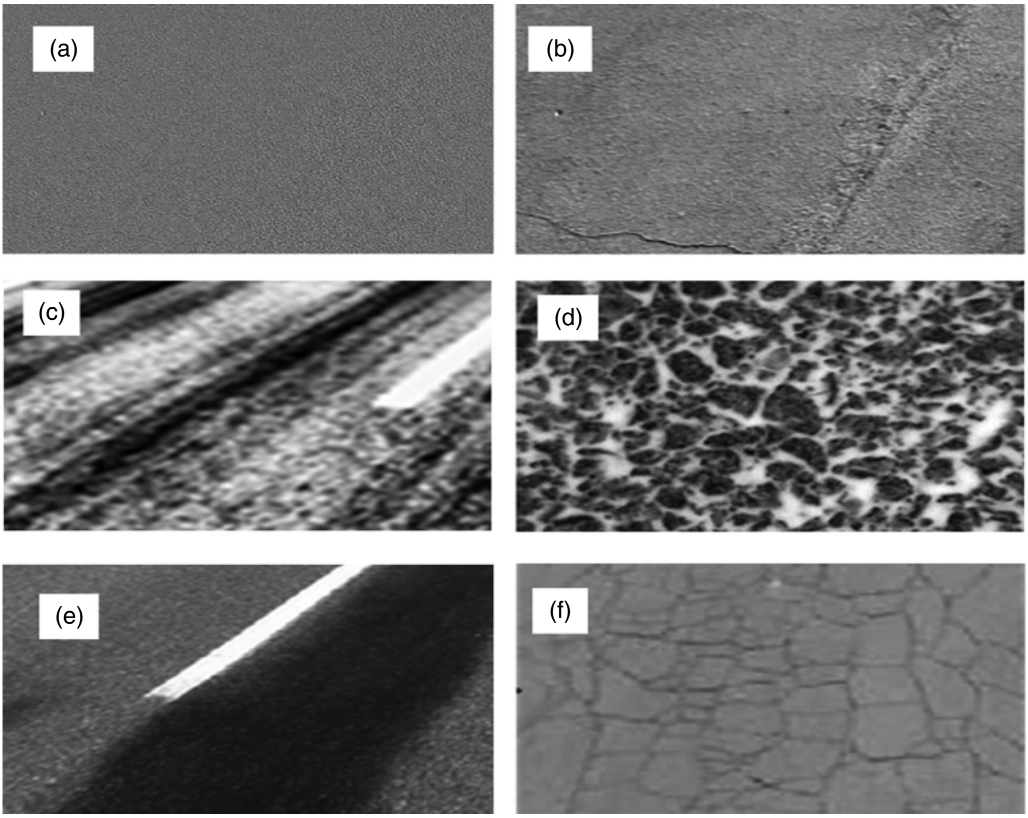

Figure 1.3 Examples of 2D images as an input for the processing step. (a) Pavement without surface damage with coarse texture, (b) pavement with small transverse cracks, (c) pavement with bitumen damage in the path of wheels, (d) pavement with high surface drainage capability, (e) pavement with rutting distress in wheel path, and (f) pavement with alligator-type surface cracking distress (fatigue cracking).

- Classification methods and their applications in infrastructure management
- Models of performance measures and quantification in automation
- Nature-Inspired Optimization Algorithms (NIOAS)

1.2 Structure and Framework of Automation and Key Performance Indexes (KPIs)

Automation is a completely systematic process that requires basic design. If any of the steps are designed incorrectly or the process is not followed correctly, it may lead to the failure of the use of automation in the future. Given the importance of this issue, the elements of infrastructure management and its automation should be considered. The three main components in automation design are the following:

- Include data retrieval (DR)
- Data processing (DP)
- Data and information (DI) interpretation

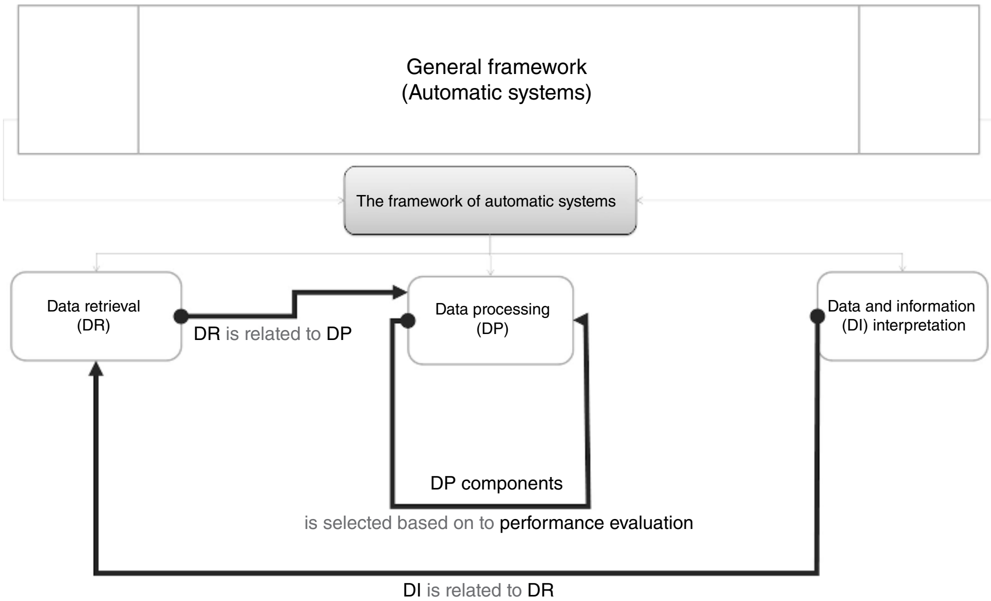

Figure 1.4 General architecture used to design the automation.

Figure 1.4 shows the general architecture used to design the automation. A discussion of the general structure and macroarchitecture of the development of infrastructure models at the network level as well as the main components of the overall system design modules is given in Chapter 2.

The initial selection of indicators and the acceptance of these indicators play an important role in the implementation of automation and its success. As a general principle, the selection of this module directly affects the selection of DR because indicators are ordered according to need. The collection of certain information requires the use of special equipment.

In national and macroautomation systems, the choice of technology depends a lot on the indicators desired by managers and affects the level of management. For this reason, the order of the automation chain is different in practice and requires a top-down design. Before designing any system, it is necessary to have a proper understanding of the types of common indicators in the management of roads and technical buildings. After fully understanding the needs, then the role of emerging technologies and future research of automation largely affects the selection of the method.

1.3 Advanced Image Processing Techniques

In order to evaluate and analyze the images, it is often necessary to extract directional information on the subjects (including cracking, texture, aggregate morphology, morphology of bitumen contents, friction, etc.) in the image. For this reason, multilevel methods are considered as efficient tools due to their ability to decompose information in several levels and the possibility of reconstructing them with the least amount of error.

In this section, various types of single and multilevel methods are introduced, then, using the indicators introduced in Section 1.2, the efficiency of each multilevel method in specialized issues

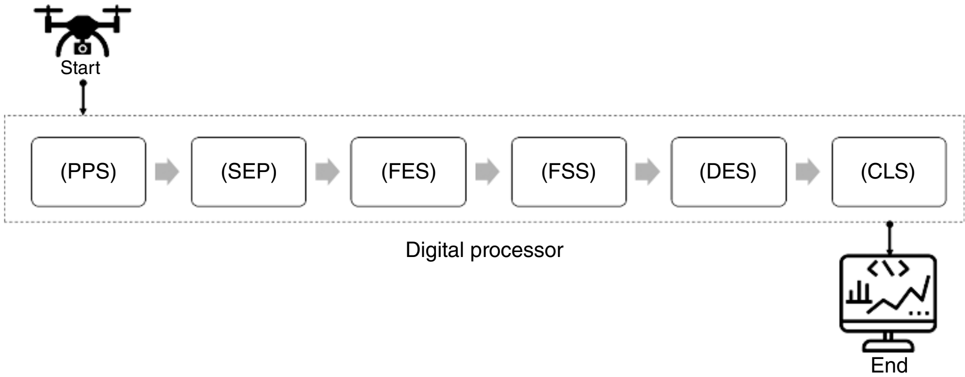

Figure 1.5 General steps of digital processing in automation.

is evaluated. The main characteristics of image quality evaluation, as shown in Figure 1.4, are evaluated for each method and with different filters.

The three main components for any automated system are the following: (i) image capture device, or the image equitization component (IAC); (ii) image analysis system and related algorithms, or the image processing component (IPC); and (iii) interpretation and indexing methods, or the image interpretation component (IIC). To perform analysis on the image, six general steps are required to obtain the result, including preprocessing, segmentation, feature extraction, feature selection, detection, and classification.

One of the most important methods of improving data quality is multilevel analysis that consists of the wavelet approach (WA), curvelet approach (CA), ridgelet approach (RA), and shearlet approach (SA), which has many applications. In this section, the capability of each of these single-level and multilevel methods in noise elimination is clearly presented, then the types of filters and optimal filter selection methods are introduced. Finally, the optimal method is selected from the existing methods as an example for case studies in the field of pavement management according to the capabilities of the method (see Figure 1.5).

The various preprocessing methods presented in Chapter 3 are used to improve the quality of images, with the aim of removing noise and enhancing the image in order to increase the detection power in the separation and detection stages via image processing. Also, different single-level and multilevel methods will be studied in detail. In general, multilevel methods work better than single-level methods. Among the multilevel methods, the complex Shearlet transform (SHT) method is a distinctive method with high capabilities, plays an important role in the image quality improvement stage, and has various filters and optimal analysis, which are widely introduced in Chapter 3. Various indicators, including the peak signal-to-noise ratio (PSNR) index, are used to evaluate the performance of algorithms and methods. This index is higher for the SHT method than other methods. On the other hand, the error index of the Shearlet complex is significantly lower than that of other methods. It should be noted that this method has a high flexibility, and by adjusting the main parameters depending on the type of problem and the nature of the image, practical results can be extracted. Due to the possibility of accessing SHT coefficients in different directions and sections with different scales, this method provides sufficient details and information for an accurate evaluation. Chapter 3 describes practical examples and case studies of the SHT method (Figure 1.6).

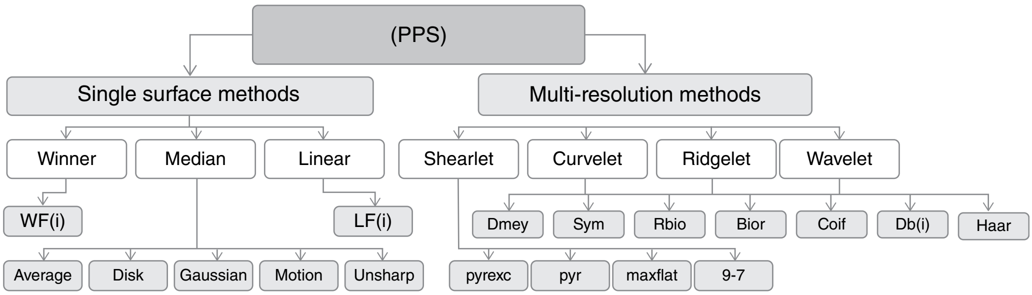

Figure 1.6 Classification of multilevel methods in preprocessing (multiresolution methods).

1.4 Fuzzy and Its Recent Advances

Among the various failures in infrastructure, infrastructure disease symptoms, such as cracking, are the most critical. The different types of pavement surface cracks include longitudinal, transverse, diagonal block, lizard, and track on the road surface that can be visually analyzed and interpreted. The use of image processing tools generates data for analysis that, in many cases, requires fuzzy methods for ambiguity or quantification. In Chapter 4, the concepts of different fuzzy sets are introduced in depth, which can be used as an emerging method to solve ambiguous problems. Fuzzy sets of type 2 and above along with their performance are examined in detail. Given that research on fuzzy set theory has recently entered the field of infrastructure management and image processing, this book summarizes the most important concepts and basic operations methods that can be used to study types 1, 2, and the type 3 fuzzy sets (see Figure 1.7) presented and it is hoped that new ideas will be generated for readers in Chapter 4.

In infrastructure management, especially road paving, we face many descriptive issues, including the severity and extent of damage, which requires the use of advanced methods for analysis. Since the description of this type of distress is usually inaccurate, these indicators are vague (low, medium, and high). By understanding fuzzy laws, fuzzy relations, fuzzy reasoning, and fuzzy facts, a new window opens to solve engineering problems with a degree of ambiguity for decision-making using the fuzzy method.

Fuzzy rules and fuzzy reasoning are essential components of fuzzy inference systems (FISs) that are the most important modeling elements based on the concept of fuzzy set and are widely used in the analysis and modeling of false and ambiguous topics. The following Section 1.4 presents an overview of fuzzy model types, while the latest achievements in the development of type 3 fuzzy modeling are discussed in Chapter 4.

1.5 Automatic Detection and Its Applications in Infrastructure

In the maintenance and management of infrastructure, the most important task and mission of the manager and network engineers are to maintain and improve the efficiency of infrastructure structures, such as roads, bridges, technical buildings, and other structures. However, before starting any treatment, the complication and its initial extent should be determined. Since it is not possible to visually inspect all infrastructures accurately and quickly, human error is one of the most greatest evaluation errors; in this regard, automated systems are used for detection. In Chapter 5, the

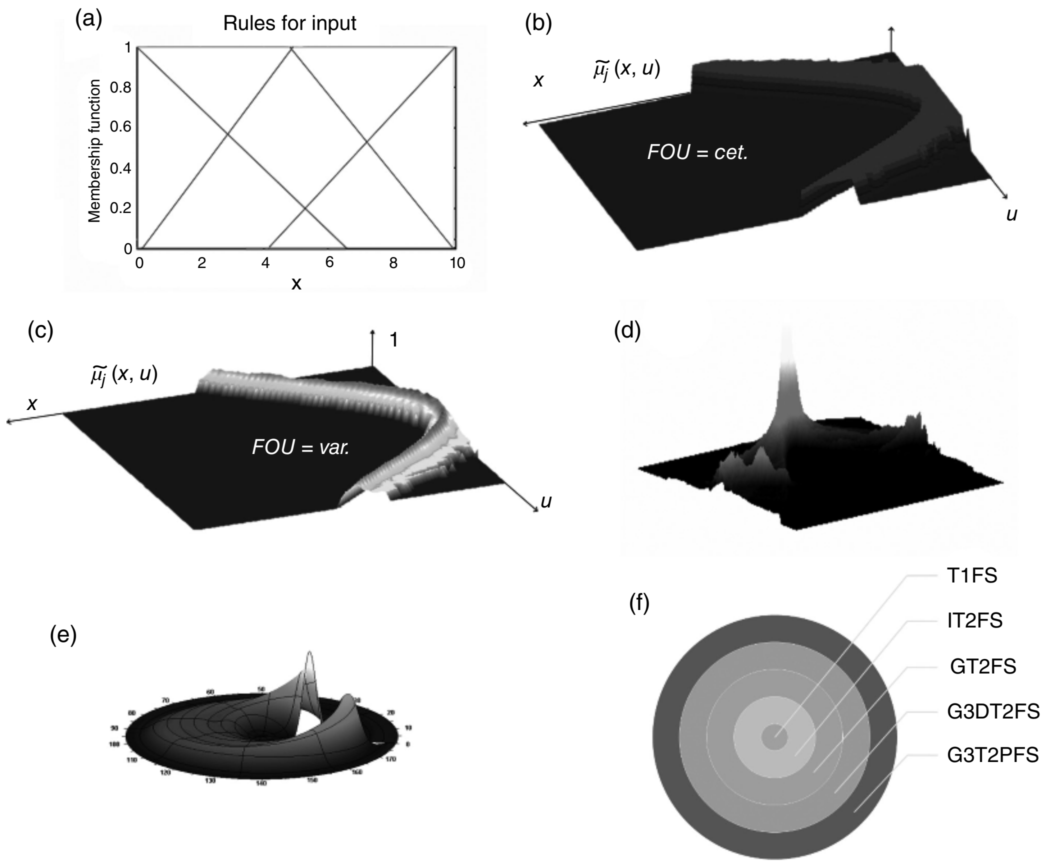

Figure 1.7 Classification of the fuzzy method and its recent advances (a) fuzzy type(T1FS), (b) fuzzy interval type 2(IT2FS), (c) fuzzy general type 2(GT2FS), (d) fuzzy type 3(G3DT2FS), (e) fuzzy type 3 in polar frame(G3DT2PFS), and (f) fuzzy domain.

principles and diagnosis methods as well as the new and effective parameters for diagnosing failure and abnormality are presented. Accurate and fast performance of the diagnostic stage is very effective in later stages of DI, including classification and evaluation.

Despite the advancement of processing methods and tools in detecting infrastructure anomalies, there is still insufficient information in data analysis and interpretation for satisfactory practical applications. Therefore, researchers continue to look for a stronger, more efficient method that is more compatible with harvesting tools. Hypotheses and general rules of diagnostic processing include one of the following statements or a combination of them:

- Abnormal pixels are darker/lighter than the original background.
- The presence of the anomaly has a nonuniform distribution in the gray image histogram.
- Abnormal morphology follows certain patterns.
- Specific anomalies are a set of continuous and continuous veins (such as cracks) or dense patterns (such as holes).
- The characteristics of anomalous patterns can vary but, overall, are a heterogeneous part of the whole set.

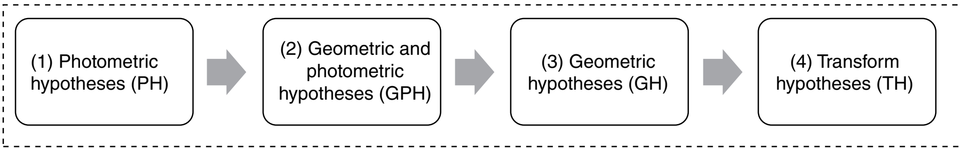

Figure 1.8 The process of the main hypotheses in the stage of diagnosis and segmentation.

- Anomalies usually have vague features around the edge.
- Geometric diagnosis of anomalies is not recommended due to the computational complexity of the diagnosis.
- Analyzing anomalies in transmitted space and applying the properties of the core is simpler and faster than the geometric method.

Each of the methods available for the diagnosis may consider one of the following hypotheses: (i) photometric hypotheses (PH), (ii) geometric and photometric hypotheses (GPH), (iii) geometric hypotheses (GH), and (iv) transform hypotheses (TH) (see Figure 1.8).

1.6 Feature Extraction and Fragmentation Methods

The main purpose of using image processing techniques is to extract meaningful features in order to perform classification and evaluation. The next step after separating the objects (or inconveniences) in the image is to convert the information into properties with the aim of collecting and reducing the amount of data for further processing. Objects separated from the segmentation stage must be converted into a property vector to be classified and constructed so that classification methods can be applied. Extracting features with a greater data transfer capability can increase the speed and efficiency of the method. Different methods for extracting features and their characteristics are examined in Chapter 6. Transformation of information into meaningful and useful features in the category is presented in this section with the aim of summarizing and increasing the speed and accuracy of detection as well as reducing the amount of image data for further processing. Extraction of desirable features to increase the ability to transmit more visual information or increase the amount of information has remained the focus of researchers. Particularly, the results of such extraction in the automatic detection of damaged images have a wide range of applications in infrastructure management (Figures 1.9 and 1.10).

In general, the eight main categories of feature extraction include the following: Low-Level Feature Extraction Methods, Shape Based Feature (SBF), 1D Function-Based Features for Shape Represent, Polygonal-Based Features (PBF), Spatial Interrelation Feature (SIF), Moments Features Extraction (MFE), Scale Space Approaches (SSA) for Feature Extraction, and Shape Transform Features (STF). To evaluate the proposed methods, four case studies in various applications of infrastructure management are presented and discussed with the interpretation of the relevant features.

1.7 Feature Prioritization and Selection Methods

There are several ways to select important and effective features, through which a subset of input variables is identified that can describe the input data more effectively and the negative effects of additional variables and input errors through topics, such as noise. Or this subset can

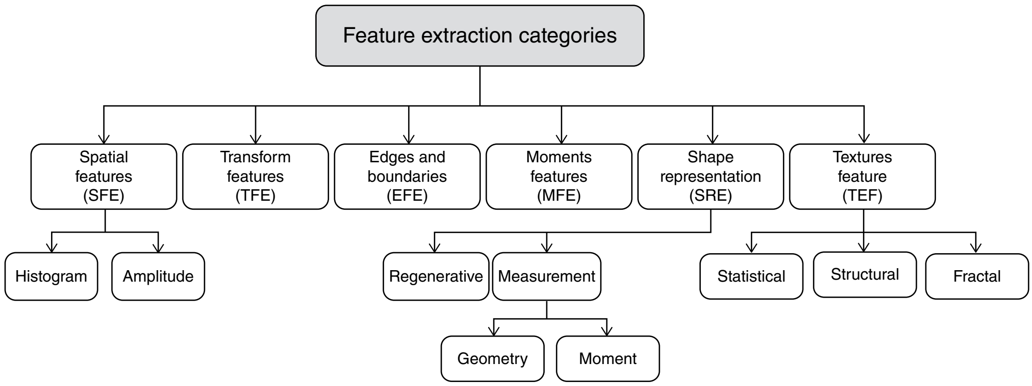

Figure 1.9 Classification of feature extraction methods.

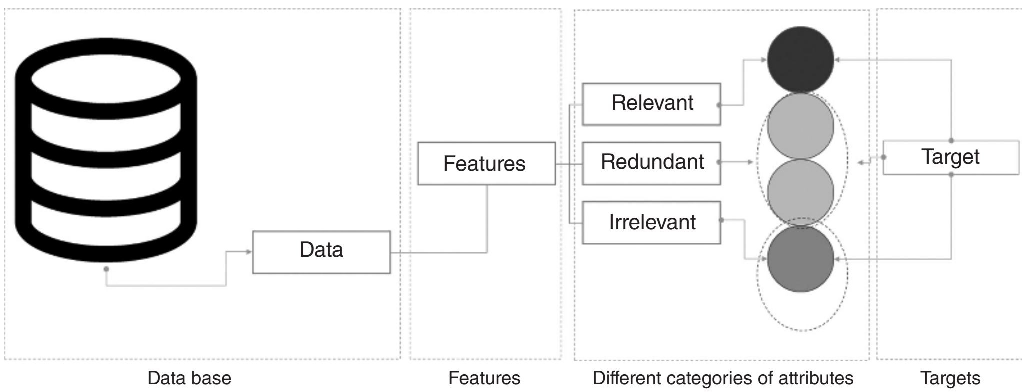

Figure 1.10 General framework of feature selection.

explain additional variables to provide better predictive results with higher speed and less computational complexity. One application of analysis is to influence the properties of a category or the extent to which features overlap to describe a subject. Standard data can contain hundreds of attributes, many of which can be closely related to other variables (for example, when two attributes are perfectly related, only one attribute is sufficient to describe the data and an additional attribute should be removed). However, dependent variables do not contain any useful information about the classification and are, therefore, an extra feature for the classification. This means that the entire content of the information can be obtained by minimizing the number of unique independent features that contain the maximum separating information. By keeping the variables independent, the number of attributes can be reduced, which improves the classifier performance (speed and accuracy). In many applications, variables that are more class-related are retained, while other attributes like noise may reduce classification performance. Therefore, choosing the right features is a prominent and key art form of designers and researchers.

Input attributes are used in attribute selection methods to reduce their number. When determining the criteria for selecting a feature, a method that separates the subset of the best useful features and considers them as a new set should be used.

There are three general types of relationships among the features extracted from the data: related (related), additional (additional), and unrelated (unrelated). The third category includes irrelevant features that do not have significant information about the target and should be removed.

Feature removal methods generally fall into one of four categories

1) Filter methods
2) Wrapper methods
3) Embedded methods
4) Hybrid methods

In filter methods, the operator is used for preprocessing to rank properties, in which high-ranking properties are selected and used for prediction. In this method, other characteristics play an additional role in processing and finally speed and accuracy increase with the optimal feature vector.

In wrapper methods, the criterion for selecting a feature depends on the performance of the predictor, i.e. the predictor is placed on a search algorithm that finds a subset with the highest prediction performance. This method is a kind of optimization with the function of maximizing performance and minimizing the number of features.

Embedded methods involve selecting variables as part of the training process that operate without dividing the data into training and testing sets.

Hybrid methods use a combination of the above three methods. In this chapter, feature selection methods using supervised, unsupervised, and semisupervised learning algorithms are first reviewed, then a new semisupervised method based on the fuzzy method for sample feature vectors is presented. It should be noted that the choice of method depends on the type of issue and quality of the characteristics. The best strategy to select a feature is to develop a method specific to the problem that requires a proper identification of the relationships and an understanding of the concept of features.

1.8 Classification Methods and Its Applications in Infrastructure Management

Classification is a type of prediction and calculation method in which a method is designed to guess the placement of data in a category. If the output is categorized and a class is located, the method is called classification, and if the output is numerical, it is called regression. Descriptive modeling, or clustering, includes assigning each input to a cluster so that similar inputs are placed in the same cluster. Finally, by observing the relationship between similar data, one can discover association rules about the relationship between inputs. By common definition, classification is an important application in data science that predicts the attribution of a variable (goal or class) based on the construction of a model using one or more numerical variables (predictors or attributes). The basis of all variables depends on the categories to which they belong. Such affiliation is calculated by using one of the following: (i) Frequency Table, (ii) Covariance Matrix, (iii) Similarity Functions. Classification is the most commonly used technique for large datasets in the research and practical applications of infrastructure management. It is also prominently applied in a variety of applications, such as detection, feature extraction, feature selection, complication type determination, severity category, scope determination, and evaluation. In this method, data analysis is based on learning-based algorithms that are supervised and consistent with data quality. In these algorithms, the goal is to detect and deduce a relationship that relates the desired variable, qualitatively, to other

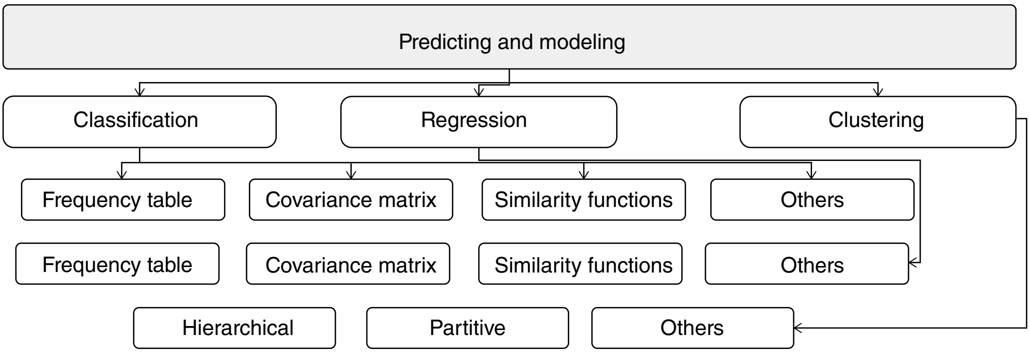

Figure 1.11 The various categories of learning modeling methods and classification.

observed variables that can be predicted. As a result, extracting this relationship is a kind of learning from data behavior that is considered as a branch of data mining. By definition, the classifier algorithm is responsible for classification, and all data are sample observations. It should be noted that classification is used when the desired variable is qualitative, such as determining the severity of a failure (low, medium, and high), type of failure (longitudinal, transverse, oblique, block, and fatigue), and extent of distress (low, medium, high, and very high) in infrastructure management.

The classification method employs various algorithms to obtain useful information, which can be categorized according to Figure 1.11. Particularly, in infrastructure management, this method is used to determine the behavior, i.e. conditions, of roads, bridges, tunnels, and technical buildings. Using these methods to classify is considered a kind of intelligence in management. By classification, a distinction is made between data that are purposefully useful (such as for the presence of cracks in infrastructure/detection of healthy sections) and irrelevant data (as in other types of failures). For example, each section can be divided into two general classes with distress and no failure(yes/no).

Chapter 8 briefly describes the most common classification methods used in infrastructure management, and examples of the application of these methods are presented in Chapter 8 or throughout the book. At the end of this chapter, new hybrid methods are presented as the development of basic methods that can be used to solve various problems. These methods are generally the development of primary methods and are used in combination with other classification methods. In this chapter, the advanced method of classifying the support vector in polar coordinates is clearly presented. Also, the basics of the fuzzy classification method used to classify ambiguous data are given as an extended method with examples.

1.9 Models of Performance Measures and Quantification in Automation

In order to evaluate the overall performance of a method or a classifier, a wide range of criteria with varying degrees of sensitivity have been identified and used to classify methods for subsequent selection and application over the past two decades. Due to the importance of evaluating these methods in infrastructure management, this section is of particular importance. In general, indicators for evaluating the methods are generally complementary, and the adequacy of each indicator alone does not mean the overall guarantee of the method. In general, the results obtained from the evaluation methods depend on the opinion of the analyst, the harvesting instructions, technology

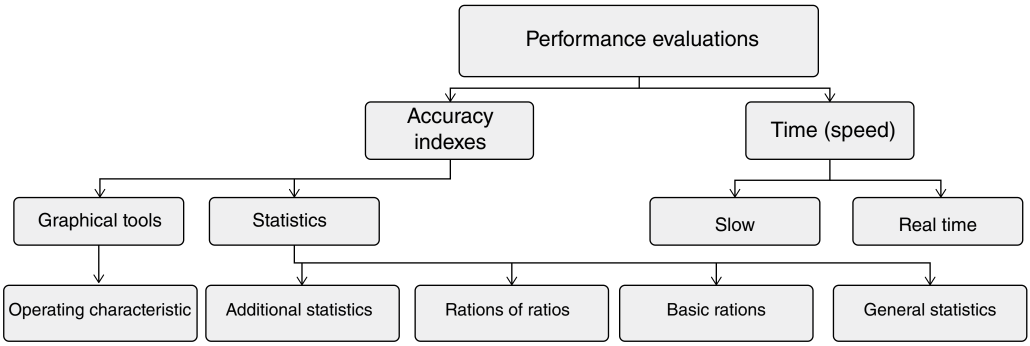

Figure 1.12 Classification of performance measurement indicators.

used, harvesting conditions, analysis speed, and many other dependent factors. For these reasons, different results of evaluating automated methods are expected. In this chapter, performance evaluation methods and indicators are first presented, then the types of general indicators in infrastructure evaluation are summarized. Figure 1.9 shows a general classification of the performance appraisal methods and common indicators. Assessing the true accuracy and performance of automated infrastructure assessment algorithms is critical in choosing the path of analysis and obtaining practical results. Many indices, such as mean square error (MSE), entropy, fuzzy index, signal-to-noise ratio (SNR), PSNR, and mean absolute error (MAE), are used for evaluation. Due to the existence of hidden characteristics, like the number of positive and negative samples as well as categories with different number of samples, the use of the accuracy index alone is not effective for evaluating the overall capability of a method.

In this Chapter 9, evaluation methods are divided into five general categories, including (i) General statistics, (ii) Basic rations, (iii) Rations of ratios, (iv) Additional statistics, and (v) Operating characteristic. Each category is then examined for each diagnosis and classification method. Based on the information extracted from the complexity matrix, indices like accuracy, error, probability of detection, productive index, selectivity, reproduction, negative predicted value (NPV), false positive rate (FPR), false negative rate (FNR), false discovery rate (FDR), false omission rate (FOR), likelihood ratio for positive tests (LRPT), likelihood ratio for negative tests (LRNT), likelihood ratio for positive subjects (LRPS), are likelihood ratio for negative subjects (LRNS), are further defined and calculated. Also, using these indicators, new indicators, such as *F*-measure, balanced accuracy, Matthew's correlation coefficient (MCC), Chisq, χ^2, difference between automatic and manual methods, differentiation index, are used for comparison and evaluation. The overall performance of a method can be evaluated based on the index matrix extracted from the complexity matrix. In Chapter 9, a definition of the classification matrix is provided, followed by an introduction to the database modeling method. Figure 1.12 classifies the types of evaluation indicators, for which the calculation and various examples are presented in Chapter 9. Pertinently, Chapter 9 concludes by describing some general specialized indicators to evaluate infrastructure.

1.10 Nature-Inspired Optimization Algorithms (NIOAS)

NIOAs are inspired by the behavior of natural phenomena to build related models. Some of these behaviors include simulating congestion intelligence, the behavior of biological systems, the behavior of physical and chemical systems, and divisions of miscellaneous behaviors. These models utilize bioinspired and physics- and chemistry-based algorithms. In general, biology-inspired algorithms encompass a class of algorithms based on crowding, swarm, and evolutionary intelligence. In general, NIOAs are an active and important branch of artificial intelligence (AI), which continuously evolve. Thus, it is not unreasonable to expect that, as you read this chapter, several new algorithms will be born.

So far a large number of interesting NIOAs inspired by natural animal behavior, biology, physics, and chemistry have been proposed and applied in many fields, such as engineering and especially in optimization. Some examples include the Genetic Algorithm (GA), Particle Swarm Optimization (PSO) Algorithm, Differential Evolution (DE) Algorithm, Artificial Bee Colony (ABC) Algorithm, Ant Colony Optimization (ACO) Algorithm, Cuckoo Search (CS) Algorithm, Bat Algorithm (BA), Firefly Algorithm (FA), Immune Algorithm (IA), Gray Wolf Optimization (GWO), Gravitational Search Algorithm (GSA), and Harmony Search (HS) Algorithm. Some newer algorithms that have also been proposed are Horse herd optimization algorithm, Mayfly Optimization Algorithm, Chimp Optimization Algorithm, Coronavirus Optimization Algorithm, Water strider algorithm, Newton metaheuristic algorithm, Black Widow Optimization Algorithm, Harris hawks optimization, Sailfish Optimizer, Spider Monkey Optimization, Grasshopper Optimization Algorithm, Fractal Based Algorithm, Bacterial Foraging Inspired Algorithm, Rainfall Optimization Algorithm, Dragonfly algorithm, Sperm Whale Algorithm, Water Wave Optimization, Ant Lion Optimizer, Symbiotic Organisms Search, Egyptian Vulture Optimization Algorithm, Dolphin echolocation, Great Salmon Run, Big Bang-Big Crunch, Flower Pollination Algorithm, Spiral Optimization Algorithm, Galaxy-based Search Algorithm, Japanese Tree Frogs, Termite Colony Optimization, Cuckoo Search, Glowworm Swarm Optimization, Gravitational Search Algorithm, Fast Bacterial Swarming Algorithm, River Formation Dynamics, Imperialistic Competitive Algorithm, Roach Infestation Optimization, Cat Swarm Optimization and krill herd optimization.

In Chapter 10, the original theory and general idea of some NIOAs are summarized, and examines the use of one or more NIOAs and provides a real-world example via a case study of how algorithms respond. Finally, a new algorithm is presented by simulating the behavior of emperor penguins along with theory and case study. The main motivation of this section is to introduce the ability to simulate and model nature-inspired behaviors at the Chapter 10. By reading this chapter, you are expected to be able to design and build your own NIOA to solve optimization problems.

The main idea of the most common NIOPAs is briefly presented based on the levels stated in the framework in Figure 1.13. In Chapter 10, general principles of these methods are presented in a simple way, and it is expected that you will acquire a better understanding of the general concepts and simplified structure of these algorithms. In general, the main steps of each NIOA pattern are the following:

Level-1: Primary population production;
Level-2: Evaluation of individuals by calculating their appropriate values;
Level-3: Creating the next population by changing the original population;
Level-4: Termination criteria; and
Level-5: Choosing the answer that has the highest value of fitness.

The general principles of each of these algorithms are similar, but in step 3 functions, they may have different models for creating the next population or changing position due to different ideas.

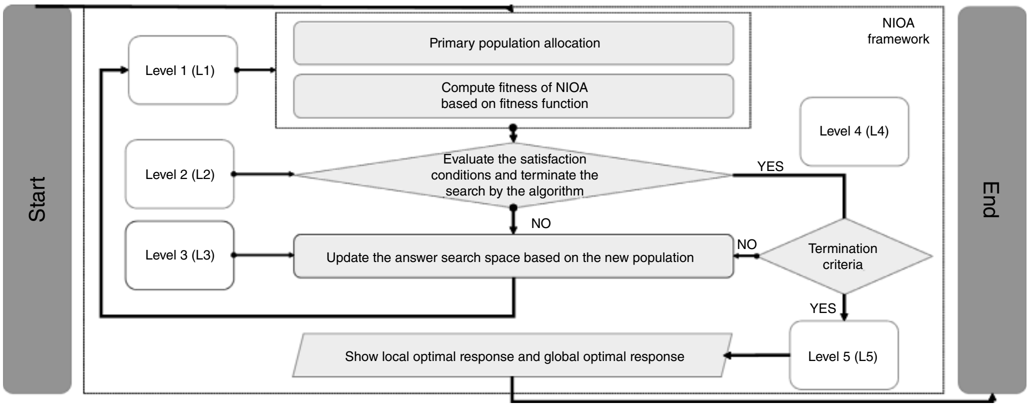

Figure 1.13 General framework and routine process of NIOAs.

1.11 Summary and Conclusion

In this chapter, we first defined automation and data collection methods and provide a summary of this book briefly as well as the importance of each chapter from design to implementation. General categories for the book chapter are presented in Chapter 10.

1.12 Questions and Exercise

1 Define automation and name some examples of its use in infrastructure management. Analyze a system that works intelligently and controls its core components.

2 Include examples of pavement, bridge, and tunnel management systems and specify their smart and automation degrees.

3 The types of key components of an infrastructure management system design are interrelated. Specify the relationship between each.