EVOLUTIONARY COMPUTATION IN MACHINE VISION FOR MANUFACTURING AND LOGISTICS INDUSTRY

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Evolutionary Computation in Machine Vision for Manufacturing and Logistics Industry

By

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Certificate of Originality

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___________________________________(Signed)

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Abstract

In the last decade, machine vision technology has improved productivity and quality control processes. Since China continues to develop an infrastructure for Hi-Tech products and the electronics industries while Hong Kong keeps developing the logistics industry, automation solutions are increasingly important in these areas. Thus, there is a growing trend to employ machine vision systems to perform tedious and demanding visual inspection tasks which are traditionally performed by human experts or highly trained operators. In typical cases, industrial visual inspection system is designed to inspect only known objects at fixed positions. These inspection systems have been considered as mature tools, however, application boundaries continue to move outward. There is a growing research curiosity in the development of new vision systems because more and more emerging vision-based problems are identified when the boundaries keep expending. Researchers and developers now consider machine vision as a discipline to develop advanced algorithms and faster hardware in order to further broaden the boundaries.

Among the different directions in this research and development trend, evolutionary computation techniques are gaining relevance as there are numerous applications in different areas where they can be applied. Although a number of successful examples of such applications can be found in the literature, they are usually specific to one single problem and reported in a scattered manner. This research is an attempt to propose a schema for incorporating the proposed chaos-based particle swarm optimization (PSO) algorithms in machine vision expert systems. It can be considered as a generic approach to solve other vision-based problems such as inspection, monitoring, guidance and navigation problems in different areas.

Benchmarking methods and exploratory case study approaches are adopted as the research method. Although the attempt is mainly research-oriented, particular care has been given to test the feasibility of the proposed approaches, in the thesis, at a level which makes them accessible to researchers and industrial practitioners. Since the expected target of this research includes industrial practitioners and researchers in machine vision who may not be familiar with evolutionary computation techniques, the main focus on applications of the proposed evolutionary approaches are described in detail, and the approaches are tested carefully and compared with other approaches. The chaos-based PSO algorithms that are proposed are also simulated and benchmarked carefully before being applied to solve the formulated vision-based problems. The proposed algorithms outperform other algorithms in both the benchmark tests, in template matching and in circle detection problems. The tests and simulations have revealed the efficiency and feasibility of the proposed algorithms in solving numeric optimization problems as well as vision-based problems.

To validate the feasibility of the proposed approaches, two case studies concerned with printed circuit board manufacturing and pick-and-pack processes have been conducted. Furthermore, the design of the proposed system, which encompasses statistical control charts, information handling and digital watermarking, has been described. The suggested solutions have been considered as effective means to address the problems in the case studies. The aim of this research is to explore how evolutionary approaches can be used to solve vision based problems, as well as tackling problems in the manufacturing and logistics industries. The deliverables of this research not only provide the design of the proposed system which will support efficient quality decision making and improve operational performance, but also open the door to incorporating evolutionary computation techniques in future machine vision systems that can be applied to different areas.

Publications Arising from the Thesis

(**11** publications arising from the thesis.)

List of Publications

- Dong, N., Wu, C.H., Ip, W.H., Chen, Z.Q., Chan, C.Y. and Yung, K.L., 2011. An improved species based GA and its application in multiple-template matching for embroidered pattern inspection, *Expert Systems with Applications*, 38, 15172-15182.
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List of Glossary

Abbreviation	Full-term	First Appearance
ACO	Ant Colony Optimization	Ch 2.3.6
AI	Artificial Intelligence	Ch 2.2.6
AOI	Area of Interest	Ch 5.2.3.1
BS	Breeding Swarms	Ch 2.3.5.2
CCD	Charge-Couple Device	Ch 2.2.1
CCTV	Closed-circuit Television	Ch 5.3.2
CLAHE	Contrast Limited Adaptive Histogram Equalization	Ch 4.2.1
CMOS	Complementary Metal–Oxide–Semiconductor	Ch 2.2.1
CPSO	Chaotic Particle Swarm Optimization	Ch 3.2.1
CSPSO	Chaotic Species-based Particle Swarm Optimization	Ch 3.2.2
DCM	Data Capture Module	Ch 1.7
DCT	Discrete Cosine Transform	Ch 2.5
EASE	Evolutionary Algorithm with Species-specific Explosion	Ch 3.3.2
EXIF	Exchangeable Image File Format	Ch 4.2.3
FP	False Positive	Ch 5.2.4
fps	Frame per Second	Ch 5.3.3.2
FN	False Negative	Ch 5.2.4
GA	Genetic Algorithm	Ch 1.3
HE	Histogram Equalization	Ch 4.2.1
HT	Hough Transform	Ch 2.2.3
HVS	Human Visual System	Ch 2.5
ISM	Information Storage Module	Ch 1.7
JPEG	Joint Photographic Experts Group	Ch 2.2.1
LCL	Lower Control Limit	Ch 2.6.1
LoG	Laplacian of Gaussian	Ch 2.2.2
MM	Monitoring Module	Ch 1.7
MTM	Multiple Template Matching	Ch 3.4.1
MVES	Machine Vision Expert System	Ch 1.2
NCC	Normalized Cross Correlation	Ch 2.2.5
PAM	Processing and Analysis Module	Ch 1.7
PSO	Particle Swarm Optimization	Ch 1.3
PCB	Printed Circuit Board	Ch 1.2
QC	Quality Characteristic	Ch 1.6
QIM	Quantization Index Modulation	Ch 2.5
RFID	Radio Frequency Identification	Ch 2.7

SBS	Species-based Breeding Swarms	Ch 3.3.2
SCGA	Species Conserving Genetic Algorithm	Ch 3.3.2
SPC	Statistical Process Control	Ch 1.2
SPSO	Species-based Particle Swarm Optimization	Ch 2.3.5.3
TP	True Positive	Ch 5.2.4
TN	True Negative	Ch 5.2.4
UCL	Upper Control Limit	Ch 2.6.1
WIP	Work in Process	Ch 1.3

Chapter 1 Introduction

1.1 Background to the Study

The world of manufacturing is changing in that customers and suppliers are becoming more demanding. Manufacturers are expected to do the right things and do things right with fewer resources. Modern manufacturing strategies have focused on the four major attributes of products, namely quality, cost, availability (or delivery time) and usability. In the meanwhile, logistics functions have played an important role in delivering complementary support for the aforementioned attributes. For example, effective logistics services contribute to productivity growth by shortening delivery time, which results in cost savings.

The transformation of Hong Kong's economic structure from manufacturing to services was dramatic when manufacturing was moved to the mainland during the 1980s and 1990s. Most remarkably, the transformation was achieved without any faltering of the general economic growth rates, and Hong Kong has become the mainland's gateway by providing support for imports and exports. In 2007, the trading and logistics sector was one of the four economic pillars of Hong Kong. It produced over four hundred billion Hong Kong dollars in value added, and contributed 25.8% to the Gross Domestic Product (Transport and Housing Bureau, HK Government, 2009). Although the 2008 and 2009 global economic downturns were unprecedented, the logistics sector prospered under the revived external trade in the first quarter of 2010 (Economic Analysis Division, HK Government, 2010). Logistics is not only the lifeblood of Hong Kong's economy but also creates demand for other services, including banking, insurance and associated professional services.

The relocation of Hong Kong manufacturing in the 1980s and 1990s massively contributed to the formation of new industrial regions, such as the Pearl

River Delta. The Pearl River Delta has become part of the world's factory, linking the global production network (Chen, 2007; Enright et al., 2005). In addition, Foreign Direct Investment from other countries, particularly Japan, US and Singapore, has boosted technology and capability in manufacturing to global competitive levels and has had an increasingly important effect on industrialization in all the industrial regions, especially Guangdong, after Mainland China became a member of the World Trade Organization in the early 2000s (Yang, 2006). China has proved that she can produce high-quality, high-technology products and that she can offer a level of convenience that other markets cannot offer (Midler, 2009). But on the other hand, China has encountered a high turnover rate of factory labor and a spate of suicides at Foxconn's Longhua factory in 2010 has highlighted concerns for the sustainability of China's manufacturing model, which has relied on an endless pool of labor, long working hours and a vast scale of production to maintain its competitive advantage. In addition, manufacturers in the mainland and foreign firms still have many conflicts because manufacturers aim at minimizing cost by sacrificing quality while foreign firms strive for a higher level of quality at reasonable prices. Factory officials in the mainland seldom talk about what to do about quality control (Midler, 2009).

China continues to develop an infrastructure for the Hi-Tech products industry and the electronics industry, while quality has been emphasized as the new industry driver. At the same time, Hong Kong is expected to continue to be an important gateway for the mainland to other countries. As the development of the logistics sector is vital for maintaining the economy and prosperity of Hong Kong, there are growing initiatives to maintain the cutting edge position of Hong Kong logistics (The HK Logistics Development Council, 2007).

Under these conditions, many Hi-Tech products and electronics manufacturers, and logistics companies in the mainland and Hong Kong have implemented integrated automation solutions to enhance the quality and improve logistics in order to drive operational performance, because they understand that the lack of automated systems and integration has resulted in variable productivity, inefficient processes and poor visibility. The focus of this research is therefore to investigate an innovative approach to help manufacturers and logistics companies to research into and design integrated solution to solve vision-based problems.

1.2 Motivation

In conjunction with the automated processes, automated vision-based inspection is desirable because human inspectors are not always consistent. They tend to get fatigued during their long working hours and miss flaws (Prieto et al., 2002). Machine vision has been successfully applied to numerous industries and has provided innovative solutions in the direction of industrial automated inspection (Davies, 2005). Areas using machine vision include delicate electronic component manufacturing (Lin and Ho, 2006), integrated circuits and printed circuit board (PCB) manufacturing (Crispin et al., 2007), supply chain management (Wu et al., 2009a) and many others. On the other hand, expert systems have also been applied in many areas and have achieved great success in recent years. The expert system has many successful applications in different industries, such as aircraft maintenance (Cheung et al., 2005), integrated circuit manufacturing (Hsieh et al., 2007) and machinery (Wu et al., 2007). It attempts to provide a solution to a problem or define risks or uncertainties where normally one or multiple human experts would need to be consulted. However, consulting human experts is expensive and their availability is not guaranteed. Thus, expert systems have been introduced by researchers as an alternative tool to assist humans to make decisions and diagnose problems. Recently, researchers have combined the strength of expert systems and machine vision to solve visual inspection problems with the aid of Statistical Process Control (SPC) techniques. SPC techniques, such as univariate control charts and multivariate control charts, are widely adopted because monitoring and control of automation processes are important to maintain the efficiency of the production process (Bersimis et al., 2007).

Utilizing quality control charts to meet this challenge of SPC has become standard industrial practice in recent years. In particular, machine vision technology and evolutionary computation techniques have achieved significant goals in the area of solving different vision-based problems. They have played an important role in transforming quality inspection and quality checking. Therefore, this research focuses on proposing a machine vision expert system (MVES), with a combination of new evolutionary algorithms and existing technologies, in order to solve vision-based problems and enhance operational efficiency in manufacturing and logistics applications.

1.3 Statement of Problem

In different industries, machine vision helps achieve improvements in product quality. Among the successful applications of machine vision, it is playing an increasingly important role in on-line measurement of the dimensions and of the quality (Bradley, 1998; Velasquez and Nof, 2008). There is a strong need in the manufacturing and logistics industries for the deployment of effective vision systems to handle in-process inspection which is robust yet flexible in solving emerging inspection and monitoring problems. However, there are two major challenges which continue to obstruct the adoption of current vision systems. First, current approaches often separate the inspection tasks and isolate them from each other. (Bradley, 1998). Second, there is lack of technology to integrate data or make the information transferrable from isolated inspection stations to other business operations (Velasquez and Nof, 2008).

Recent research proposes various hybrid approaches using EAs to solve different vision-based problems which have demonstrated better flexibility and efficiency in computational costs and time. In the field of research and development, some researchers have exploited artificial intelligence techniques and EAs although many possibilities still remain untapped (Alcock, 2004). Many artificial intelligence techniques and EAs such as Neural Networks and Genetic Algorithms (GAs) have emerged to provide solutions, and have achieved great success (Russell and Norvig, 2003). For example, there were automated inspection methods for PCB components using GA and Particle Swarm Optimization (PSO) approaches proposed by Crispin and Rankov (2007) and Wu et al. (2009b) respectively. However, the re-initializing of EAs with a population is time-consuming (Branke, 2001). Chaos theory is an emerging method, which is promising, for enhancing the robustness and efficiency of evolutionary methods (Xie et al., 2002; Iqbal et al., 2005; Liu et al., 2005). Song et al. (2007) mentioned that when different random sequences are used during the PSO search, the final results may always be very close but will not be the same. However, no analytical results guarantee an improvement of the performance indexes of PSO algorithms which depend on the changing choice of a particular generator.

A review of the literature also shows that different approaches to vision systems have been developed not only on the basis of machine vision and EAs but also on the basis of SPC techniques, such as a textile thickness inspection system with a single variable control chart (Horst and Negin, 1992). A machine vision approach for solving surface inspection problems has been proposed by Kumar et al. (2005) and an approach which integrates machine vision and SPC has also been proposed by Liao et al. (2004). Chiu and Lin (2009) proposed a hybrid approach, which is based on machine vision, Hotelling statistics and EAs, for the detection of display blemishes in liquid crystal display panels.

Various approaches and systems have been designed and developed to perform vision-based inspection and quality monitoring in different areas, however, an integrated machine vision system, which is able to tackle vision-based problems for manufacturing and logistics applications, and to address the two aforementioned challenges which continue to obstruct the adoption of current vision systems, is still an area that requires more study and investigation based on an integrated view. These issues are summarized as follows:

(i) How evolutionary algorithms can be applied to solve vision-based problems effectively

(ii) How a generic structure of vision-based system can be developed to solve vision-based problems in various industries and handle related information systematically

(iii) How the feasibility of the proposed system structure and the proposed algorithms can be verified

1.4 Research Objectives

Although most of the current machine vision approaches provide well developed algorithms to solve the specific vision-based inspection task, the inspection tasks are separated and isolated (Bradley, 1998), and the inspection information was ineffectively integrated and shared (Velasquez and Nof, 2008). However, many researchers considered the above issues separately. And, there were few comprehensive and evaluated evolutionary approaches proposed for solving vision-based problems in the past decade. A detailed review, especially of machine vision and evolutionary computation techniques, is provided in Chapter 2.

To overcome the aforementioned drawbacks, this research focusses on the integration instead of on machine vision, EAs and expert systems separately. Novel chaos-based PSO algorithms are developed to solve the simulated vision-based problems efficiently and effectively, and the performance of the algorithms is assessed carefully. Furthermore, infrastructural design of the system is constructed and evaluated for the vision-based problems in two case studies which are related to manufacturing and logistics areas respectively. The detailed methodology is explained in the next section.

The aim of this research is to *explore how evolutionary approaches can be used to solve vision based problems, as well as tackling problems in the manufacturing and logistics industries*. The specific objectives of this research are:

(i) To propose novel chaos-based PSO algorithms which can be successfully used to solve benchmark problems and vision-based problems, and to show their advantages by comparing them with other algorithms.

(ii) To propose a schema of a vision-based system, which has a generic structure for solving practical problems.

(iii) To verify the proposed solutions for tackling the vision-based problems, by applying them to two representative cases in a manufacturing firm and in a logistics company.

1.5 Methodology

At present, research into evolutionary approaches for solving vision-based problems and into developing a machine vision expert system for manufacturing and logistics areas, is still at the emerging stage. Therefore, it is appropriate to adopt an exploratory case study approach. According to Gerring (2007), a single case could be used to clarify a larger class of cases, and thus contribute to a larger group. Partington (2002) stated that case study research is about engaging theories with the complexities of the real world, and making sense of them. Eliot (1992) mentioned that case study methods may help to ground empirical laboratory-setting examinations in expert system investigation. In addition, evaluating the proposed algorithm and system is also an important issue in this research. According to Philips et al. (2000), the design and development process of machine vision systems must encompass a methodology in which performance criteria can adequately be defined. On the other hand, Grogono et al. (1991) mentioned that relatively few descriptions of the actual application of software engineering methods to expert system development can be found, but the development should not be constrained by a restrictive development model, and the evaluation techniques must be flexible and accommodating (Hilden and Habbema, 1990). In this research, evaluation techniques such as benchmarking, M^{c}Nemar test and design review (Pfleeger, 1987), are fully involved in the design and the testing processes. Clark and Clark (2004) suggested that M^{c}Nemar test is appropriate as far as techniques in technology and application evaluations are concerned. An illustration of these two evaluations is shown in Figure 1.1.

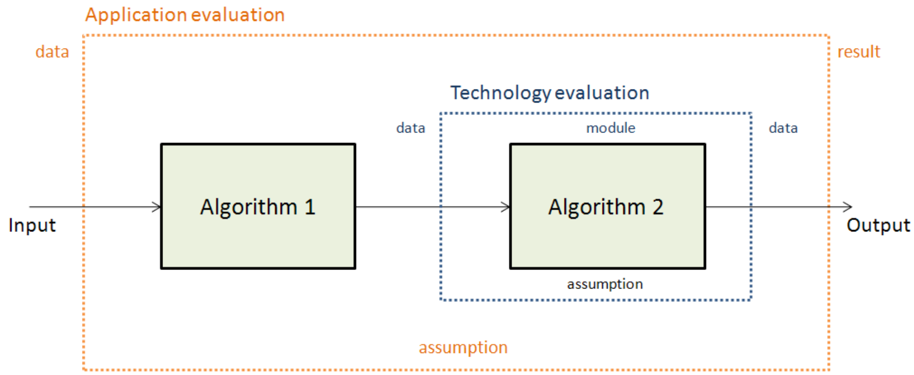


Figure 1.1 The technology evaluation and application evaluation (Thacker et al., 2002; Clark and Clark, 2004)

Firstly, at the start of this research, literature review is conducted. As a part of the literature review, a systematic review technique is applied in order to obtain a comprehensive coverage and analysis of the related literature. According to (Biolchini et al., 2007), a systematic review is a specific research methodology for gathering, summarizing and synthesizing the existing findings focusing on a particular subject topic. Thus, it can be considered as a secondary study which depends on the results of primary research. In particular, this methodology will be used to classify vision systems with respect to industrial applications. Several intermediate-level of image analysis techniques will also be included.

Secondly, after the literature review, the proposed chaos-based PSO algorithms in this thesis are presented and discussed. Although it is a very natural question to ask which algorithm is the best algorithm, it is potentially risky because this kind of thinking could suppress further research into other algorithms if all researchers advocate an algorithm as the standard and concentrates on improving it only (Clark and Clark, 2004). In this thesis, there is no intention to claim that the proposed algorithm is the best, so a better approach, namely benchmarking, is conducted. The proposed algorithm is developed using MATLAB programming language. Simulation tests are undertaken on these benchmark functions, including the Ellipsoidal function (Harris and Stocker, 1998), Rastrigin function (Torn and Zilinskas, 1989), Ackely function (Ackely, 1987), Deb's 1st function (Deb and Goldberg, 1989), Himmelblau function (Beasley et al., 1993) and Six-hump Camel Back function (Michalewicz, 1996). In order to make a performance comparison of the proposed algorithm with the 'straw man' algorithms and the state-of-the-art algorithms, the results of a standard GA (Holland, 1975), a standard PSO algorithm (Kennedy and Eberhart, 1995), a Breeding Swarm algorithm (Settles and Soule, 2005), an Evolutionary Algorithm with Species-specific Explosion (Wong et al., 2009) and a Species Conserving GA (Li et al., 2002) are summarized and compared with the performance of the proposed algorithm. Thus, the benchmark results tell whether the proposed algorithm is worth using or not.

In addition, simulation tests of different vision-based problems, such as template matching and circle detection, are also undertaken using simulated and natural images to show the wide applicability of the proposed algorithm in solving different problems. The performance and the response of the proposed methods to factors such as the adjustment of tuning parameters are evaluated (Thacker et al., 2002; Clark and Clark, 2004). After the individual assessment, the performance comparison is conducted. In this case, comparing the success rate is not good enough in order to reveal which method is better because the size of the dataset may be so small that any difference in performance could have been boosted up solely by chance. Thus, McNemar test is applied to perform a comparison because it takes this chance factor into account (Clark and Clark, 2004).

The remaining work is based on simulation and tests of MVES. In order to further evaluate MVES and demonstrate their feasibility, two case studies are conducted. It can be seen that a bias toward quantitative methods of inquiry has been found in the information systems and computing sciences research but a growing interest in the use of case studies has been observed (Eliot, 1992). In the case studies, the MVES with the proposed chaos-based PSO algorithms are applied to solve two selected vision-based problems related to PCB manufacturing and to the pick-and-pack process respectively. Thus, possible benefits of the proposed system to manufacturing and logistics are also revealed. In addition, a design review (Pfleeger, 1987) is included in both case studies. The design review is a kind of structured-walkthrough which serves as a quality assurance meeting. The system's design features, characteristics and test results are presented to the stakeholder groups such as operators, in-house developer and supervisor for comments and suggestions. The design review is necessary because input from all stakeholder groups is very important in order to generate an effective design for an application (Conrath and Sharma, 1991). Due to the stochastic nature of the proposed algorithms, all the presented results are averaged with standard deviations provided. In order to make a balance between the computational expensive nature of some simulations and confidence in the results obtained, results are taken over 30 runs. M^{c}Nemar test is also deployed in order to assess the proposed methods for solving the vision-based problem related to PCB manufacturing.

To summarize, the exploratory case study approach is adopted as the research method. Case studies and various evaluation techniques are included in the design and development of the proposed algorithms and system. Figure 1.2 illustrates the research method adopted in this research.

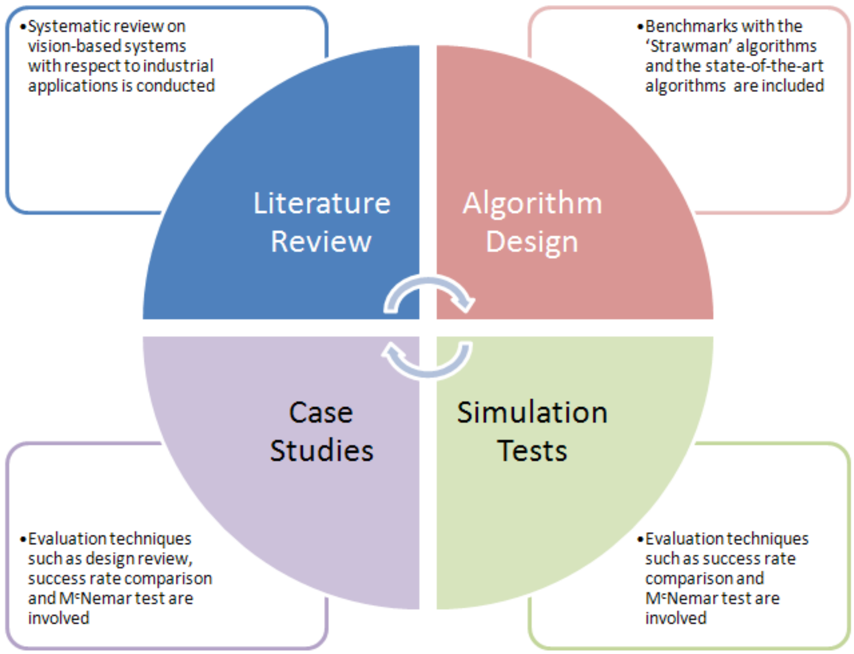


Figure 1.2 The illustration of the methodology adopted in the design and development of MVES

1.6 Significance of the Research

Numerous approaches which currently exist are confined to focusing on a specified task. For example, the separate visual inspection task is usually completed in an isolated inspection station. Therefore, it is hard to transfer the related information or integrate it for further analysis and other business operations. This research is concerned with a generic approach to integrating machine vision technology, the chaos-based PSO algorithms and other technologies in order to propose MVES for solving challenging vision-based problems. Its aim is to solve the problems effectively using evolutionary approaches and to improve the utilization, storage and retrieval of the useful information. This also enables industrial practitioners to make better quality decisions with the support of the control charts. In addition, the details of the chaos-based PSO algorithms, the simulations and tests of MVES in two scenarios selected from the manufacturing and logistics areas are presented.

According to the benchmark test results, the proposed chaos-based PSO algorithms can be considered as more stable and effective approaches to solve single modal and multi-modal optimization problems. After performing the analysis carefully and validating the results empirically, the results obtained demonstrate that the proposed approach can successfully solve these problems with better performance, and encourages information integration across operational boundaries in a process. In the first case study, the proposed CSPSO-based method has been used to solve a PCB component detection problem. In the second case study, a novel solution, which is based on the proposed CPSO-based digital watermarking method, has been used to solve the video data enrichment problem. Most work in this research is original and makes a significant contribution to the proposed schema in designing MVES for encouraging the adoption of machine vision and evolutionary algorithms in different industries.

1.7 Thesis Outline

The dissertation is divided into 7 chapters. The aspects covered in the dissertation are as follows:

(i) Chapter one provides the needs of vision systems and describes the background and motivation for this research.

(ii) Chapter two is an academic review of existing machine vision and evolutionary computation techniques. In the second case study, the digital watermarking technique is used in a data enrichment solution, so the basic knowledge of digital watermarking is included. It also introduces the basic knowledge of chaos, followed by an overview of existing quality control approaches. The aforementioned systematic review technique is applied to the details of machine vision systems in section 2.2.6. This chapter finally deals with the existing research issues in the present manufacturing and logistics scenarios with respect to vision-based problems, thus providing direction necessary for this research work.

(iii) Chapter three builds upon the work done and bridges the research gap revealed from the literature review in Chapter two. The proposed chaos-based PSO algorithms are presented. The proposed algorithms center on the efficiency and accuracy compared with other state-of-the-art algorithms. Further, the ability and utility of the proposed algorithms for tackling vision-based problems is shown through the simulations and by using simulated images and natural images.

(iv) Chapter four is divided into two main sections. The first section describes the framework of MVES and presents the system infrastructure which consists of Data Capture Module (DCM), Processing and Analysis Module (PAM), Information Storage Module (ISM) and Monitoring Module (MM). The chaos-based PSO algorithms embedded in MVES will be explained as well as the methods to interpret the outlier signal are also described. Section two introduces the proposed protocols for information handling. The standard procedure for standardizing the corresponding information in solving a vision-based problem within the integrated workflow is also explained.

(v) Chapter five is about validating and studying the feasibility of MVES in solving two selected vision-based problems related to PCB manufacturing and to the pick-and-pack process. Parts of the inspection processes, quality control and monitoring processes within these two scenarios are chosen to demonstrate the feasibility of the proposed solutions. An evaluation of them is presented in this chapter.

(vi) Chapter six consists of two sections. They are the general discussion of MVES, and the discussion of the possible implications arising from industrial practitioners in the two case studies. Thus, the limitations and some comments on the proposed system with an indication of further modification of some features are included.

(vii) Chapter seven draws conclusions from the work undertaken. In this chapter, the areas for future research are also identified.

Chapter 2 Literature Review

2.1 Introduction

In order to survive in the increasingly quality-oriented marketplace, many companies have to meet increasing customer expectations. In the manufacturing and logistics industries, manufacturing and operational processes have become more and more complex in the age of mass customization. Still, it is vital to improve quality and operational performance. Integrated automation solutions are increasingly common in organizations for enhancing quality and reducing waste in order to drive operational performance. In addition, automation solutions emphasize efficiency and the monitoring of certain QCs, resulting in the widespread adoption of statistical control charts (Bersimis et al., 2007). Automated inspection, however, as a part of automation solutions, is still less mature than automated manufacturing, which creates manufacturer and consumer uncertainty. Hi-Tech products, and electronics manufacturers and logistics companies, can suffer from variable defect types which result from different processes and cause failures as an outcome. Increasing scenarios currently exist that require extracting QCs repetitively and quickly, and monitoring and controlling of QCs simultaneously. Thus, monitoring these QCs automatically and simultaneously is essential to enhance the efficiency of quality decisions making in manufacturing and logistics applications. Although there is no machine vision system that can yet compare with some capabilities of human vision, in terms of image comprehension, tolerance to lighting variations and image degradation, vision systems can achieve promising performance in solving various vision-based problems in terms of processing speed, availability, consistency and repeatability (Kopardekar et al., 1993; Prieto et al., 2002).

This chapter aims to provide an overview of machine vision techniques, Evolutionary algorithms and existing quality control approaches as revealed in academic publications. The first section is a literature review of different machine vision techniques from low level to intermediate level. Also, different machine vision systems are classified with respect to corresponding industrial applications. The other sections provide a brief discussion of stochastic optimization methods and different evolutionary algorithms with more emphasis on PSO, and the basis of digital watermarking has been included. The reason for including digital watermarking is that the digital watermarking technique has been applied to solve a goods tracking problem in the second case study. The final section is a review conducted with the objective of exploring two widely used approaches to support quality control and enhancement in existing industrial practice.

2.2 Review of Machine Vision

The advantage of machine vision is in extracting descriptions of the world from images or sequences of images. Image taking is non-destructive. Image acquisition and processing has been researched since the 1980's. It is absolutely useful to quality control, security and surveillance, environmental and archaeological inspection, document processing, and so forth (Graham and Barrett, 1997). The application of machine vision is increasing, and there has been massive growth in orders for imaging equipment for different operations in various industries, especially for inspection in the manufacturing and logistics areas. There are many researchers who have proposed machine vision systems for inspection, recognition, and measurement. Wu et al. (1996) proposed an automated inspection system for printed circuit boards through machine vision, Urena et al. (2001) proposed a machine vision system for seeds germination quality evaluation using fuzzy logic, Sousa et al. (2006) proposed an optical character recognition system based on fuzzy logic for of old printed documents and Gao et al. (2009) applied machine vision to detect drill hole in printed circuit boards.

While some machine vision systems having unique and advanced algorithms, like object classification and face recognition, are being developed, the majority of vision algorithms are essentially interchangeable in terms of speed and accuracy. With this in mind, the most important point of a machine vision system for industrial application is not the number or complexity of the algorithms but robustness, speed and flexibility. This section provides a detailed look at some machine vision techniques which are essential to industrial applications and various vision-based systems.

2.2.1 Image Acquisition

The first stage of any vision system is the image acquisition. After the image has been captured, it will be digitalized. A digitalized image is an image $f(x,y)$ in which both spatial coordinates and brightness have been digitized. Having the digitalized image, various processing methods can be applied to the image to perform specific vision tasks required by different applications. Image acquisition is very important because if an unqualified image is acquired then the intended vision tasks may not be achievable, even with the aid of image pre-processing and image enhancement at the later stages. Image acquisition is hardware dependent, and many different devices can be used to produce digital images. There are three principal sensors that the devices need to use when acquiring images. Figure 2.1 shows these three types of sensor, which simply transform the incoming energy into a voltage output.

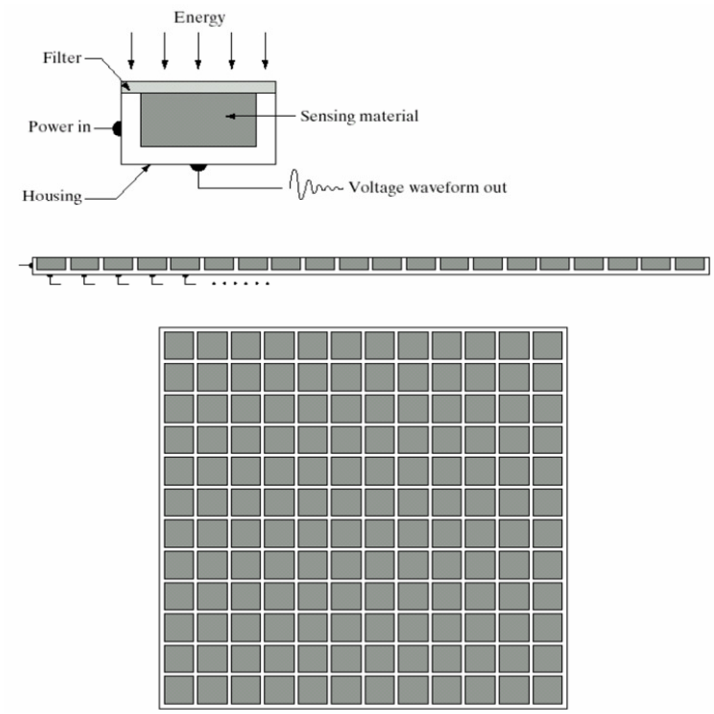


Figure 2.1 Single imaging sensor, line sensor system and array sensor system (from the top) (Myler, 2000)

The energy of the illumination source is reflected from the scene element into the imaging system. The imaging system collects the incoming energy and focuses it onto the image plane. Then, the array sensor that is on the image plane produces outputs proportional to the received energy. The continuous voltage outputs are then converted into digital form through sampling and quantization (Figure 2.2), in which the sampling digitizes the coordinate values and the quantization digitizes the amplitude values. Finally, the digital image is generated. After discussing the basic principle of image sensing, two typical array image sensors, Charge-Coupled Device (CCD) and Complementary Metal–Oxide–Semiconductor (CMOS), are presented.

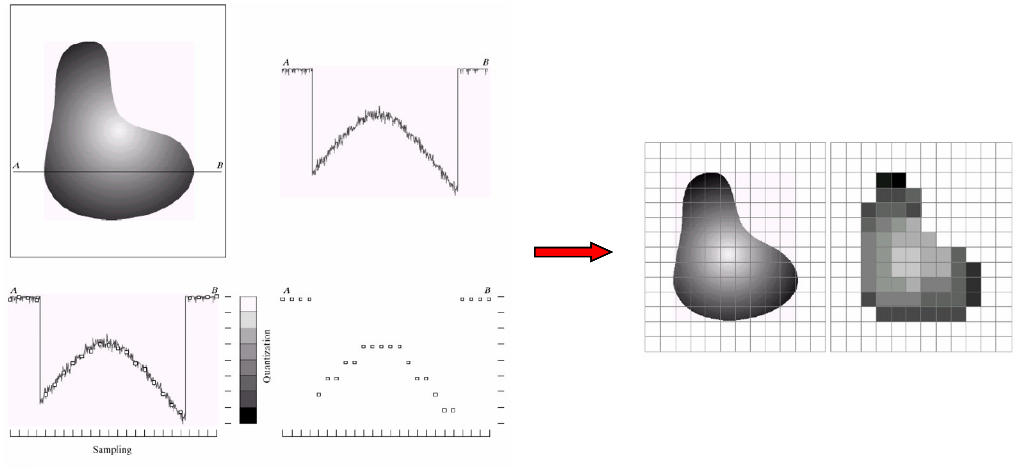


Figure 2.2 Generation of a digital image (Myler, 2000)

CCD stands for Charge-Coupled Device, and was invented in 1969 by Willard Boyle and George E. Smith at the AT&T Bell Labs (Myler, 2000). A CCD sensor is constructed with a rectangular grid of electro-collection sites laid over a thin silicon wafer. The sites will collect electrons when exposed to light and pass the electrons from one charge-collecting bucket to another charge-collecting bucket. A sequential readout and good output uniformity are obtained through this method. However, significant amounts of power are consumed when they are transported across the chip and read the values of each cell. Such high power consumption is necessary for the CCD to maintain its image quality and to limit noise (Micron Technology, 2006). Up to now, the fidelity and light sensitivity of CCD is high but the production costs of CCD chips are relative high, too.

CMOS stands for complementary metal–oxide–semiconductor. CMOS circuits were invented in 1963 by Frank Wanlass at Fairchild Semiconductor (Myler, 2000). CCD and CMOS technologies have the same working principle, however, CMOS sensors have a different structure. The CMOS sensors have three or four transistors in each electro-collection site, which amplify and move the charge provided by the incoming energy. This structure allows the pixel to be read individually, but the CMOS pixel might not be as sensitive as a CCD pixel since some of the light may enter a given pixel and land on a transistor, not on the sensor's light-detecting photodiode (Taylor, 1998). The CMOS image sensors operate at a very low gain and also produce more noise than CCD sensors. Nevertheless, CMOS manufacturing processes use standard microprocessor technology, which can lower the production cost significantly and make the integration simpler (Shapiro and Stockman, 1998).

Digitalized images are widely used in machine vision and communication, in recent years. There are many different types of image file formats in use. The general image file contains both image file header information and the raw image data. The image file, header is a set of parameters containing necessary information on the image file such as the image size, the number of bands, the number of bits per pixel and the file type. Bitmap and vector are the two categories of image data. The bitmap image may be a stream of bytes encoding a two dimension array of image pixels. It also called a raster image. Vector images store key points that are sufficient to define the lines, curves and shapes. In image processing, the bitmap images are most commonly used. Since Bitmap files do not provide compressed image data and therefore the file size is typically much larger.

In some cases, the Bitmap files are compressed for storage after processing. In general, the usual compressing process involves several steps. First of all, the rate (bits available) and distortion (tolerable error) parameters for the target image must be specified. Then, the image data is divided into various classes based on its importance and the available bit budget among these classes, such that the distortion is minimized. Then, each class is separately quantized using the bit allocation information. Finally, each class is separately encoded using an entropy coder and written to a file. In contrast, when someone wants to decompress the file, the quantized data has to be read from the file first by an entropy decoder. The next step is de-quantizing the data and rebuilding the image (Umbaugh, 2005). The Joint Photographic Experts Group (JEPG) is a commonly used compressed file format. It provides a practical compression of high quality colour still images. A JEPG image can have up to 64K x 64K pixels of 24 bits and is independent of the colour coding system. It also allows real-time hardware for coding and decoding.

2.2.2 Edge Detection

Edge detection has been considered as an alternative to segmentation. In fact, it has an additional advantage in that it can immediately reduce, by a large factor, the redundancy inherent in the image data. This is very useful for machine vision because it reduces both the memory space needed to store the data and the computational resources for subsequently processing and analyzing (Davies, 2005). Laplacian based and gradient based edge detection, and two well-known edge detectors are described in this section.

Both Laplacian based edge detection (Laplacian) and gradient based edge detection are the main and most important strategies for detecting edges. Laplacian has the fastest change in brightness when a 2D analogue of the second derivative vanishes. Gradient-based edge detection explicitly searches for points where the magnitude of the gradient is extreme. Laplacian is a historically important, but gradient-based edge detection is the most popular now (Forsyth and Ponce, 2003). In Laplacian based edge detection, by finding the zero crossings of the second derivative of the image intensity, the edge points of an image can be found. However, in the process of calculating the second derivative, it is very sensitive to noise. This noise must be filtered out before edge detection is done on the image. So, 'Laplacian of Gaussian' (LoG) is used to achieve this purpose. This method combines Gaussian filtering with the Laplacian for edge detection (Claypoole et al., 2007). In Figures 2.3 and 2.4, once the edge has been found, it becomes 'thick' due to the thresholding. The edge shown in Figure 2.5, however, occurs at the peak, and edge can be localized by computing the Laplacian and finding the zero crossings.

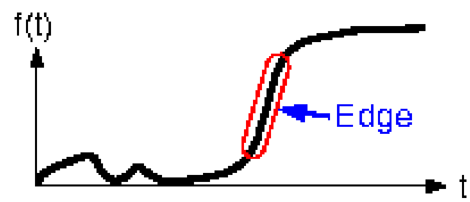


Figure 2.3 Lplacian of one-dimensional signal (Claypoole et al., 2007)

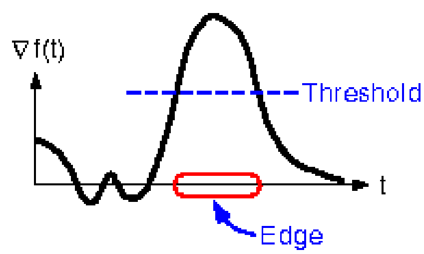


Figure 2.4 Edge indicated on the gradient which over the threshold (Claypoole et al., 2007)

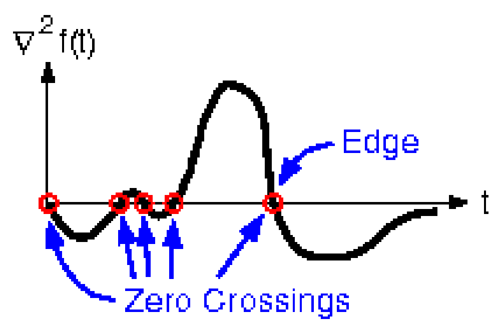


Figure 2.5 Zero crossing (Claypoole et al., 2007)

There are three main steps in LoG: Filtering, Enhancement and Detection. Firstly, Gaussian filter is used for smoothing. Secondly, the second derivative of the image is used for the enhancing the signal. Finally, the presence of a zero crossing in the second derivative with the corresponding large peak in the first derivative is used for detection (Claypoole et al., 2007).

In gradient based edge detection, there is an assumption that edges are the pixels with high gradients. The edge pixels are the pixels with a fast rate of change of brightness in any direction given by the angle of the gradient vector. In the pixel highlighted in Figure 2.6, the intensity changes from 0 to 255 in the direction of the gradient. The magnitude of the gradient indicates the strength of the edge. If the gradient is in uniform regions, there will be a 0 vector that means there is no edge pixel in the regions (Claypoole et al., 2007).

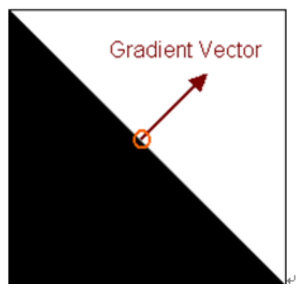


Figure 2.6 The gradient and an edge pixel (Claypoole et al., 2007)

In natural images, it is difficult to find the total discontinuity or the uniform regions, so one can calculate the magnitude of the gradient to make a decision on whether or not it is an edge pixel. The simplest processing is to apply a threshold. If the gradient magnitude is larger than the threshold, a decision is made that the corresponding pixel is an edge pixel (Forsyth and Ponce, 2003). Normally, an edge pixel can be described by two features: edge strength is equal to the magnitude of the gradient, or the edge direction is equal to the angle of the gradient (Claypoole et al., 2007). In Figure 2.7, at the center, gradient magnitude estimated using the derivatives of a Gaussian with $\sigma = 1$ pixel; on the right, the gradient magnitude is estimated using the derivatives of a Gaussian with $\sigma = 2$ pixels. The larger the values of the gradient magnitude are, the thicker the trails (Fisher et al., 2003). An appropriate search direction for the next edge point is perpendicular to the gradient, so points r and s, which are shown in Figure 2.8, should be considered (Forsyth and Ponce, 2003). In fact, the gradient is not defined for a discrete function. It can be defined for the totally continuous image, and is estimated using some operators such as Roberts, Sobel and Prewitt (Claypoole et al., 2007).

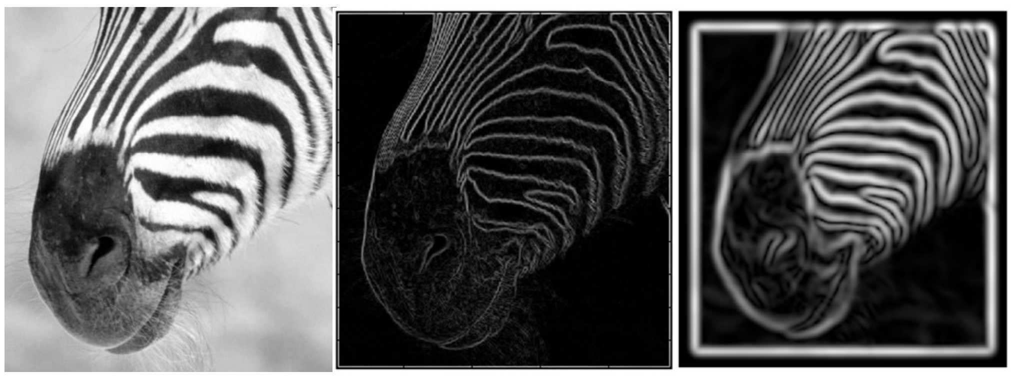


Figure 2.7 The derivatives of a Gaussian with different σ (Forsyth and Ponce, 2003)

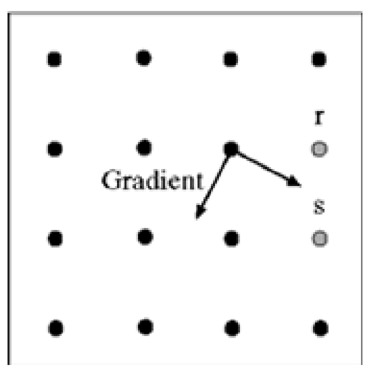


Figure 2.8 Predicting the next edge point (Forsyth and Ponce, 2003)

The Sobel operator is used to avoid having the gradient calculated about an interpolated point between pixels. It uses a 3 x 3 neighborhood for the gradient calculations as shown in Figure 2.9, (Green, 2002a). The arrangement of pixels around the specific pixel [i, j] shown in the Figure 2.9 is considered as the Sobel operator. It is the magnitude of the gradient calculated by $M\sqrt{s_x^{\ 2}+s_y^{\ 2}}$. The partial derivatives s_x and s_y are computed by $\begin{cases} s_x = (a_2 + ca_3 + a_4) - (a_0 + ca_7 + a_6) \\ s_y = (a_0 + ca_1 + a_2) - (a_6 + ca_5 + a_4) \end{cases}$,

where c is a constant and equal to two (Green, 2002a). In two-dimensions, there is an accurate approximation for computing the derivative of a two-dimensional image. The Sobel operator can perform a two-dimensional spatial gradient measurement. Normally, the Sobel operator is used to find the approximate absolute gradient magnitude at each pixel in an input grayscale image. The Sobel edge detector will make use of a pair of 3x3 convolution masks: one is to estimate the gradient in the x-direction and the other is to estimate the gradient in the y-direction. These two convolution masks shown in Figure 2.10 are much smaller than the actual image. They will be slid over the image and a square of pixels will then be manipulated (Green, 2002a). In short, the Sobel operator focuses on pixels that are closer to the center of the mask and, nowadays, it is one of the most commonly used edge detectors.

a_0	a_1	a_2
a_7	$[i, j]$	a_3
a_6	a_5	a_4

Figure 2.9 The labeling of neighborhood pixels

s_x =

-1	0	1
-2	0	2
-1	0	1

s_y =

1	2	1
0	0	0
-1	-2	-1

Figure 2.10 Two convolution masks of Sobel operator

Canny's Operator is a well known as an optimal edge detector, with a low error rate. It is important that edges occuring in images should not be missed and non-edges should not have any responses. Also, the edge points in the image are well localized. In other words, the distance between the edge pixels as found by the detector and the actual edge is at minimum. Furthermore, it has only one response to a single edge. This is very important because the first two advantages are not strong enough to completely avoid the possibility of multiple responses to an edge (Green, 2002b). There are four main steps in Canny's operator: Firstly, the image is smoothed by a Gaussian filter. Secondly, gradient calculation is done to calculate the gradient magnitude and orientation using finite-difference approximations for the partial derivatives. In Figure 2.11, the gradient is within the yellow range, and the edge direction is set to 0 degrees; within the green range, edge direction is set to 45 degrees; within the blue range, edge direction is set to 90 degrees; within the red range, edge direction is set to 135 degrees. Furthermore, non-maxima suppression is applied to the gradient magnitude which means that an edge point is defined as a point with its strength being locally a maximum in the direction of the gradient. At the end, a double thresholding is used for reducing the false edges and to avoid missing any edge, so that all the edges can be detected and linked better (Green, 2002b).

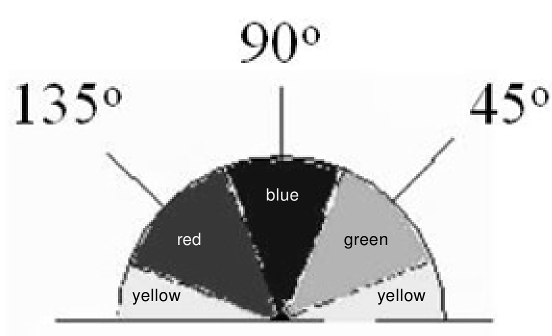


Figure 2.11 Gradient orientation (Green, 2002b)

2.2.3 Line Detection

Straight lines are among the most common features in vision tasks. It is obvious that the majority of manufactured objects and components contain straight lines. The Hough Transform (HT), named after Paul Hough who patented this method in 1962 (Hough, 1962), is a powerful means for detecting straight lines. The principle involves locating lines by the HT is point-line duality (Davies, 2005). A single point can be defined either as a pair of coordinates or in terms of the set of lines passing through it (Figure 2.12). If there are straight lines in an image, all the straight lines passing through a single point must satisfy Equation 2.1 for varying values of *m* (slope) and *c* (intercept).

$$y_i = mx_i + c \tag{2.1}$$

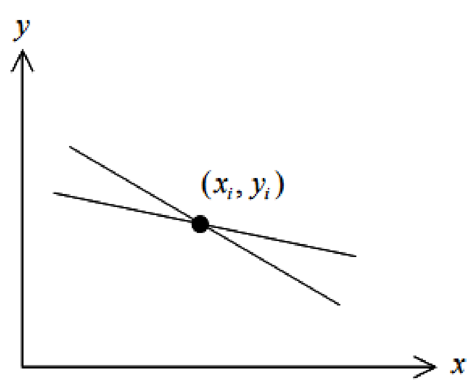


Figure 2.12 Straight lines passing through a point in the Cartesian domain

If the variables are reversed in Equation 2.1, *m* and *c* are treated as a function of the image point coordinates. Equation 2.2 can be formulated and it describes a straight line on a graph of *c* against *m* as shown in Figure 2.13.

$$c = y_i - mx_i \tag{2.2}$$

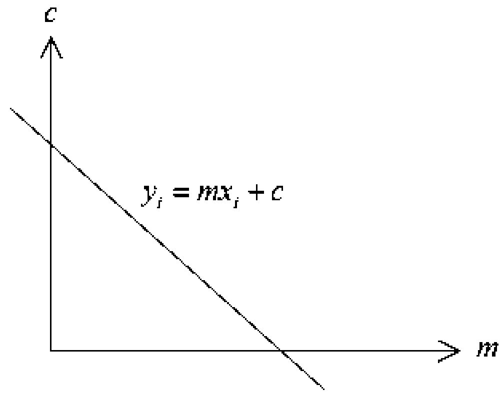


Figure 2.13 A graph of *c* against *m*

It can be seen that every line through the point (x_i, y_i) corresponds to one of the points on that line in the (*m*, *c*) domain. If considering two pixels A and B which lie on the same straight line, all the possible lines can be identified through each pixel by a single line in the (*m*, *c*) domain. Thus, a line in the (*x*, *y*) domain that passes through the two pixels must lie on the intersection of the two lines in the (*m*, *c*) domain. In short, all pixels which lie on the same line in the (*x*, *y*) domain are represented by lines which pass through a single point in the (*m*, *c*) domain, as shown in Figures 2.14 and 2.15 (Davies, 2005).

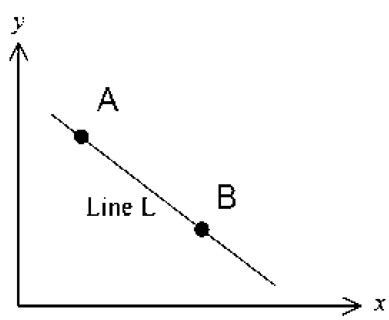


Figure 2.14 Pixels A and B on the same straight line

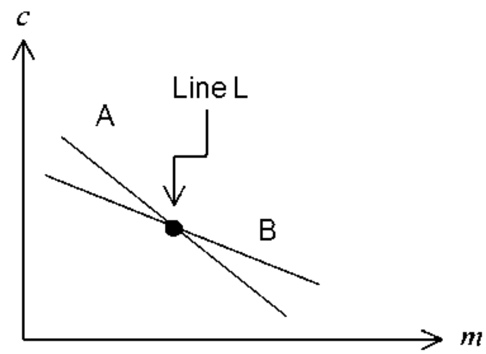


Figure 2.15 Mapping of A and B from Cartesian domain to the (m, c) domain

With this concept, straight lines can be detected by the HT with five steps (Hamarneh et al., 1999). Firstly, all the edge points in an image are identified by a suitable edge detector, such as the aforementioned one in last section. Secondly, the (m, c) domain is quantized into a two-dimensional matrix H with appropriate quantization levels. Thirdly, H is initialized to zero. Then, each element of H is incremented by 1 if it corresponds to an edge point. The result is a histogram or a vote matrix showing points lying on a common line. Finally, threshold is applied to the histogram of H so that only the large valued elements are left. Thus, these remaining elements represent lines in the original image. However, the detected lines are in (m, c) values, but not finite lines, with infinite lines described by their defined end points (Hamarneh et al., 1999). In order to avoid the problem of infinite m values occurring when vertical lines are found in the image, the alternative formulation which can be used to describe a line, is shown in Equation 2.3.

$$x \cos\theta + y \sin\theta = r \tag{2.3}$$

With this modified formulation, a point in the (x, y) domain is represented by a curve in the (r, θ), domain, as shown in Figure 2.16 (Davies, 2005).

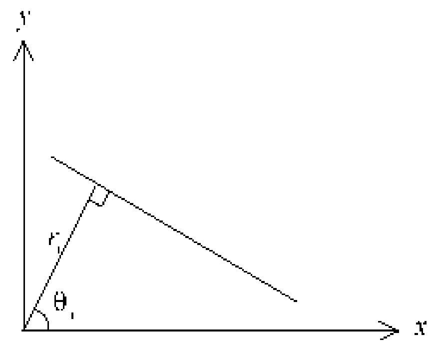


Figure 2.16 The improved representation of a line

Although the computational load is relatively heavy when using the HT for straight line detection, the HT is very robust because it focuses only on positive evidence for the existence of objects (Davies, 2005). It is also capable of detecting a straight line where the pixels are lying on one line which is not contiguous. This advantage makes the HT highly robust in detecting lines against short breaks, noise and background clusters.

2.2.4 Circle Detection

The location of round objects is important in many areas of image analysis, such as circle detection to detect traffic signs by Mainzer (2002). However, it is especially vital in industrial vision tasks, such as in automatic inspection of many circular components in the electronics and automotive industries (Davies, 2005). In many cases, manufactured parts or assemblies have to be checked and inspected with high precision. These objects can always be identified by their holes, so finding round holes or circular features is part of a larger problem in automated vision inspection. This section reviews some aspects of this problem.

The application of the HT to circle detection is a widely used technique. The basic concept can be divided into several steps. Firstly, smoothing of the captured image is needed to reduce the amount of noise. For smoothing, a two-dimensional

Gaussian smoothing filter is suggested. Since it is relatively complicated to approximate the values of the distribution function by normal distribution, a probability density function can be used (Borovicka, 2003).

$$smoothfilter[i, j] = \frac{1}{(\sqrt{2\pi\sigma})^2} \cdot e^{-\frac{i^2+j^2}{2\sigma^2}} \qquad (2.4)$$

Secondly, an edge detection procedure is required. The aforementioned Sobel operator can be applied. In order to improve the edge detection result, a second-derivative filter is recommended to support the Sobel operator. Since the Sobel operator is based on identifying the maxima of the first-derivative, the additional second-derivative filter focuses on zero crossings of the second-derivative. Thirdly, a circular HT is accomplished on the thresholded edge map. The concept of the circular HT is that bright hot spots in the centers of the circles can be obtained by projecting perpendicular lines to each edge point of the edge map. The line clusters in the (a, b) space can be created by:

$$\left.\begin{aligned} a &= r\sin\theta \\ b &= r\cos\theta \end{aligned}\right\} where\ r \in (\min r, \max r) \qquad (2.5)$$

where min r and max r is the range of circle radii provided.

$$A(i \pm a, j \pm b) \leftarrow A(i \pm a, j \pm b) + E(i, j) \qquad (2.6)$$

A is the (a, b) space array and $E(i, j)$ is the strength of the edge. The resulting (a, b) space is then convoluted with a 17 x 17 Mexican Hat filter in order to enhance the hot spots by concentrating the highest brightness in the center of gravity of the hot spots, because the spots may be diffused and dimmed if the circles are distorted. The (a, b) space is thresholded and the centers of the hot spots obtained (Figure 2.17). Finally, the r-space is accumulated to locate the most observable circles' centers. The accumulation is done in a one-dimensional space where the radius of concentric circles with the given center is coordinated. For every radius in the range of circle radii, the sum of the edge strength E for the points P along the a circumference with the given radius r is calculated by:

$$R(r) = \sum_{P \in circle(r)} E(P) \tag{2.7}$$

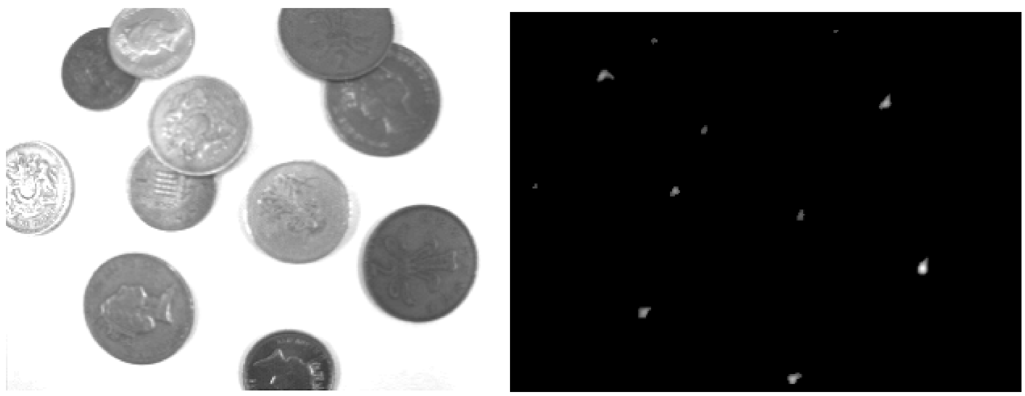


Figure 2.17 (Left) Original image; (Right) Hot spots shown in the thresholded (a, b) space (Borovicka, 2003)

The circle detection problem has not yet been solved. The HT based techniques have been widely used and further modified in the last decade. Lam and Yuen (1996) proposed an approach which is based on hypothesis filtering and HT to detect circles. Han et al. (1993) and Shaked et al. (1996) proposed new approaches to the HT which are the fuzzy HT and the probabilistic HT respectively. Rosin and Nyongesa (2000) suggested a soft computing approach to shape classification. Borovicka (2003) further refined coordinates and radii to sub-pixel accuracy of the HT based method. Recently, Ayala-Ramirez et al. (2006) proposed a GA-based method to solve the circle detection problem based on three-edge-point circle representation, which can overcome the drawback of the HT method in dealing with high dimensional problems.

2.2.5 Template Matching

Template matching is a technique for finding out how well a template image (sub-image) matches with part of a captured image (Seul et al., 2000). It is widely used in manufacturing as an element of quality control (Aksoy et al., 2004). There are various approaches for accomplishing template matching, some performing better than others, and some finding better matches. The basic idea of template matching is to loop the template through all the pixels in the captured image and compare the similarity. While this method is simple and easy to implement, it is the slowest method. A common method nowadays is usually implemented by creating the template first. The template is represented as *T(x, y),* where *x* and *y* are the coordinates of a pixel. The center of this template will be moved over each *(x, y)* point in the captured image, which is called *F(x,y),* and the degree of matching between *T* and the corresponding pixels in *F* is often determined by evaluating the Normalized Cross Correlation (NCC) value (Figure 2.18). NCC is an effective similarity measurement method at each pixel of the given image. NCC has long been a standard similarity measurement method in feature matching and object recognition (Duda and Hart, 1973; Gonzalez and Woods, 1992). The NCC value between a given image *F* of size *M x N*, and a template image *T* of size *m x n* at coordinate *(x, y)* is given.

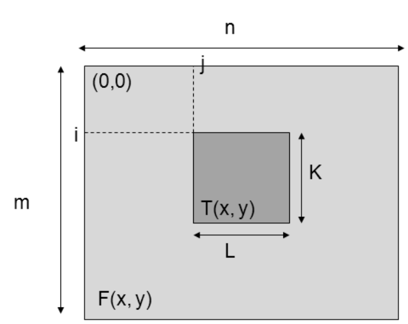


Figure 2.18 An illustration of template matching process

$$\gamma = \frac{\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}[F(x+i, y+j) - \overline{F}]\cdot[T(i,j) - \overline{T}]}{\{\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}[F(x+i, y+j) - \overline{F}]^2 \cdot \sum_{i=0}^{m-1}\sum_{j=0}^{n-1}[T(i,j) - \overline{T}]^2\}^{1/2}} \tag{2.8}$$

The term $\overline{F}$ is the grey-scale average intensity of the captured image in the region coincident with the template image and $\overline{T}$ is the grey-scale average intensity of the template image. The NCC value is represented by γ which is scaled from -1 to 1 and is scale-free in the captured image and the template. The image dimension is represented by *m* and *n*, and the template location is identified by *i* and *j*. A maximum value will be obtained by a 'perfect' match between *F* and *T*. Correlation based template matching has been commonly used in several different applications (Stefano et al., 2004). Its operation, which requires sliding the template across a candidate image (captured image), and the computing cost of the correlation at every possible pixel is high, especially as the candidate image is large and multiple matches of the image are required, such as tracking multiple components on a PCB. Thus, various researchers have improved the NCC based template matching or searching process, such as Wei and Lai (2008) who combined a multilevel winner update with the NCC criterion and Wu et al. (2009b) who proposed three acceleration strategies for the NCC based template matching process.

2.2.6 Machine Vision Systems

In this section, the basic concept of machine vision systems is first provided, and the focus is then on the research trend described in the literature. Further, the classification of machine vision systems existing in the literature is investigated. This is because the fundamental machine vision techniques are significantly mature; however research in machine vision techniques is continuous and it is better to understand how the new elements are applied in different machine vision systems for tackling various vision tasks. To find answers to the above mentioned issues, a systematic review technique is adopted.

The main components of a typical machine vision system have been described in the literature (Golnabi and Asadpour, 2007; Davies, 2005; Awcock and Thomas, 1995). In general, six basic stages are involved in a machine vision system, as illustrated in Figure 2.19. These stages are image acquisition, preprocessing, feature extraction, associative storage, knowledge base, and recognition and/or interpretation. These stages correspond to low, intermediate, and high level processing, in which a captured image will be digitalized. A digitalized image is an image $f(x, y)$ in which both spatial coordinates and brightness have been digitized. After a digitalized image is obtained, pre-processing take place which is considered as low level processing. A number of well developed pre-processing techniques based on spatial domain or frequency domain are available, including gray scale manipulation, smoothing, noise filtering, geometric correction, restoration, etc. The pre-processing stage in a machine vision system also deals with brightness perception as well as problems like image restoration, image reconstruction and edge map generation.

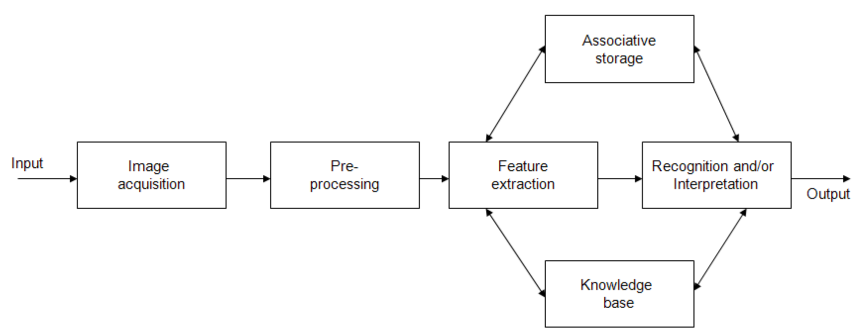


Figure 2.19 A simple block diagram for a typical machine vision system

The next level of processing is the intermediate level. The processes on this level attempt to build a coalition of tokens which are obtained in the low-level processing and to extract meaningful entities. Feature extraction is a well-known processing on this level. The main purpose of feature extraction is to reduce data by measuring certain features that distinguish the input patterns. During the last thirty years, many techniques have been developed for feature extraction. These include the Hough transform, the Fourier transform, moment invariants, the Wigner distribution, orthogonal polynomials, Gabor functions, etc (Kulkarni, 2001).

Edges are important features in an image since they represent significant local intensity changes. They provide important clues to separate regions within an object or to identify changes in illumination. Most vision applications, such as image registration, image segmentation, region separation, object description, and recognition, use edge detection as a start for feature extraction. Real images, such as remote sensing images, can be corrupted with point noise. The real problem, as well in undertaking this research, is how to enhance noisy images and simultaneously extract the lines, circles and polygon with higher efficiency.

The last three stages are associative storage, knowledge base, and recognition and/or interpretation which correspond to high level processing. The human memory can recall complete information from partial information or a subset. Associative memories are content-addressable memories. The recognition and/or interpretation stage deals with classification. It assigns a label to an object based on the information provided by its descriptors. Conventional classification techniques are grouped into two groups: supervised and unsupervised. In a supervised mode, a ‘teacher’ presents and a classifier learns by the training set provided by the teacher. In an unsupervised mode, a classifier learns without a training set but on its own. The knowledge base interacts not only with the feature extraction and recognition, but also with the associative storage. Usually any prior knowledge about an object can also be encoded in the knowledge base. The knowledge can greatly help in detailing regions of an image where the information of interest is known to be located.

In order to study the development trend of a machine vision system, the following three online citation databases have been selected for the study; they are

1. Science Direct: http://www.sciencedirect.com
2. Springer LINK: http://www.springerlink.com
3. IEEE Xplore: http://ieeexplore.ieee.org/Xplore/dynhome.jsp

These three data sources comprehensively cover all the major journals and magazines in the fields of computer science, electronics, manufacturing, industrial engineering, including journals such as IEEE Signal Processing Magazine, IEEE Transactions on Image Processing, Pattern Recognition, Computer Vision and Image Understanding, Machine Vision and Applications, Journal of Intelligent Manufacturing etc. The three keywords, machine, vision and system, are used with the following combinations: 'machine vision', 'vision system' and 'machine vision system'. The search is directed to all content including the title of the article, abstract and the keywords in all the relevant journals and magazines. The restriction imposed upon the year of publication is from 1990 to 2010. This was done on 2010-10-01 in order to find out the development trend of machine vision systems in the last twenty years. The search yielded a huge number of articles and after applying filters in the respective websites, 619, 183 and 1268 articles were obtained from the Science Direct, Springer LINK and IEEE Xplore respectively. The distribution of the articles over the last 20 years is shown in Figure 2.20 that shows the number of articles involving the term 'machine vision system' on the vertical axis and the corresponding year of publication on the horizontal axis.

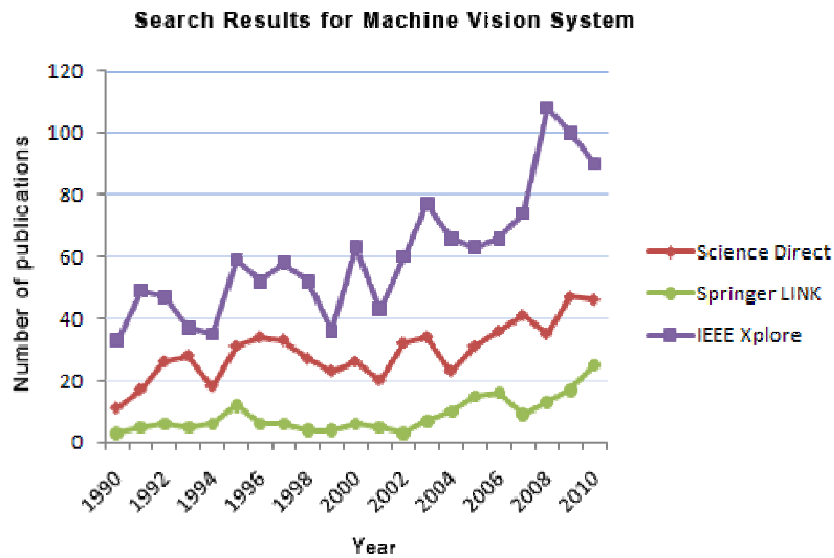


Figure 2.20 Distribution of articles (in three selected databases) using the term 'machine vision system'

A preliminary analysis was performed on the search results with the help of the plots shown in Figure 2.20. These plots indicate that the general trend in research and development of machine vision systems has grown from 1990 to 2010. It should be noted that the drop in the curves in the last period section of Science Direct and IEEE Xplore is because only articles published up till to the third quarter of the year 2010 were considered. Since the number of articles found is enormous, 45 articles were chosen for the analysis based on their relevance to machine vision systems and with citations. A further classification was performed through careful study of the selected 45 articles.

Previous important general reviews that cover all the fields of machine vision or vision inspection have been done by Taylor et al. (1988), Newman and Jain (1995) and Malamas et al. (2003). The major categories of vision systems for industrial applications are Dimensional quality checking, Surface quality checking, Structural quality checking and Operational quality checking. Malamas et al. (2003) listed out the potential features of inspected products which are shown in Table 2.1. On top of the categories suggested in the literature, the type of artificial intelligence technique involved in a particular system is added in this review. The categories are briefly described in the following section.

Dimensional quality checking is related to the inspection of whether the dimension of an object is within preset tolerances or the shape of an object. For example, Shiau and Jiang (1999) proposed a measurement algorithm for visual inspection. Surface quality checking means checking the surface of an object for scratches, cracks, wear or for the required finishing level, roughness and texture. For example, Kumar et al. (2005) proposed a machine vision system for surface roughness evaluation. Structural quality checking stands for checking missing components on an assembly or checking the presence of any unwanted object. For example, Wu et al. (2009b) proposed a PCB components inspection system based on a template matching approach. Operational quality checking means verification of the correct or accurate operation based on predefined standards or guidelines. For example, a monitoring system for the laser butt joint welding process was developed by Jeng et al. (2000). The type of artificial intelligence (AI) or evolutionary algorithm involved means whether or not the proposed system embeds AI or evolutionary algorithm such as Neural Networks, Fuzzy Logic, GA and PSO. Table 2.2 illustrates the classification of the vision systems for various vision tasks.

Table 2.1 Potential Features of Inspected Products

Surface	Dimensions, shape, positioning, orientation, alignment, roundness, corners
Dimensional	Assemble (e.g. holes, slots, screws, rivets, clamps), foreign objects (e.g. dust, grease, bur, clamps)
Structural	Pits, scratches, cracks, wear, finish, roughness, texture, continuity, seams-fold-laps
Operational	Incompatibility of operation to standards and specifications

Table 2.2 Classification of Machine Vision Systems in Solving Different Industrial Vision Tasks

Inspection Type	Reference	Application	Type of AI or evolutionary algorithm applied
Surface	Li & Jin (1994)	Wafer surface inspection	-
	Barni et al. (1997)	Chicken meat inspection	-
	Shafarenko et al. (1997)	Granite surface checking	-
	Drake & Packianather (1998)	Wood veneer surface	Neural Networks
	Lacey et al. (1998)	Surface approximation	-
	Tsai et al. (1998)	Surface Roughness	-
	Bahlmann et al. (1999)	Textile seam defects	Neural Networks
	Bhandarkar et al. (1999)	Internal wood defects	-
	Smith et al. (1999)	Surface defects	-
	Tsai & Hsieh (1999)	Directional texture	-
	Packianathe & Park (2000)	Wood veneer surface	Neural Networks
	Boyer & Ozguner (2001)	Surface corrosion	-
	Kumar et al. (2005)	Surface roughness	-
	Lee et al. (2005)	Tooling inspection	-
	Sun et al. (2010)	Surface defects	Particle Swarm Optimization
Dimensional	Hunsicker et al. (1994)	Screw threads checking	-
	Hunter et al. (1995)	Automotive parts inspection	-
	Magee & Seida (1995)	Object classification	-
	Janannathan (1997)	Solder joints inspection	-
	Cucchiara (1998)	Object classification	Genetic Algorithms
	Goulermas & Liatsis (1998)	Circular parts inspection	-
	Kavoussanos & Pouliezzos (1998)	Packaging	-
	Oyeleye & Lehtihet (1998)	Solder joints inspection	-
	Torres et al. (1998)	Banknotes inspection	-
	Anard et al. (1999)	Packaging	Genetic Algorithms
	Hou & Pern (1999)	Machined parts inspection	-
	Jimenez et al. (1999)	Fruit checking	-
	Kim et al. (1999)	Solder joints inspection	-
	Tsai (1999)	Circular parts inspection	-
	Shiau & Jiang (1999)	Line segment measurement	-
	Jimenez et al. (2000)	Fruit harvesting	-
	Kondo et al. (2000)	Fruit checking	Neural Networks
	Urena et al. (2000)	Seeds germination checking	Fuzzy Logic
	Lahajnar et al. (2002)	Electric plates inspection	-
	Derganc et al. (2003)	Bearings measurement	-
	Duan et al. (2007)	Beer bottle inspection	-
	Jarimopas & Jaisin (2008)	Fruit sorting	-
	Sun (2009)	Roundness measurement	Particle Swarm Optimization
Structural	Tretter et al. (1995)	Object assembly	-
	Cootes et al. (1996)	PCB inspection	-
	Crispin & Rankov (2007)	PCB inspection	Genetic Algorithms
	Wu et al. (2009b)	PCB inspection	Particle Swarm Optimization
Operational	Jeng et al. (2000)	Laser butt joint welding	-
	Van Kuren (2005)	Electronics disassembly	-
	Edinbarough et al. (2005)	Electronic manufacturing	-

In summary, there is a continuous growth in machine vision system research and development, especially for inspection in the manufacturing and food industries. However, there is little application in the logistics area. Although some classifications of machine vision system are available in the literature, no previous work includes the classification of the embedded AI or evolutionary algorithm in the machine vision system. Evolutionary algorithms such as GA and PSO have been shown to be tools which can be used effectively in developing machine vision system in complex domains of high industrial relevance. This short review reveals that PSO is a relatively 'young' technique to be adopted in machine vision systems. Since 2009, PSO has been applied to solve vision-based surface, dimensional and structural problems. However, there is no attempt made in solving operational problem with an aid of AI or EAs. The PSO approach used in the developed system is a start and it has many other potential applications in different areas such as object tracking and segmentation (Cagnoni et al., 2007). Thus, the proposed chaos-based evolutionary algorithms are based on PSO. It is believed that this classification provides a stepping stone for future researchers to conduct further reviews and identify relevant research directions.

2.2.7 Factors in Design of Machine Vision Systems

Since this research focuses on the proposed chaos-based algorithms, and on the design and feasibility of MVES with the algorithms, the descriptions and explanations have been presented with more emphasis on the evolutionary approaches and on integration with other technologies. In fact, there are several more factors in an optimal design of a vision system which are normally considered by professional development teams. The factors in the design of the system share a lot of common aspects which are reported in the literature (Zuech, 2000; Hornberg, 2006; Golnabi and Asadpour, 2007). As a summary, these factors are problem formulation, scene consideration, image acquisition, pre-processing, image processing, application justification and systematic consideration. These factors are shown in Figure 2.21.

Figure 2.21 Factors in design and application of MVES

Image acquisition, which directly affects system performance, is one of the most essential processes because the following processing and analysis could be easily achieved with the high quality and well formatted image produced. Both the hardware and software are involved in this process and the selection of suitable components is very important to image acquisition as well as to the display of the image. Image capturing can be done by using single, stereo, and multiple cameras.

The quality of the image captured is dependent on the illumination and the lighting conditions such as diffused light, back lighting and strip lighting arrangements, etc. For the usual industrial applications, the active light source is more common. However, some situations require a passive light source, such as light from the sun or light sources from the environment for the purposes of illumination, hence the light intensity level and possible frustration must be considered. The choice of the light source is an important factor. The wavelength of the electromagnetic wave is another important consideration in image capturing. In some cases, the invisible, infrared or X-ray region of the spectrum can be used for illumination.

The general approach to developing a vision system must include the systematic consideration and justification of a target application. For example, one team is going to solve a vision-based problem on the factory floor for which a production line, process and machine specifications should be gathered. The scene specifications and all the requirements and constraints must be considered. The size and type of target objects or object groups must be studied in order to provide a feasible system design and operation for solving the problem. Besides this, materials, limitations in image capturing, and positions and orientation of the objects are also important. According to the given conditions of the problem, the vision-based problem must be carefully formulated while the required pre-processing and processing techniques, object features, position and orientation of the object, and the lighting condition must be accurately and appropriately selected.

2.3 Academic Study of Optimization Methods

This section provides a brief overview of optimization methods. First of all, the objective of optimization is discussed. Stochastic algorithms and evolutionary algorithms (with more emphasis on PSO) are then presented. This is followed by a brief discussion of PSO itself and its improvement. Lastly, a short overview of ant colony optimization is provided.

2.3.1 Optimization

The objective of optimization is to seek a set of parameters that maximize or minimize objective functions subject to certain constraints (Rardin, 1998). The choice of selected values of the parameter set that satisfy all constraints is a feasible solution. An optimal solution is a feasible solution which gives objective function value(s) as good as the values of any other feasible solutions (Rardin 1998). Any maximization problem can be converted into a minimization problem by taking the negative of the objective function, and vice versa. Optimization techniques are applied in our daily lives such as scheduling, industrial planning, resource allocation, vehicle routing etc. Research in optimization is very active in business, engineering and computer science. Thus, new or improved optimization methods are frequently proposed. A minimization problem can be defined as follows (Pardalos et al., 2002):

$$\begin{gathered}\text{Given } f : S \to \Re^{N_d} \text{ and } N_d \text{ is the dimension of the search space } S \\ \text{find } x^* \in S \text{ such that } f(x^*) \le f(x), \forall x \in S\end{gathered} \qquad (2.9)$$

x^* is the global maximizer of f and $f(x^*)$ is the global maximum value of f. Thus, global optimization is the process of searching for the global maximum solution (or the global optimal solution). Global optimization problems are very difficult to solve and are categorized under the class of nonlinear programming (Gray et al. 1997).

According to previous literature, global optimization problems can be considered as general unconstrained problems, general constrained problems and combinatorial problems, where a linear or nonlinear function is defined over a finite but very large set of solutions (Gray et al. 1997; Pardalos et al. 2002).

2.3.2 Stochastic Algorithms

The basic idea of traditional optimization algorithms is that if a problem can be solved or the best solution can be found, then the algorithm should be able to search for the global best solution. Exhaustive searching is an example of the traditional optimization algorithms. However, the traditional optimization algorithms are not suitable for some problems, namely NP-hard problems, because the time spent on exhaustively searching in an NP-hard problem increases exponentially with problem size. Thus, stochastic search algorithms are proposed to find near-optimal solutions in solving NP-hard problems. The basic assumption of stochastic search algorithms is that good solutions are close to each other in the search space. This assumption is valid for many real world problems (Spall, 2003). The stochastic algorithms are better than the traditional optimization algorithms because they can be implemented easily, used efficiently in multiprocessor environments, do not have requirement for a continuous problem definition function, and most importantly, can report the best solution found so far any time during a run (Venter and Sobiezczanski-Sobieski, 2002). Three well-known stochastic algorithms are Hill-Climbing (Michalewicz and Fogel, 2000), Simulated Annealing (Van Laarhoven and Aarts, 1987) and Tabu searching (Glover, 1989; 1990). The potential solution is randomly selected in Hill-Climbing while Simulated Annealing is similar to Hill-Climbing, but a small value is added to the current solution to generate a new solution. Tabu searching has a list to remember previously visited solutions in order to improve the next performance of the search process.

2.3.3 Evolutionary Computation Techniques

Evolutionary computation is a subfield of AI that mainly involved in solving combinatorial optimization problems. It involves the concept of growth or development in a population in terms of iteration. This population is then selected in a guided random search until the desired end is reached. Such processes are usually inspired by biological evolution (DeJong, 2006). Evolutionary algorithms are evolutionary computation techniques, which are considered as a subset of evolutionary computation. They can be considered as general-purpose stochastic search methods by simulating natural selection and evolution in the biological world. The main difference between evolutionary algorithms and stochastic search algorithms is that evolutionary algorithms maintain a population of potential solutions for a problem but not single solution (Engelbrecht, 2002). Up to now, most evolutionary algorithms work to the general pseudo code shown in Figure 2.22.

```
Initialize the population
Evaluate the fitness of each individual in the population
Repeat
        Apply selection on the population to form a new population
        Alter the individuals in the population using evolutionary operators
        Evaluate the fitness of each individual in the population
Until some convergence criteria are satisfied
```

Figure 2.22 General pseudo code for evolutionary algorithms (Gray et al., 1997)

Evolutionary operators are higher order transformations. The two most common evolutionary operators are mutation and crossover. The main purpose of mutation is to provide some diversity by adding more genetic material into the population in order to prevent being trapped in a local optimum. This small diversity is done by inverting the value of a binary digit in the binary representations or by adding/subtracting a small number to/from selected values in floating point representations. A suggested strategy is to start with a high probability of mutation and decreasing it in the mean time (Salman, 1999). Crossover combines two or more individuals together in order to generate new individuals (Michalewicz, 1996). Since evolutionary algorithms have population-based natures, they can prevent themselves from trapped in a local optimum and keep searching for the global optimal solutions. Thus, evolutionary algorithms can be treated as a means to solve global optimization problems. Although evolutionary algorithms can avoid trapping in local optima, evolutionary algorithms cannot guarantee obtaining global solutions. Gray et al. (1997) reported that evolutionary algorithms may fail in converging to a global optimum. Nonetheless, evolutionary algorithms have been successfully been applied to solve a wide range of optimization problems, such as scheduling, vehicle routing, pattern recognition, etc. (Gray et al., 1997; Goldberg, 1989).

2.3.4 Genetic Algorithms (GAs)

Genetic Algorithms (GAs) were proposed by Holland (1962; 1975). GAs are evolutionary algorithms and they encompass selection, crossover and mutation operators. The basic concept of GAs follows the general pseudo code shown in Figure 2.22. Individuals in GAs are chromosomes. GAs encode a potential solution to a specific problem on a chromosome, such as like data structure, and apply recombination operators to generate a new individual in a search space. Each chromosome consists of a string of cells, namely genes, and the value of each gene is called an allele. Researchers, largely working from an experimental perspective, have introduced many GA models. Many researchers are application-oriented and are typically interested in GAs as optimization tools (Whitley, 1994).

Selecting a fitness function which accurately quantifies the solution quality is a fundamental element in GAs. A good fitness function enables the chromosomes to solve a problem effectively. Both the fitness function and solution representation should be problem dependent parameters. A good selection of these two parameters will boost up the performance of GAs. So, choosing a solution representation is another important element, while binary representation is widely used in GAs. Other representations have also been proposed by various researchers such as Janikow and Michalewicz (1991) who proposed floating point representations, Bramlette (1991) who proposed integer representations, and Michalewicz (1996) who proposed matrix representation. In general, non-binary representations need extra operators for each representation. Janikow and Michalewicz (1991) pointed out that floating point representations are better than binary representations in terms of speed, consistency and precision. After selecting solution representation and defining fitness function, the flow a basic GA is listed below (Hopgood, 2000):

- The initial population is randomly generated.
- Chromosomes are evaluated according to the predefined fitness function.
- Chromosomes are selected for reproduction based on their fitness; the fitter an individual, the more likely it is to be selected as parent
- Reproduction of chromosomes, to produce the next generation, is achieved by “breeding” between pairs of chromosomes using the crossover operator and then applying a mutation operator to each of the offspring.

A selection operator is used to select elitist chromosomes, namely parents, for mating in order to generate new chromosomes, namely offspring. Angeline (1998) mentioned that selection operators are used as mechanisms to focus the search on apparently more profitable regions in the search space. There are various selection operators, for example roulette wheel selection is based on probability and fitness to select parents (Gray et al., 1997). Rank selection is based on fitness and base selection on the rank order of all chromosomes. It helps to reduce the problem of highly fit individuals dominating the selection process (Gray et al., 1997). Tournament selection is a widely used approach (Goldberg, 1989). It is based on the collection of the fittest chromosome from the population. The collection process is repeated until the mating pool contains enough chromosomes to mate. Elitism selection means the fittest chromosome or a preset number of the best chromosomes is cloned to the next generation. Since a best candidate always exists, the GA performance can be improved (Gray et al., 1997).

According to Salman (1999), crossover operator is the ‘main explorative operator in GAs’. A predefined probability is required to execute crossover, namely crossover probability. There are four main crossover operators that can be found in the literature; they are single point crossover, two point crossover, uniform crossover and arithmetic crossover. Single point crossover divides parents into two parts randomly and then these two parts are swapped to create two offspring. Two-point crossover is similar to single point crossover but the two positions are randomly selected. For example, Parent A is ‘11**00**11’ and Parent B is ‘**01**101**10**’, then Offspring A will be ‘**0110010**’ and Offspring B will be ‘1110111’. Uniform crossover copies alleles from either the first or second parent with some probability, usually 0.5. Arithmetic crossover uses floating point representations. An offspring is generated based on the calculation of the arithmetic mean of the parents (Michalewicz, 1996).

A mutation operator is considered as a background operator because it is used to explore new areas in the search space and to add diversity to the population. It is contrary to the selection and crossover operators which are used to reduce diversity. Mutation is executed after crossover is done. In GAs using binary representation, mutation is done by inverting the alleles based on a predefined probability, namely mutation probability. Again, this probability is problem dependent (Goldberg, 1989). Kennedy and Spears (1998) observed that a GA using either mutation or crossover performed better than a GA using both operators when the GA is used to solve a set of random multimodal problems.

As aforementioned, GAs have been successfully applied in many business and engineering fields, and research areas (Onwubolu and Babu, 2004). Leung et al. (2003) presented a GA approach to be used in the electroplating industry for capturing the optimization of process parameters. A rule-based GA approach with embedded project scheduling was developed for solving the problems in partner selection (Ip et al., 2003). The Bin-packing model was developed based on GAs to improve production efficiency (Chan et al., 2007). In addition, Crispin and Rankov (2007) proposed an automated PCB components inspection system based on the GA approach. Ayala-Ramirez et al. (2006) applied GAs to solve circle detection problems and successfully recognized partially occluded circles in both synthetic and natural images.

2.3.5 Particle Swarm Optimization (PSO)

PSO has been in existence for roughly a decade. It is a population based stochastic optimization modeled after the simulation of the social behavior of bird flocks (Kennedy and Eberhart, 1995). PSO is similar to evolutionary algorithms because both are population based and each individual has a fitness function. In addition, the adjustments of each individual in PSO are relatively similar to the arithmetic crossover operator used in GAs (Coello-Coello and Lechuga, 2002). However, there are two major differences in that PSO is influenced by the simulated social behavior and each individual benefits from its history (Shi and Eberhart, 2001; Coello-Coello and Lechuga, 2002). PSO is relatively easy to implement when compared with GAs and has been successfully applied to solve a wide range of optimization problems, including continuous nonlinear, discrete and constrained optimization problems (Kennedy and Eberhart, 2001; Banks et al., 2008).

2.3.5.1 The PSO Algorithm

In PSO, a swarm of individuals, namely particles, fly through the search space in order to look for the optimum. Each particle represents a candidate solution to the optimization problem. The position of a particle is influenced by the best position it visits (i.e. its history) and the position of the best particle in the neighborhood. The best position in the neighborhood is referred to the global best particle when the neighborhood of a particle is the entire swarm. Thus, the algorithm is considered as a *gbest* PSO. When smaller neighborhoods are used, the algorithm is referred as a *lbest* PSO (Shi and Eberhart, 1998). The performance of each particle is measured using a fitness function which is problem dependent.

Each particle in the swarm has following characteristics:

- The current position of the particle: x_i
- The current velocity of the particle: v_i
- The personal best position of the particle: p_i
- The neighborhood best position of the particle: p_g

The personal best position p_i is the best position visited by the particle i so far. Let f is the objective function, p_i of a particle at time t is updated as

$$p_i(t+1)=\begin{cases} p_i(t) & \text{if } f(x_i(t+1)) \geq f(p_i(t)) \\ x_i(t+1) & \text{if } f(x_i(t+1)) < f(p_i(t)) \end{cases} \tag{2.10}$$

For the gbest model, the best particle is determined from the entire swarm by choosing the best personal best position. If s is the swarm size, the position of the global best particle is p_g , then p_g can be obtained by:

$$p_g(t) \in \{y_0,\ldots y_s\} = \min\{f(y_0(t)),\ldots f(y_s(t))\} \tag{2.11}$$

Since the particles fly over the search space, the velocity $v_{i,j}$ is updated by

$$v_{i,j}(t+1) = wv_{i,j}(t) + c_1 r_{1,j}(t)(y_{i,j}(t) - x_{i,j}(t)) + c_2 r_{2,j}(t)(p_{g_j}(t) - x_{i,j}(t)) \tag{2.12}$$

The terms c_1 and c_2 are cognitive components which determine the balance between the influence of the balance between the influence of the individual’s knowledge and that of the group, and w is the inertia weight. Uniformly distributed random numbers r_1 and r_2 are in the range of 0 to 1. Eberhart and Shi (2000) pointed out that the optimal strategy is to initially set w to 0.9 and reduce it linearly to 0.4. Van den Bergh (2002) indicated that preventing the PSO from exhibit divergence in cyclic behavior, the relation between the inertia weight and cognitive components should satisfy $((c_1+c_2)/2) - 1 < w$ in order to have guaranteed convergence. There are many researchers who have studied the relationship between the inertia weight and the cognitive components (Clerc and Kennedy, 2001; Van den Bergh, 2002; Zheng et al., 2003). The position of a particle i, x_i, is then updated by:

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{2.13}$$

Thus, the PSO updates the swarm using Equations 2.12 and 2.13. This process is repeated until the maximum iteration is reached or the velocity updates are close to zero. The quality of particles is measured by the fitness function. The general pseudo code of PSO is shown in Figure 2.23.

```
For each particle i ∈ 1,...s do
    Randomly initialize x_i
    Randomly initialize v_i (or just set v_i to zero)
    Set p_i = x_i
Endfor
Repeat
    For each particle i ∈ 1,...s do
        Evaluate the fitness of particle i, f(x_i)
        Update p_i using equation (2.10)
        Update p_g using equation (2.11)
        For each dimension j ∈ 1,...N_d do
            Apply velocity update by equation (2.12)
        Endloop
        Apply position update by equation (2.13)
    Endloop
Until some convergence criteria is satisfied
```

Figure 2.23 The general pseudo code of PSO

2.3.5.2 PSO vs. GA

Comparisons between GAs and PSOs have been performed by many researchers. Venter and Sobieszczanski-Sobieski (2002) indicated that the PSO is an inherently continuous algorithm while GAs are inherently discrete algorithms. The work done by Veeramachaneni et al. (2003) supports the previous statement because they found that PSOs performed better than GAs in some continuous optimization problems. Robinson et al. (2002) pointed out that PSOs performed better than GAs in solving difficult engineering design problem. In some early application of PSO, it was used to train Neural Networks. Results showed that PSOs are better than GAs and other training algorithms (Eberhart and Shi, 1998b; Van den Bergh and Engelbrecht, 2000). Kennedy and Spears (1998) also tested binary PSO and binary GA. They observed that the binary PSO is generally faster, more robust and more effective than the binary GA, especially when the dimension of a problem increases.

Eberhart and Shi (1998a) and Angeline (1998) both concluded that a hybrid of the standard GA and PSO models could lead to further advances. Veeramachaneni et al. (2003) proposed a hybrid approach combing PSO and GA to optimize the profiled corrugated horn antenna. The idea was the taking the population of one algorithm when it has no further fitness improvement and using it as initial population in another algorithm. Totally, there were two versions, namely GA-PSO and PSO-GA, proposed. The experimental results showed that the PSO-GA performed slightly better than PSO while both PSO and PSO-GA outperformed both GA and GA-PSO. Recently, another hybrid GA/PSO algorithm. The Breeding Swarm (BS), that combining the strengths of GA with those of PSO, was proposed by Settles and Soule (2005). The performance of BS is competitive with both the GA and PSO. The BS was able to locate an optimal significantly faster than either GA or PSO. The hybrid algorithm combines the standard velocity and position update rules of PSO with the ideas of selection, crossover and mutation from GA. The operations inherited from GA facilitate a search globally, but not exactly, while the interactions of PSO effectuate a search for an optimal.

According to Lovberg (2002), and Krink and Lovbjerg (2002), PSO performance is not dependent on the population size as long as the swarm size is not too small. Consequently, a PSO with a smaller swarm size performs comparably to a GA with larger populations. Lovberg (2002) also verified that PSO scales efficiently. From the perspective of implementation, the advantages of PSO are in its simplicity, shorter CPU run time and fewer parameters to adjust when compared with GAs (Wu et al. 2009b).

2.3.5.3 Drawbacks of PSO and Improvements to PSO

Similar to other stochastic search algorithms, PSO has two major drawbacks (Lovberg, 2002). The first one is that the swarm may prematurely converge. Angeline (1998) indicated that PSO searches for good solutions much faster than other evolutionary algorithms but the solution quality cannot be improved by increasing the iteration number, especially in solving multi-modal optimization problems. One of the reasons is that particles in *gbest* PSO converge to a single point which is on the line between the global best position and the personal best position. However, it is not guaranteed to be even a local optimum (Van den Bergh, 2002). The second drawback is that PSO performance is problem-dependent. This dependency results from the parameter settings of each stochastic algorithm. Thus, the same stochastic algorithm with different parameter settings results in variable performance. This problem is magnified in PSO where modifying the parameter settings may result in a proportionally large effect (Lovberg, 2002). For example increasing the value of inertia weight will give more exploration and less exploitation, and vice versa. Therefore, looking for the best value for the inertia weight is not an easy task and, more importantly, it may differ from one problem to another.

In order to solve the problem-dependent performance of PSO, self adaptation has been successfully applied to PSO by researchers such as Clerc (1999), Yasuda et al. (2003) and Zhang et al. (2003). Lovberg (2002) also stated that hybridization may alleviate the problem-dependent performance problem. Different types of hybridization have been proposed by Krink and Lovbjerg (2002), Veeramachaneni et al. (2003), Higashi and Iba (2003) and Settles and Soule (2005).

In order to overcome the shortcomings of the PSO in solving multimodal optimization problems by allowing the particles to search for multiple optima (either local or global) simultaneously, species-based PSO (SPSO) has been proposed (Li, 2004; Parrott et al., 2006; Brits et al., 2007). The idea of the species can be defined as a group of particles, sharing the same similarities, and is measured by a radius parameter r_s. The species seed (the centre of a species) is the fittest particle in the species and all the particles in the species are confined within a circle of radius r_s. Each particle represents a position which is initialized within the search space and is encoded in float format. The solution is represented by the rounded value of the particle location. The particles start searching for the optimum of a given objective function by moving through the search space at a random initial position. The manipulation of the swarm can be represented by Equations (2.13) and (2.14). Equation (2.14) is the modified version of Equation (2.12) where $lbest_i$ is the neighborhood best of particle i.

$$v_{i,j}(t+1) = wv_{i,j}(t) + c_1 r_{1,j}(t)(y_{i,j}(t) - x_{i,j}(t)) + c_2 r_{2,j}(t)(lbest_i - x_{i,j}(t)) \quad (2.14)$$

In this decade, researchers have continued to study this problem and have proposed improvements to PSO, for example, adding constriction factors to ensure convergence (Clerc, 1999); applying a new velocity update equation to avoid the velocity from depending only on a single term $wv_i(t)$ (Van den Bergh, 2002);

introducing a multi-start strategy to make PSO become a global search algorithm (Van de Bergh, 2002); adding random mutation to PSO to prevent premature convergence (Xie et al., 2002); extending PSO with Self Organized Criticality to increase the population diversity and to avoid premature convergence (Lovberg and Krink, 2002); and adding a new term in the velocity update equation which allows particles to move towards its neighbors to have a better personal best position (Veeramachaneni et al., 2003).

2.3.6 Ant Colony Optimization (ACO)

Ant Colony Optimization (ACO) is another population-based stochastic approach. ACO was inspired by the observation of real ant colonies. Ants communicate with each other indirectly by depositing pheromone. Thus, ants use pheromones to search for the shortest path to food. This indirect way of communication is called stigmergy (Dorigo et al., 1999). ACO was first introduced by Dorigo (1992). Similar to PSO, PSO has particles while ACO has artificial ants. The ants cooperate via stigmergy to search for quality solutions in the search space. ACO has been applied to various optimization problems such as the traveling salesman problem and in routing. ACO is outside the scope of this thesis, and more details about ACO can be found in Dorigo and Di Caro's (1999) work.

2.4 Overview of Chaotic Systems

Chaos is a field of study in applied mathematics with applications in various disciplines. Examples of Chaos are the earth's weather system, the behavior of water boiling on a stove, and migratory patterns of birds (Lorenz, 1995). Chaos is also a kind of characteristic of nonlinear systems. Chaos studies the behavior of dynamical systems that are highly sensitive to initial conditions. A well-known effect is referred to as the butterfly effect. Small differences in initial conditions (such as those due to rounding errors in numerical computation) result in highly diverging outcomes for chaotic systems. In most cases, rendering long-term prediction is impossible (Kellert, 1993). A commonly used definition says that for a dynamical system to be classified as chaotic, namely a chaotic system, it must have the following properties (Hasselblatt and Anatole, 2003):

- it must be sensitive to initial conditions
- it must be topologically mixing
- its periodic orbits must be dense

The meaning of sensitivity to initial conditions is that each point in a chaotic system is arbitrarily closely approximated by other points, with significantly different trajectories in the future. Topological mixing is found when the system evolves over time so that any given region or open set of its phase space will eventually overlap with any other given region. Density of periodic orbits means that every point in the space is arbitrarily and closely approached by periodic orbits (Elaydi, 1999).

In many cases, chaotic behavior is found only in a subset of the phase space of a system, but some chaotic systems, like the one-dimensional logistic map, are chaotic everywhere. The most interesting case is that chaotic behavior takes place on an attractor, then orbits led by a large set of initial conditions converge to this chaotic region (Elaydi, 1999). A chaotic motion can traverse every state in a certain region by its own regularity, and every state is visited only once.

2.4.1 Applying Chaos to Optimization

Due to this unique ergodicity and special ability to avoid being trapped in local optima, chaos searching has a much higher performance than other stochastic algorithms (Li and Jiang, 1998; Xu et al., 2000). It, however, usually needs a large number of iterations to reach the global optimum and is not effective in a large searching space. Mathematically, chaos is the randomness of a simple deterministic dynamic system. A chaotic map is a discrete-time dynamic system. The chaotic sequence is a spread-spectrum sequence which can be used as a random number sequence. Chaotic sequences have been adopted instead of random sequences, and very interesting and somewhat good results have been shown in many applications such as secure transmission (Wong et al., 2005; Suneel, 2006), nonlinear circuits (Arena et al., 2000), and image processing (Gao et al., 2006). The choice of chaotic sequences is justified theoretically by their unpredictability, such as by their spread-spectrum characteristics and ergodic properties.

Currently, there are two ways of applying chaos to optimization. The first one is through a chaotic neural network (Aihara et al., 1990) by incorporating chaotic dynamics into a neural network. Through the rich non-equilibrium dynamics with various concomitant attractors, chaotic neuron-dynamics can be used to continually search for the global optimum by following chaotic ergodic orbits (Liu et al., 2005). The other is by using the chaotic optimization algorithm (Li and Jiang, 1998; Lu et al., 2003) based on the chaotic evolution of variables. The simple philosophy of the chaotic optimization algorithm contains two main steps; firstly mapping from the chaotic space to the solution space, and then searching the optimal regions using chaotic dynamics instead of random searching. However, simple chaotic neural network and chaotic optimization algorithm often need a large number of iterations to reach the global optimum and are sensitive to the initial conditions (Liu et al., 2005).

Recently, several studies of PSO using chaotic methods have been made. Xie et al. (2002) introduced chaos into a system by randomly reinitializing the particle positions with a small constant probability, while Iqbal et al. (2005) improved it with a time-dependence on the probability of reinitialization. Liu et al. (2005) incorporated chaos into PSO with an adaptive inertia weight factor to construct a chaotic PSO. These research studies are based on a logistic map to generate the chaos variables. Song et al. (2007) proposed chaotic PSO-based neural network predictive control for nonlinear processes by using a tent map. They discovered the outstanding advantages and higher iterative speed of the tent map. However, the most effective way of embedding chaos into PSO is still an open research question.

2.5 Review of Existing Quality Control Approach

According to Besterfield (2004), quality is not the responsibility of any one particular person or functional area; it is everyone’s job. Independently, each mistake seems negligible; but collectively, mistakes can be a major barrier to achieving world-class quality standards (Hinckley, 2001). Kondo (1999) stated that quality is usually classified as a must-be quality (backward-looking quality) and as an attractive quality (forward-looking quality). Good handling in the must-be quality will be effective in reducing the costs of poor quality. Quality control charts are a common tool applied to control of a manufacturing process. Expert systems can automate the different phases in the use of quality control charts (Lall and Stanislao, 1992). This section provides a brief overview of different quality control chart techniques, and the ways of how expert systems can help in quality control.

2.5.1 Statistical Control Charts

In today's competitive and unpredictable environment, many companies work very hard to produce high quality goods to achieve customer satisfactory. Thus, monitoring is needed to check whether manufactured products or parts meet specifications or not. In general, there are two types of QCs: deviations from target specifications and excessive variability around target specifications (Hill and Lewicki, 2007). During the early stages of developing the production process, design of experiments is often used to model and optimize these two QCs (Wu et al., 2009c). After that, the methods required in quality control are on-line or in-process quality control procedures to monitor on-going production processes.

The general approach to on-line quality control is straightforward in that samples of a certain size from the ongoing production process are extracted. Then, line charts of the variability in those samples are plotted. Based on the charts, their closeness to target specifications is the main focus. If a trend is found or if samples falling outside pre-specified limits are observed, then the process is declared to be out of control. Consequently, the cause of the problem needs to be found. These types of charts are also referred to as Shewhart control charts (Shewhart, 1931).

The types of charts are often classified according to the type of QC that they are supposed to monitor: there are quality control charts for variables and control charts for attributes. The charts listed in Table 2.3 are commonly constructed for industrial applications (Hill and Lewicki, 2007).

Table 2.3 Common Type of Charts

Control Chart	Description
X-bar chart	The sample means are plotted in order to control the mean value of a variable (e.g., size of parts, strength of materials, etc.).
R chart	The sample ranges are plotted in order to control the variability of a variable
S chart	The sample standard deviations are plotted in order to control the variability of a variable
S2 chart	The sample variances are plotted in order to control the variability of a variable
C chart	This chart assumes that defects of the quality attribute are rare, and the control limits in this chart are computed based on the Poisson distribution (the number of defectives per batch, per day, per machine, etc. is plotted)..
U chart	Unlike the C chart, this chart does not require a constant number of units, and it can be used, for example, when the batches are of different sizes (the number of defectives divided by the number of units inspected is plotted).
Np chart	The number of defectives (per batch, per day, per machine) is plotted as in the C chart but the control limits in this chart are not based on the distribution of rare events, but rather on the binomial distribution. So, this chart should be used if the occurrence of defectives is not rare
P chart	The percent of defectives (per batch, per day, per machine, etc.) is plotted as in the U chart but the control limits in this chart are not based on the distribution of rare events but rather on the binomial distribution (of proportions). So, this chart should be used if the occurrence of defectives is not rare.
Short run chart	Observations of variables or attributes for multiple parts on the same chart are plotted. Short run control charts were developed for short production runs and to address the requirement that several dozen measurements of a process must be collected before control limits are calculated. Meeting this requirement is often difficult for operations that produce a limited number of a particular part during a production run. All of the aforementioned charts can be adapted for short production runs, and for multiple process streams.
Hotelling T^2 Chart	When there are multiple related quality characteristics, a simultaneous plot for all means based on Hotelling multivariate T^2 statistic is needed.
CUSUM Chart	Cumulative Sum (CUSUM) Chart is constructed by calculating and plotting a cumulative sum based on the data. The cumulative sum is not the cumulative sum of the values. Since the average is subtracted from each value, the cumulative sum also ends at zero, it is the cumulative sum of differences between the values and the average.
MA Chart	Moving Average (MA) Chart is a powerful measure of trend direction. The aforementioned CUSUM chart is capable to monitor trends and to detect small permanent shifts in the process average. MA chart uses some weighting scheme that summarizes the means of several successive samples and moves such a weighted mean across the samples.

In line charts, the horizontal axis represents the different samples. The vertical axis, for example the X-bar chart and the R chart, represents the means for the QC and the ranges respectively. The center line in the X-bar chart would represent the desired standard length, while the center line in the R chart would represent the acceptable range of samples based on the predefined specification. Thus, the R chart presents the variability of the process. Usually, a typical chart also includes two additional horizontal lines to represent the upper control limit (UCL) and the lower control limit (LCL). Since the sample points shown in the chart are connected by a line, the moment of the line can be observed. If it moves outside the

UCL or LCL or shows systematic patterns across consecutive samples, then a quality problem may potentially exist (Hill and Lewicki, 2007).

Sometimes, there is a choice between variable control charts and attribute control charts. Attribute charts sometimes bypass the need for expensive, precise devices and time-consuming measurement procedures because these charts allow for a quick summary of various aspects of the quality of a product. Thus, products can be quickly justified as acceptable or unacceptable based on various quality criteria. Also, these charts tend to be more easily understood by the management who are unfamiliar with quality control procedures. Evidence of quality problems may be presented more easily and persuasively (Hill and Lewicki, 2007). On the other hand, variable control charts are more sensitive than attribute control charts (Montgomery, 1985). Therefore, these charts may give alerts before any actual quality problems are found. Montgomery (1985) described the variable control charts as 'leading indicators of trouble' that will sound an alarm before the amount of scrap increases in the production process.

Process capability indices express (as a ratio) the proportion of parts or items produced by the current process that fall within user-specified limits. It is usually produced with variable control charts. For example, the so-called Cp index is computed as:

$$C_p = (\mathrm{USL} - \mathrm{LSL})/(6\sigma) \tag{2.15}$$

where σ is the estimated process standard deviation, and USL and LSL are the upper and lower limits.

If the distribution of the respective quality characteristic or variable (e.g., a dimension) is normal, and the process mean is equal to the design center, then this index can be interpreted as the proportion of the range of the standard normal curve that falls within the specification limits. If the process is not centered, an adjusted index C_{pk} is used instead. In most cases, the C_p index should be greater than 1, so that the specification limits would be larger than 6 times the σ limits. Thus, over 99% of all goods or parts produced could be expected to meet predefined specifications (Montgomery, 1991; Hill and Lewicki, 2007).

Detailed descriptions of these charts and extensive applications can be found in the literature (Grant and Leavenworth, 1980; Montgomery, 1991; Shirland, 1993; Yeung, 2007; Hill and Lewicki, 2007).

2.5.2 Quality Control Expert Systems

Traditionally, control charts are selected by quality engineers based on their experience, knowledge and standard procedural documents. When the appropriate charts have been selected, the control chart parameters need to be set. These parameters must be carefully evaluated based on statistical aspects (Montgomery, 1985). Although statistical standards and empirical solutions for determining control chart parameters can be found in the literature, these solutions usually cannot provide an optimal setting for the process (Kuo and Mital, 1993). Moreover, there are many quality inspection and quality control techniques, with wide ranges of applicability. Since there are many options available for those who want to devise an inspection process, various techniques have their own characteristics and utilization and provide useful results based on certain contexts. In order to choose the optimal technique for a particular situation, all the information related to quality inspection and quality control should be well organized. Otherwise, the quality evaluation process can not be compromised (Paladini, 2000). Because of these limitations, many researchers have studied and developed expert systems that would effectively address the use of inspection techniques and interpretation of control charts. Here are some examples: Alexander and Jagannathan (1986) indicated that the performance of different control charts can be varied in different ways, such as Type I and Type II errors, sensitively to change detection. Then, the authors developed an expert advisory system with a set of control chart selection rules to assist appropriate control chart selection. Gipe and Jasinski (1986) proposed an expert system based on a three-level evolutionary approach to help the quality teams to identify quality problems and determine assignable causes. Scott and Elgomayel (1987) developed a knowledge based diagnosis system for identifying and interpreting random or assignable patterns observed in X-bar or R charts. Dagli and Stacey (1988) designed and developed an IBM based expert system to assist quality teams in the selection and design of an optimal control chart such as X-bar chart, R chart, c chart and u chart, for a given application. Brillhart and Wible (1989) developed a real-time expert system for monitoring, characterizing and controlling a frontend photolithographic process. The system provided process capabilities indices which were aimed at the process mean, and variability reduction. Lee et al. (1989) developed an expert system for evaluating quality inspection. Brink and Mahalingam (1990) reported the development of an expert system which evaluates quality at the manufacturing level, detects defects and takes corrective action during the process. Frerichs (1990) proposed an expert system with an SPC package and real-time process diagnostic techniques. The system can advise the operator and take corrective action during a process change.

2.6 The Basic of Digital Watermarking

Watermarking techniques prevent counterfeit and unauthorized copies of the original physical objects. Digital watermarking is similar to physical watermarking except that the watermarking technique is used for the digital content instead of the physical object. In digital watermark techniques, a low-energy signal is imperceptibly embedded in the source signal. The low-energy signal is called a watermark and it represents some meta-data, such as copyright information on the source signal (Cox et al., 2008). The watermarked source signal is referred to as a cover signal because it covers the watermark. The cover signal is generally an image, audio, video or a text document in digital format.

The digital watermarking system basically consists of a watermark embedder and a watermark detector (Figure 2.24). The watermark embedder inserts a watermark into the source signal and the watermark detector detects the presence of the watermark. There is an entity called the watermark key which is used during the process of embedding and detecting watermarks. The key has a one-to-one correspondence with the watermark, hence a unique watermark key exists for every watermark. The key is private and is known by authorized parties only. It ensures that only authorized parties can detect and extract the watermark. Since noise and hostile security attacks can often be found in communication channels, the digital watermarking technique should be resilient to both noise and security attacks (Cox et al., 2008).

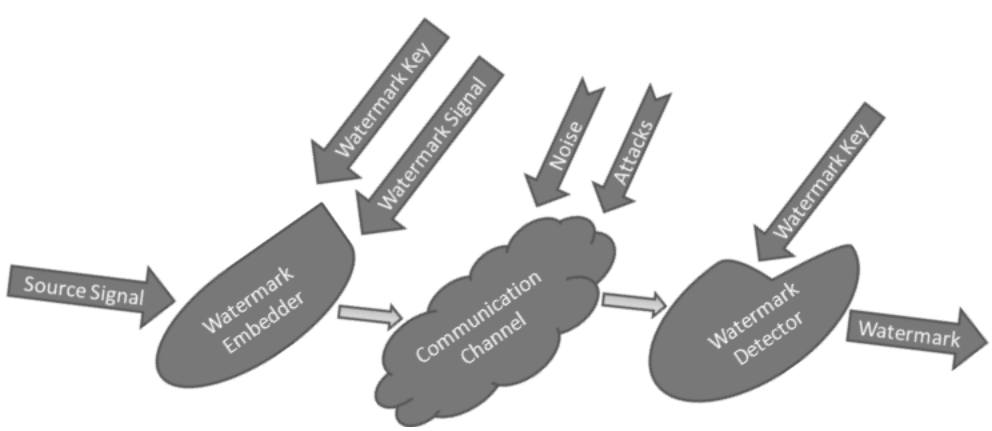


Figure 2.24 The general watermarking system

It is obvious that the watermark should be robust and imperceptible for copyright protection but the requirements of imperceptibility and robustness conflict with each other. Recently, two kinds of methods have emerged to strive for a balance between robustness and imperceptibility. The first one is to make use of Human Visual System (HVS) based algorithms. For example, Podilchuk and Zeng (1998) proposed a just-noticeable-difference based watermarking algorithm in the discrete cosine transform (DCT) domain and the discrete wavelet transform domain separately. A spatial method was devised by Qi et al. (2008), which embeds watermarks adaptively based on luminance masking, texture masking and edge masking. Jung and Ro (2003) proposed a watermarking embedding technique based on HVS. The second method applies EAs, such as GA and PSO, to watermarking. The basic idea of the evolutionary optimization based methods is to maximize a fitness function which takes the robustness and the imperceptibility into account simultaneously. Shieh et al. (2004) proposed a GA based robust watermarking algorithm for digital images in the DCT domain. Wu et al. (2011) proposed a PSO based flexible watermarking scheme for digital video.

The quantization index modulation (QIM) watermarking embedding algorithm was first proposed by Chen and Wornell (2001). The QIM system has considerable performance advantages over previously proposed spread-spectrum systems. The basic idea of QIM is to quantize the host data to different quantization intervals according to the watermark bit. Dither modulation is a most popular realization for QIM. In a simple example shown in Figure 2.25, a scalar uniform quantizer is set with step size Δ . X is a real axis equally divided by Δ. Each interval is mark by ‘1’ or ‘0’. $C_o[i, j, k]$ is the DCT coefficient in which a watermark bit is to be embedded. According to the watermark bit to be embedded, $C_o[i, j, k]$ is dithered to the center of its nearest interval '1' or '0'. $C_w[i,\ j,\ k]$ is the watermarked and dithered version of $C_o[i,\ j,\ k]$. If $C_w[i,\ j,\ k]$ lies in interval '1', the watermark bit is embedded as '1', otherwise the watermark bit '0' is embedded. Therefore, the maximum modification for a coefficient is Δ and it controls the performance of the algorithm, where a larger Δ means more robustness but more distortion is introduced.

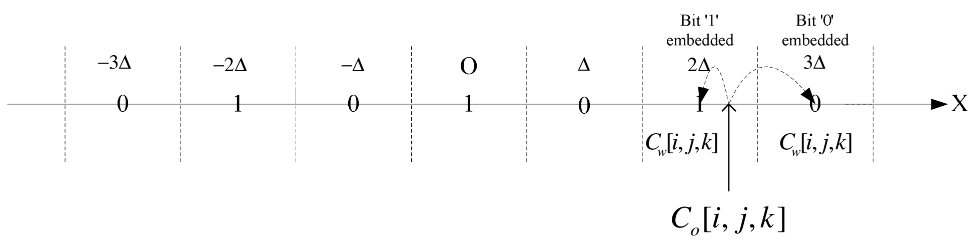


Figure 2.25 Illustration of dither modulation

2.7 Summary of the Literature Review

In terms of academic research, several fields related to the vision-based inspection and quality monitoring were reviewed. Most of the vision based systems perform dimensional quality and surface quality inspection but there are relatively less vision based systems performing structural and operational quality checks. The evolutionary optimization techniques used in vision based system were reviewed. In addition, GAs and PSO, which have been adopted in some machine vision systems were also introduced. The use of these techniques may offer potential as an alternative to solve various industrial vision tasks, which becomes more and more challenging. Furthermore, chaos theory has been introduced, and combining it with PSO can be a direction to develop an improved evolutionary optimization technique which can help in solving industrial vision tasks with higher speed, accuracy and robustness. The vision based system has attracted a widening interest in manufacturing applications. One point that should be noted is that there are few vision systems applied to the logistics areas. Quality control has got a number of effective techniques with a wide range of applicability. Since there are a lot of techniques available, especially in control charts selection, there are many choices for quality control teams to select the appropriate techniques in different cases. Nevertheless, this situation poses difficulties as to the correct selection of different techniques, because most the techniques have their own capabilities and yield results valid only within specified objectives. The need for a vision based expert system for quality control has appeared. The challenge is to develop a system which has more sophisticated techniques to solve challenging vision tasks and to assist quality control teams in analyzing the integrated inspection information easily and quickly so as to streamline overall quality control process.

In summary, there are a number of approaches and systems, which have been designed and developed to perform vision based inspection. First, there is a lack of literature on vision systems proposed in quality control for enhancing quality decision and inspection data sharing. Although different successful inspection methods proposed have significant influences on the machine vision algorithm development have been found in the literature, few attempts have been made to incorporate ideas of formulating the vision tasks as an optimization problem which can be solved by evolutionary optimization techniques, control charts and efficient data exchange to solve challenging vision tasks in manufacturing and logistics application. It is believed that incorporating the aforementioned elements to design an intelligent vision based inspection system will help improve the quality control processes.

As PSO is a relatively ‘young’ technique to be adopted in the development of vision-based systems, the chaos-based PSO algorithms are developed based on the concept of PSO and SPSO proposed by Kennedy and Eberhart (1995) and Li et al.

(2004) respectively. In order to evaluate the feasibility of the proposed algorithm in solving vision-based problems, two important simulation tests about template matching and circle detection are conducted. The reason of choosing these two simulation tests because extracting and using features such as edges, lines, circles, polygon and templates with higher efficiency and accuracy in order to tackle real world problems are important research areas. After the simulation tests, the proposed algorithms are embedded in MVES which supports evaluating quality inspection, identifying and interpreting random or assignable patterns in control charts. These functions are evaluated in the first case study which is about a PCB components inspection task. For the second case study, since the case company has applied Radio Frequency Identification (RFID) technology to track goods, the main problem faced by the case company is how to combine the RFID data and the video records. Thus, instead of applying MVES to solve the goods tracking problem, MVES has been proposed with the deployment of digital watermarking techniques in order to provide an innovative data enrichment solution and enhance the traceability of data records. In the second case study, the proposed solution can illustrate the flexibility of MVES in solving practical problems based on different industry requirements. It is a challenge to build such a system to cope with solving vision tasks, quality control and inspection or monitoring data handling, hence MVES is proposed to create a flexible and feasible approach, and is intended to be applied to Hi-Tech and the electronics manufacturing industries, and to logistics companies.

Chapter 3 Design of the Chaos-based PSO Algorithms

3.1 Introduction

This chapter focuses on the design and development of chaos-based PSO algorithms in order to provide efficient and effective tools for solving different, challenging vision-based problems, and with the improved efficiency and effectiveness in quality decisions making. In this research, one of the selected case studies concerns PCB component inspection. A typical surface mount device PCB assembly comprises three major processes which are, in order, screen printing solder paste on a PCB, component placement and then solder re-flow in a convection oven. There is an increased need for visual inspection in these three main tasks in PCB assembly, especially for component placement inspection. Since the size of components is continually getting smaller, component density is getting higher, and the speed of manufacturing is getting faster, the inspection task is becoming more and more challenging. Thus, one of the objectives in the research is to propose effective algorithms which can be used to efficiently solve the challenging visual inspection problem in the Hi-Tech products and electronics manufacturing fields. On the other hand, machine vision system has rarely been designed for solving vision-based problems in the logistics areas, as previously mentioned in the literature review. In the second case study, there is a need to have an effective algorithm to support the novel approach used in monitoring the transfers of goods and integrating two sources of data into one for efficient retrieval in the future.

The proposed algorithms are based on the concepts of PSO and SPSO proposed by Kennedy and Eberhart (1995) and Li et al. (2004) respectively. The special nonlinear characteristic and ergodicity of chaos are incorporated in the proposed algorithms in order to enrich the search ability. To test its performance, the proposed chaos-based PSO algorithms are compared with standard GA, PSO and other state-of-the-art algorithms. In the design of MVES, the proposed algorithms play an instrumental role in demonstrating how vision-based problems can be solved by evolutionary approaches. Apart from the design and development of the algorithms and the benchmark test results, two simulations are presented to show the feasibility of applying the proposed algorithms to solve vision-based problems. The two selected simulations are the multiple template matching and the circle detection problems. Since conventional methods, such as direct subtraction and normalized cross-correlation template searching are not efficient or effective for solving practical problems in PCB manufacturing, there is a need for an efficient and effective method. A similar situation can be found in the second simulation where the circle detection problem can be solved by Hough Transform-based methods but the computational load is increased dramatically in high dimensional problems. Thus, methods based on evolutionary approaches are desirable because they can attain a good solution quickly without the need for a large memory and high computation power. In the following sections, the proposed algorithms and simulation results are described.

3.2 Chaos-based PSO Algorithms

A PSO algorithm is an optimization technique which maintains a population of individuals, namely particles, where each particle is guided by social interaction in order to reach the most promising area of the search space (Kennedy and Eberhart, 1995). The particles start at a random initial position in a multi-dimensional search space and search for the minimum or maximum of a given objective function by flying through the search space. The movement of the *i*-th particle, x_i, depends on its velocity, v_i, and the location where the personal best position so far, $p_i = (p_{i1}, p_{i2}, \ldots p_{id})$, has already been found, or the neighborhood best position, $lbest_i = (lbest_{i1}, lbest_{i2}, \ldots lbest_{id})$. When a particle's neighborhood is defined as the whole swarm, the PSO is called the global version, otherwise it is a local one. After simplification of Equations 2.12 and 2.13, Equations 3.1 and 3.2 are shown below. Equation 3.1 updates the velocity of each particle, whereas Equation 3.2 updates each particle's position in the search space, c_1, c_2 are cognitive coefficients and φ_1, φ_2 are two uniform random numbers from zero to one.

$$v_{id} = w \cdot v_{id} + c_1 \cdot \varphi_1 \cdot (p_{id} - x_{id}) + c_2 \cdot \varphi_2 \cdot (lbest_i - x_{id}) \tag{3.1}$$

$$x_{id} = x_{id} + v_{id} \tag{3.2}$$

3.2.1 Chaotic PSO Algorithm (CPSO)

In 2005, Liu et al. proposed to enrich the searching behavior in a local search and to avoid being trapped into a local optimum, chaos dynamics is incorporated in the local search technique. The well-known logistic map (May, 1976) is used, defined as

$$x_{n+1} = \mu \cdot x_n\,(1 - x_n),\ \ 0 \le x_0 \le 1 \tag{3.3}$$

where μ is the control parameter and x is a variable and n = 0,1,…

Equation 3.3 is deterministic but when μ = 4 and x_0 is not equal to {0, 0.25, 0.5, 0.75, 1}, it exhibits chaotic dynamics. A small difference in the initial value of the chaotic variable would result in a big difference in its long time behavior. The chaotic local search has been defined by:

$$cx_i^{(k+1)} = 4cx_i^{(k)}\,(1 - cx_i^{(k)}),\ \ i = 1, 2, \ldots, n \tag{3.4}$$

The track of the chaos variable can travel ergodically throughout the whole search space. Figure 3.1 shows the chaotic dynamics when $cx_i^0 = 0.01$, $k = 300$.

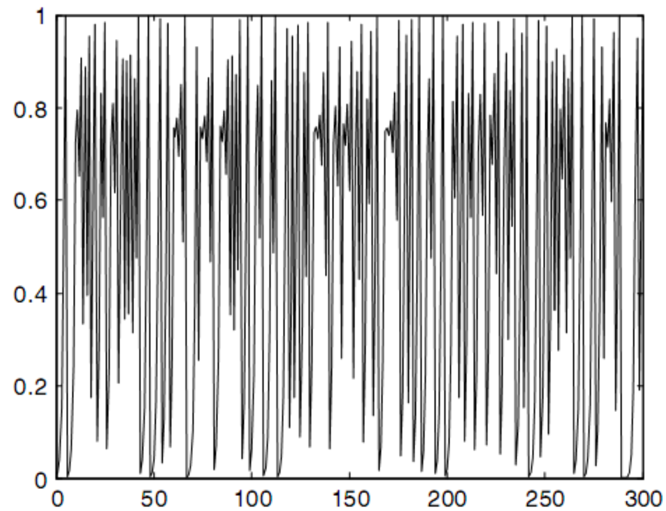


Figure 3.1. Dynamics of logistics map (Liu et al., 2005)

In the proposed algorithm, chaotic dynamics is also incorporated into the PSO, so that the search behavior can be enhanced. Comparing the tent map with the logistic map, the tent map shows outstanding advantages and higher iterative speed (Zhang et al., 2008), which is more suitable for the uniform distribution function in the interval [0, 1]. In this study, chaos variables are generated using the tent map for initialization. The tent map is defined by the following formula:

$$z_{n+1} = \mu\left(1-2\left|z_n - 0.5\right|\right), 0 \le z_0 \le 1，n = 0,1,2,\cdots \tag{3.5}$$

where $\mu \in [0,1]$ is a bifurcation parameter.

When $\mu = 1$, the tent map exhibits entirely chaotic dynamics and ergodicity in the interval [0, 1]. Figure 3.2 shows the distribution of two chaos sequences after 1500 iterations with the initial point ($x_{10} = 0.231$, $x_{20} = 0.356$) in a 2D space. Each point can be described by (x_{1j}, x_{2j}), j = 1, 2, …, 1500.

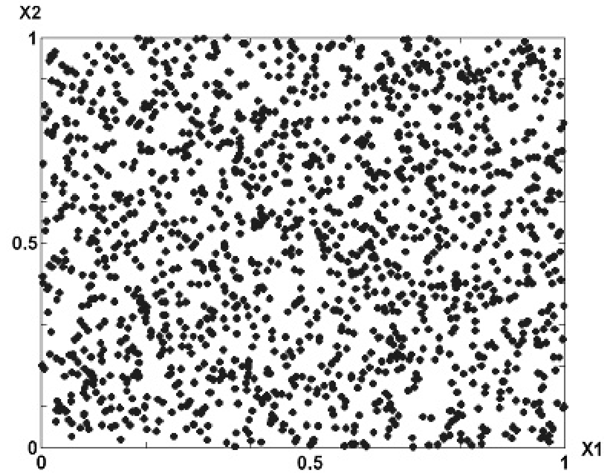


Figure 3.2 Distribution of chaos variable generated by tent map

Tent-map chaotic dynamics is used to initialize the particle swarm in PSO. Firstly, the tent map, $\mu = 1$, is used to generate the chaos variables and update Equation 3.5, and gives:

$$z_j^{(i+1)} = \mu\left(1 - 2\left|z_j^{(i)} - 0.5\right|\right) \quad j = 1, 2, \cdots, P \tag{3.6}$$

where z_j denotes the j-th chaos variable, and i denotes the chaos iteration number.

Setting $i = 0$ and P chaos variables are generated by Equation 3.6, letting $i = 1, 2, \ldots, m$ to generate the initial swarm. Then, the above chaos variable $z_j^{(i)}$ will be mapped into the search range of the decision variable:

$$x_{ij} = x_{\min,j} + z_j^{(i)}\left(x_{\max,j} - x_{\min,j}\right),\ j = 1, 2, \cdots, P \tag{3.7}$$

The chaotic-initialized particle swarm, X_i, can be obtained by:

$$X_i = (x_{i1}, x_{i2}, \cdots, x_{iP}) \quad i = 1, 2, \cdots, m \tag{3.8}$$

3.2.2 Chaotic Species-based PSO Algorithm (CSPSO)

In recent years, the PSO has shown to be an effective technique for solving complex and difficult optimization problems in different areas. However, the original PSO fails to locate multi optima since the principle of PSO uses the "best known positions" to guide the whole swarm to converge to a single optimum in the search space. Li (2004) proposed a species based PSO which allows the particles to search for multiple optima (either local or global) simultaneously to overcome the deficiency of the original PSO in multimodal optimization problems. The species used in this research can be defined as a group of particles that share common attributes based on some similarity metric. This similarity metric could be based on the Euclidean distance for genotypes using a real coded representation, or the Hamming distance for genotypes with a binary representation. The smaller the Euclidean (or the Hamming) distance between two individuals, the more similar they are. The definition of species also depends on another parameter, a radius parameter r_s, which denotes the radius measured in Euclidean distance from the center of a species to its boundary. The centre of a species, called species seed is the fittest particle in the species and all the particles in the species are confined within a circle of radius r_s. The particles start searching for the optimum of a given objective function by moving through the search space at a random initial position. The manipulation of the swarm can be represented by Equations 3.1 and 3.2.

Once the species seeds have been identified from the population, one can then allocate each seed to be the *lbest* to all the particles in the same species at each iteration step. The SPSO accommodating the algorithm for determining the species seeds described above can be summarized in the following steps:

- Step 1: Generate an initial population with randomly generated particles.
- Step 2: Evaluate all particle individuals in the population.
- Step 3: Sort all particles in descending order of their fitness values (i.e., from the best fit to least fit ones).
- Step 4: Determine the species seeds for the current population.

- Step 5: Assign each species seed identified as the *lbest* to all individuals identified in the same species
- Step 6: Adjust the particle positions according to steps 3 and 4.
- Step 7: Go back to step 2, unless the termination condition is met.

In order to enrich the search behavior, chaotic dynamics is also incorporated into the SPSO. As aforementioned, the tent map gives the uniform distribution function in the interval [0, 1]. The tent map shows outstanding advantages and higher iterative speed than the logistic map, so the tent map is used to generate chaos variables. Tent map chaotic dynamics have been used to initialize the swarm in SPSO. The detailed process of chaos initialization is the same as the process mentioned in CPSO. When $\mu=1$, the tent map exhibits entirely chaotic dynamics and ergodicity in the interval [0, 1]. Chaos variables are obtained by Equation 3.6 when $i = 0$. After that, let $i=1, 2,\ldots, m$ in turn and generate the initial swarm. Then, the above chaos variable $z_j^{(i)}, i = 1, 2, \cdots, m$, will be mapped into the search range of the decision variable by Equations 3.7 and 3.8. The pseudo code of the CSPSO is shown in Figure 3.3.

```
Begin
Initialize all the particles by chaos initialization
For each particle
Evaluate its fitness value
End for
While (not satisfying the stopping criterion or not reaching the maximum of the
iteration steps)
Do
Finding species seeds
For each particle
Update each particle according to equations 3.1 and 3.2
Evaluate its fitness value
End for
Iteration = iteration + 1
End
End
```

Figure 3.3 The pseudo code of the CSPSO

3.3 Simulation Results of Benchmark Tests

In order to test the effectiveness of the proposed algorithms, CPSO and CSPSO, a number of benchmark tests are conducted. Since CSPSO has the advantage over CPSO in solving multimodal problems, they are tested separately.

3.3.1 CPSO vs. State-of-the-art Algorithms in Solving Single Modal Problems

Three numeric optimization problems were chosen to compare the performance of the proposed CPSO with other algorithms such as BS (Settles and Soule, 2005), PSO and GA. These functions are standard benchmark test functions and are all minimization problems. Details are shown in Table 3.1.

Table 3.1 Benchmark Test Functions

Function Name	Equation	Range
Ellipsoidal function	$F1(x)=\sum_{i=1}^{n} ix_i^2$	[-100,100]
Rastrigin function	$F2(x)=\sum_{i=1}^{n}(x_i^2-10\cos(2\pi x_i)+10)$	[-5.12,5.12]
Ackley function	$F3(x)=20+e-20e^{-0.2\sqrt{\frac{1}{n}\sum_{i=1}^{n}x_i^2}}-e^{\frac{1}{n}\sum_{i=1}^{n}\cos(2\pi x_i)}$	[-32.768,32.768]

Each function was run for 50 trials. Tests using 10 dimensions were allowed to run for 500 generations. Tests using 20 dimensions were allowed to run for 1000 generations. Finally tests using 30 dimensions were allowed to run for 1500 generations. The smaller the mean value obtained, the better the performance is.

The GA's parameters in the setup were: population size 120, crossover ratio 0.75, mutation ratio 0.15, and maximum generation 1500. The standard PSO's parameters in the setup were: swarm size 120, inertia weight ω linearly decreasing from 0.9 to 0.2, and cognitive coefficients $c_1 = c_2 = 2$. For BS, tournament selection was used, with a tournament size of 3, to select individuals as parents. Gaussian mutation was used, with mean 0.0 and variance that reduced linearly for each generation from 1.0 to 0.1, the other parameters being the same as the PSO's. For CPSO, the parameters in the setup were the same as the PSO's. The test results are shown in Table 3.2, where it can obviously be seen that the proposed CPSO outperformed GA, PSO and BS in most runs in all dimension, through which the feasibility and effectiveness of the chaotic approach has been fully illustrated.

Table 3.2 Benchmark Test Results

Function	Dims	Gens	GA (Mean and Std. err.)	PSO (Mean and Std. err.)	BS (Mean and Std. err.)	CPSO (Mean and Std. err.)
F1	10	500	5.25E-03 (1.32E-03)	4.59E-28 1.081E-28	2.55E-28 (4.34E-28)	3.6177e-30 (4.9341e-30)
	20	1000	2.06E-03 (1.02E-03)	2.93E-28 (5.30E-28)	3.00E-26 (7.43E-26)	1.1257e-28 (1.6703e-28)
	30	1500	0.0735 (0.0231)	2.495E-26 (3.087E-26)	2.09E-23 (4.16E-23)	1.0156e-26 (1.7476e-25)
F2	10	500	2.329 (1.561)	5.632 (1.205)	3.2834 (1.2625)	0.7296 (1.4288)
	20	1000	22.2022 (7.4051)	12.013 (5.32)	9.2531 (2.2270)	1.5919 (2.8791)
	30	1500	47.607 (12.302)	20.412 (8.69)	16.616 (2.920)	5.6381 (7.1070)
F3	10	500	0.1820 (0.057)	4.175E-14 (1.628E-14)	1.235E-14 (2.186E-14)	2.6645e-015 (0)
	20	1000	0.2261 (0.045)	8.48E-15 (2.13E-15)	4.237E-14 (2.621E-14)	6.5331e-15 (1.0656e-14)
	30	1500	0.2502 (0.063)	2.087E-12 (0.674E-12)	1.026E-12 (1.283E-12)	1.0151e-12 (3.0470e-11)

3.3.2 CSPSO vs. State-of-the-art Algorithms in Solving Multi-modal Problems

Multimodal optimization is used to locate all the optima within the searching space, rather than one and only one optimum, and has been extensively studied by researchers. Many algorithms based on a large variety of different techniques have been proposed in the literature. It is believed that the vision-based inspection can benefit from the algorithm's ability in solving multimodal problems. After showing the feasibility and effectiveness of incorporating chaos dynamics in PSO, more attention is paid in testing the CSPSO which is introduced to solve multimodal problems.

In order to test the ability of the proposed algorithm to locate the optima and the accuracy of the optima found, the peak ratio and the average minimum distance to the real optima have been used as the performance metrics (Wong et al., 2009).

- A peak is considered 'found' when an individual exists within a 0.5 Euclidean distance to the peak in the last population. The peak ratio can be expressed in the following formula:

$$PeakRatio = \frac{Number\ of\ peaks\ found}{Total\ number\ of\ peaks} \tag{3.9}$$

- The average minimum distance to the real optima is determined using the following formula:

$$D = \frac{\sum_{i=1}^{n} \min_{indiv \in pop} d(peak, indiv)}{n} \tag{3.10}$$

where n is the number of peaks, *indiv* denotes an individual and *pop* denotes a population of individuals.

In the following, all algorithms were run up to a maximum of 50000 fitness function evaluations. The above performance metrics are obtained by taking the average and standard deviation of 100 runs. Three typical benchmark functions (Table 3.3) are introduced here to test the performance of the proposed CSPSO. For fair comparison, the notion of species is also incorporated into the BS algorithm, namely Species based BS (SBS), so that it has an enhanced ability to solve multi-modal problems. The parameters in the setup, for both SBS and CSPSO, are: swarm size 100, inertia weight ω is linearly decreased from 0.9 to 0.2, and cognitive coefficients $c_1 = c_2 = 2$. For SBS, its tournament size is 3, with the mutation ratio reducing linearly in each generation from 1.0 to 0.1. As a comparison, two additional state-of-the-art algorithms are also included. The test results of the Species

Conserving Genetic Algorithm (SCGA) and the Evolutionary Algorithm with Species-specific Explosion (EASE) (Wong et al., 2009) can be found in Table 3.4.

Table 3.3 Multi-modal Benchmark Test Functions

Function Name	Equation	Range
Deb's 1st function (F1)	$F1(x) = \sin^6(5\pi x)$	$0 \le x \le 1$
Himmelblan function (F2)	$F2(x_1, x_2) = (x_1^2 + x_2 - 11)^2 + (x_1 + x_2^2 - 7)^2$	$-6 \le x_1$ $x_2 \le 6$
Six-hump Camel Back function (F3)	$F3(x_1, x_2) = (4 - 2.1x_1^2 + \frac{x_1^4}{3})x_1^2 + x_1x_2 + (-4 + 4x_2^2)x_2^2$	$-1.9 \le x_1 \le 1.9$ $-1.1 \le x_2 \le 1.1$

Table 3.4 shows the experimental results, from which one can observe that, in most cases, promising results can be obtained by the proposed CSPSO when compared with other methods. Although EASE achieved the best value in the standard deviation of D in F1, a minority of relatively poor results deteriorates the mean of D. So, CSPSO outperforms other algorithms in terms of minimum, mean, median and standard deviation of D. In F3, all algorithms can identify all the peaks in all runs but CSPSO outperforms SCGA and SBS algorithms in terms of minimum, mean, median and standard deviation of D and outperforms EASE algorithm in terms of mean and standard deviation of D. In F2, EASE and CSPSO can identify all the peaks in all runs. While CSPSO outperforms EASE and other two algorithms in terms of minimum, mean, median and standard deviation of D in F2, in general, CSPSO is relatively more stable and effective for locating multiple optima in these benchmark tests.

Table 3.4 Benchmark Test Results for the Comparison of CSPSO, SBS, EASE and SCGA

Benchmark	Measurement	SCGA	EASE	SBS	CSPSO
F1	Mean of D	1.32E-03	2.14E-10	3.26E-10	1.858E-10
	StDev of D	9.87E-04	**6.71E-11**	1.68E-10	1.617E-10
	Min of D	1.20E-04	1.22E-10	5.57E-11	2.5E-12
	Median of D	1.03E-03	2.01E-10	3.48E-10	1.27E-10
	Mean of Peak Ratio	1.000	1.000	1.000	1.000
	StDev of Peak Ratio	0.000	0.000	0.000	0.000
F2	Mean of D	2.48E-01	1.12E-06	3.66E-06	3.554E-07
	StDev of D	1.27E-01	3.07E-06	1.01E-05	2.39E-07
	Min of D	5.72E-02	5.44E-07	1.10E-08	7.40E-09
	Median of D	2.11E-01	5.44E-07	5.16E-07	2.578E-07
	Mean of Peak Ratio	0.825	1.000	0.458	1.000
	StDev of Peak Ratio	0.187	0.000	0.224	0.000
F3	Mean of D	1.10E-02	2.11E-06	4.035E-07	4.03E-07
	StDev of D	1.49E-02	9.36E-06	1.20E-09	9.0565E-10
	Min of D	1.28E-04	3.91E-07	4.018E-07	4.017E-07
	Median of D	5.65E-03	4.02E-07	4.039E-07	4.034E-07
	Mean of Peak Ratio	1.0000	1.000	1.000	1.000
	StDev of Peak Ratio	0.0000	0.000	0.000	0.000

3.4 Simulation Results of Solving Vision-based Problems by CSPSO Approaches

Although the effectiveness of the proposed algorithms has been shown in previous benchmark test results, it does not indicate that they are useful in solving vision-based problems. Thus, in this section, the proposed CSPSO is applied to solve two vision-based problems which are formulated as multi-modal optimization problems. Since template matching and circle detection are the key problems in machine vision and have been widely used in different industrial vision applications

(Davies, 2005), the template matching problem and the circle detection problem are selected for simulation tests. In these tests, the evolutionary approaches proposed are based on the NCC-based template matching method and three-edge-point circle representation method (Ayala-Ramirez et al., 2006), which can reduce the search space.

3.4.1 Template Matching Problems

Using cross-correlation for template matching is motivated by the idea of distance measure, which is the squared Euclidean distance.

$$d_{I,t}^2(u,v) = \sum_{x,y}[I(x,y) - t(x-u, y-v)]^2 \tag{3.11}$$

where I is the source image and the total sum is over x, y under the template, t, located at u, v.

In the expansion of d^2:

$$d_{I,t}^2(u,v) = \sum_{x,y}[I^2(x,y) - 2I(x,y)t(x-u, y-v) + t^2(x-u, y-v)] \tag{3.12}$$

The term $\sum(t^2(x-u, y-v)$ is constant, and if the term $\sum I^2(x,y)$ is approximately constant, then the cross-correlation term can be expressed by:

$$C(u,v) = \sum_{x,y}[I(x,y)t(x-u, y-v)] \tag{3.13}$$

where C is a similarity measure between the window of the source image and the sub-image (template).

However, several shortcomings can be found when applying Equation 3.13 for template matching. For example, the equation is variant to changes in image amplitude, the image energy $\sum I^2(x,y)$ cannot vary with position, and the range of C is dependent on the size of the template. Thus, normalizing the image and feature vectors to a unit length overcomes the disadvantages:

$$NCC(x,y)=\frac{\sum_{x,y}[I(x,y)-\bar{I}_{u,v}][t(x-u,y-v)-\bar{t}]}{\{\sum_{x,y}[I(x,y)-\bar{I}_{u,v}]^2\sum_{x,y}t[x-u,y-v)-\bar{t}]^2\}^{1/2}} \tag{3.14}$$

The term $\bar{t}$ is the mean grey-level intensity of the template and $\bar{I}_{u,v}$ is the mean grey-level intensity of the captured image in the region coincident with the template. NCC is the Normalized Cross Correlation. In Multiple Template Matching (MTM), at each point (x, y), the NCC_{M} value refers to the maximum of a set of NCC values which are calculated using corresponding templates. For example, at (x, y), NCC_1 is computed using template 1 and NCC_2, obtained using template 2 respectively. k is the number of templates. The NCC_{M} value at a particular location can be found by:

$$NCC_M(x,y)=\max\{NCC_1(x,y),NCC_2(x,y),\ldots\ldots,NCC_k(x,y)\} \tag{3.15}$$

where,

$$NCC_k(x,y)=\frac{\sum_{x,y}[I(x,y)-\bar{I}_{u,v}][t(x-u,y-v)-\bar{t}]}{\{\sum_{x,y}[I(x,y)-\bar{I}_{u,v}]^2\sum_{x,y}t[x-u,y-v)-\bar{t}]^2\}^{1/2}}$$

Although one can directly apply the multiple template matching technique for multiple objects detection, it is not efficient. Since the obtaining of one NCC value at each pixel needs repeated calculation of a set of *NCC* values to select the maximum, it is exceedingly time consuming. In the multiple template matching problem, the computational complexity, O, for an given image of size $W \times L$ and a total of b objects is $(W \bullet L)^b$. For a test image (Figure 3.4), the complexity is around $(712 \bullet 612)^4$, which is approximately $3.6\text{x}10^{22}$. In order to get an optimal solution with a shorter computational time, an efficient search method which can track multi-peaks (multiple NCC_{M}) becomes essential.

When the NCC based matching method is adopted, objects can be matched with one template. If the multiple-template matching method is used, multiple objects can be matched with the corresponding template. Both require a NCC value space of a captured image, for example, the test image (Figure 3.4), with 762 pixels x

612 pixels, has been tested in previous research studies (Crispin and Rankov, 2007; Wang et al., 2008). Each *NCC* value is calculated at each pixel by the multiple-template matching method. It is a fact that there are six global optima and many local optima. Each global optimum identifies a successful matching of the template and the preferred object. The problems of locating the component and locating multiple resistors can be solved when all the global optimum are detected. Applying the CSPSO, each particle, initialized within the 2D search space and encoded in float format, represents one position. The solution is in terms of a rounded value of the particle location, which shows the corresponding pixel coordinates. The fitness function is Equation 3.15. The flow chart of the CSPSO-based MTM method is shown in Figure 3.5.

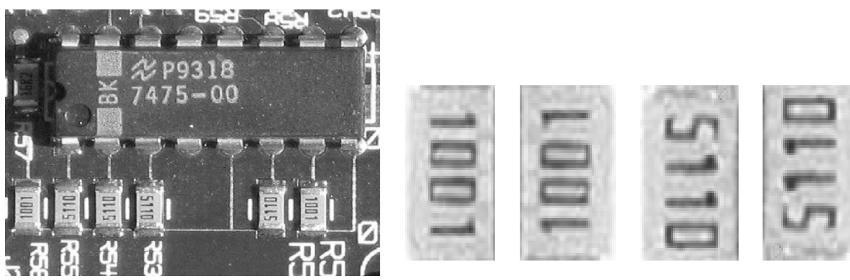


Figure 3.4 The test image of the PCB and the resistor templates

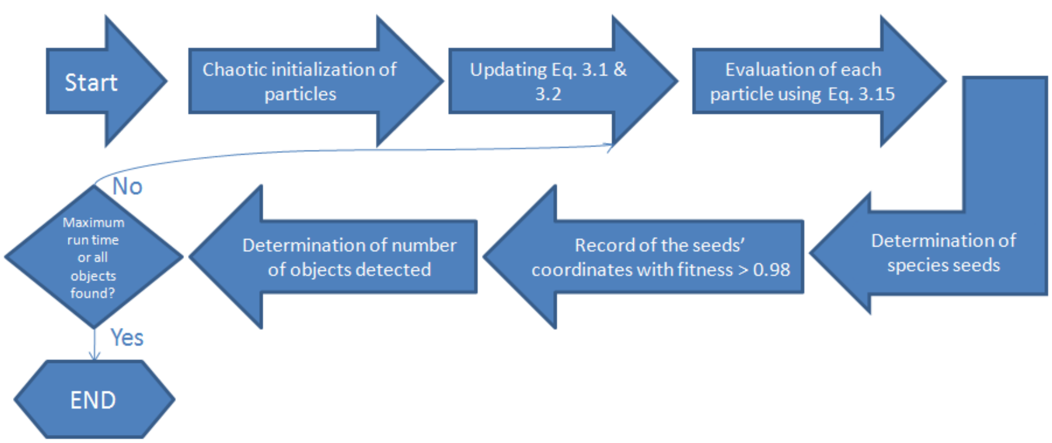


Figure 3.5 The flow chart of the CSPSO-based multiple-template matching

In order to reveal the improved performance of the proposed CSPSO-based approach, a simulation test has been conducted. In the trial test, the template matching process based on different approaches are undertaken based on the captured image of the main board (Figure 3.4). Then, the parameter setting and results are analyzed. The algorithm is coded in MATLAB and executed on a desktop computer with an Intel(R) 1.66GHz CPU and a 1G RAM. The acceleration strategies of re-initialization and the NCC value table (Wu et al., 2009b) are adopted in the test. In this simulation, the re-initialization interval is 500 which not only guarantees the current species can be fully converged but also unleashes them to search for more potential optima.

Satisfactory results in the trial tests were obtained and are shown in Table 3.5. The CSPSO based MTM algorithm parameters in the setup are: the inertia weight ω=0.5, cognitive coefficients $c_1 = c_2 = 2$ and the particle velocity is initialized between [−4, 4]; the whole process becomes more stable when r_s changes from 30 to 80. The minimum mean time for locating all resistors and the corresponding setup are bolded in Table 3.5. For comparison, the SPSO based MTM method (without incorporating chaos dynamics), the GA based MTM and other conventional methods for checking multiple components are included. The parameters setup of the SPSO based MTM algorithm is the same as the CSPSO based MTM method. The minimum mean time for locating all resistors and corresponding setup are bolded in Table 3.6. The GA parameters are fixed as: crossover ratio 0.6, mutation ratio 0.05 and 0.1, maximum generation 5000. The computation result is shown in Table 3.7.

Table 3.5 Trial Test Results of Six Resistors Detection based on CSPSO-based Approach

Particle number	r_s	**Min. Run Time** (s)	**Max. Run Time** (s)	**Successful Rate*** (%)	**Time** (Mean and Std. err.)	**Checked pixels** (Mean and std. err)
50	30	13.141	72.656	100	36.16±20.79	33050±17338
	50	6.109	50.125	100	29.66±13.35	32954±9523
	80	**9.016**	**39.579**	**100**	**15.71±4.35**	**25632±6826**
80	30	11.297	72.844	100	26.26±6.64	31963±7390
	50	8.516	61.250	100	26.11±16.35	32560±15602
	80	8.797	39.203	100	25.45±11.99	28652±10255
100	30	15.328	53.062	100	30.69±12.99	34185±9656
	50	11.000	49.766	100	24.59±12.20	30154±13652
	80	9.844	24.047	100	16.94±4.80	27435±8265

* Successful rate means how many times that all resistors can be successfully detected out of 100 runs

Table 3.6 Trial Test Results of Six Resistors Detection based on SPSO-based Approach

Particle number	r_s	**Min. Run Time** (s)	**Max. Run Time** (s)	**Successful Rate*** (%)	**Time** (Mean and Std. err.)	**Checked pixels** (Mean and std. err)
50	30	11.281	83.657	100	40.31±26.06	41050±18685
	50	10.313	75.437	100	33.78±22.28	34456±19745
	80	13.625	53.360	100	32.39±14.48	33568±12865
80	30	12.625	77.187	100	37.98±21.89	40830±20471
	50	9.297	44.234	100	26.36±11.93	32750±9658
	80	**15.343**	**43.953**	**100**	**25.96±7.52**	**29737±7550**
100	30	14.187	83.297	100	35.55±27.78	35206±13214
	50	16.312	81.844	100	32.24±16.32	36857±10052
	80	21.579	67.469	100	43.45±25.86	46858±22566

* Successful rate means how many times that all resistors can be successfully detected out of 100 runs

Table 3.7 Trial Test Results of Six Resistors Detection based on GA-based Approach

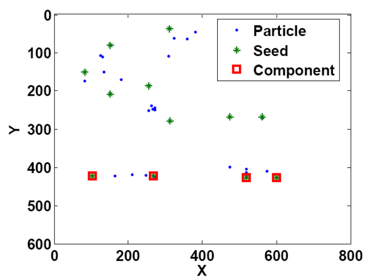
POPSIZE	**Recombine ratio**	**Mutation ratio**	**Average number of resistors found**	**Time** (Mean and Std. err.)	**Checked pixels** (Mean and std. err)
120	0.6	0.05	2.60	56.40±6.79	56373±7148
120	0.6	0.1	3.00	68.30±20.86	78501±21974
160	0.6	0.05	2.90	77.33±1.68	96457±5698
160	0.6	0.1	3.20	95.45±45.17	126755±57362

In order to get an optimal parameter set for a fair test, statistical analysis has been performed with different parameters settings in the trial tests. From the results, it is obvious that the GA based MTM method could not locate all the components in every run and a smaller mutation ratio brought about a worse performance. Although the increased mutation ratio helps to increase the successful detection rate, the checked pixels and computation time increase dramatically as well. Choosing the best parameter settings for all the approaches; a particle number of 50 and r_s of 80 for CSPSO based MTM; a particle number of 80 and r_s of 80 for SPSO based MTM; a particle number of 120, crossover ratio 0.6, mutation ratio 0.1 for GA, a 40-second-constrainted test is assigned to each approach for detecting the components. The average computation results of 100 independent runs are shown in Table 3.8.

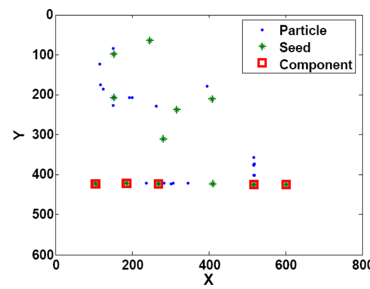
Table 3.8 Experimental Results of How Many Resistors Can be Detected Successfully within 40s for Different Approaches

Algorithm	Min. detected resistors	Max. detected resistors	Detected resistors (Mean of 100 runs and Std. err.)
GA	0	5	1.72±1.32
SPSO	2	6	5.11±1.37
CSPSO	6	6	6.00±0.00

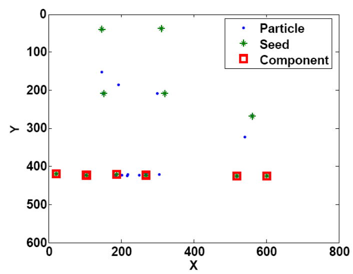
According to the comparisons, it can be seen clearly that it is much faster and more effective to locate all the six resistors by the CSPSO based MTM than by other approaches. The best average processing duration for detecting all six resistors by CSPSO based MTM is 15.71s. In addition, only the proposed CSPSO based MTM method has a 100% success rate in locating all components within 40s. The corresponding parameter setting, a particle number of 50 and r_s of 80, is said to be the optimal setting. Figure 3.6 shows the prior run searching process, with the corresponding parameter settings, at different stages.



The searching process of CSPSO at the3100th iteration (4 resistors detected)



The searching process of CSPSO at the 5000th iteration (5 resistors detected)



The searching process of CSPSO at the 6500th iteration (6 resistors detected)

Figure 3.6 The snap-shots of the CSPSO-based MTM process

The average search time against the number of objects found by both the SPSO and the proposed CSPSO methods are shown in Figure 3.7. Each method performs a search for all objects in 100 independent runs. The results are also collected to perform the M^{c}Nemar test. The Z value obtained is 2.85. That means there is a 99% confidence level that the CSPSO-based approach and the SPSO-based approach do not give equivalent results and there is a 99.5% confidence level that the CSPSO-based approach is better than the SPSO-based approach. According to Figure 3.7, the results also show that the proposed CSPSO method produces better mean time values as the object number increases and, definitely, is a better approach for multi-object matching.

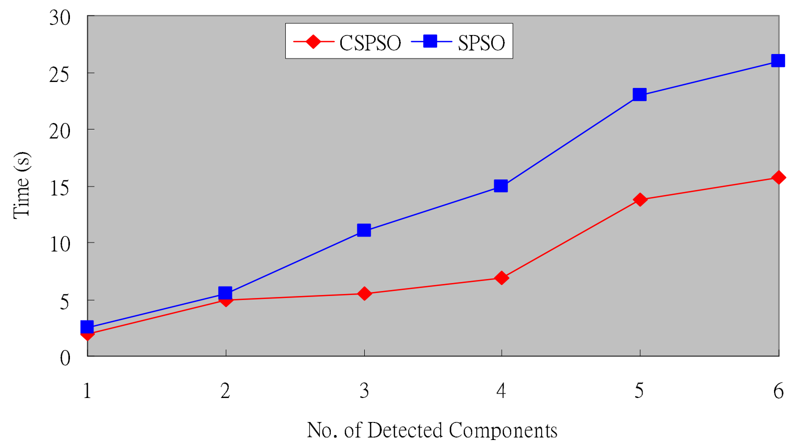


Figure 3.7 Mean search time against the number of objects being detected for both SPSO- and CSPSO- based approaches

According to the comparisons shown in Table 3.9, the CSPSO-based approach successfully locates all resistors and a satisfactory result is obtained effectively (25632 out of 466344 pixels are visited only) and has advantages over the other evolutionary and conventional approaches. So, the chaotic dynamic introduced to the SPSO algorithm can boost up the performance of the algorithm. Although both CSPSO and SPSO methods have 100% success rate in locating all components, the CSPSO-based approach has a better efficiency than the SPSO-based approach in terms of averaged, maximum and minimum run time. In the forty-second-constrained test, the SPSO-based approach could not detect all six components in all runs, unlike the CSPSO-based approach (Table 3.8). The CSPSO-based approach guarantees detecting all components within the time constraints which can be considered as the processing time upper limits for the inspection. The MTM process has been improved over 20% using the CSPSO-based approach, in terms of averaged run time.

Table 3.9 Simulation Results Obtained by Different Approaches without Iteration Limit

Method	**Run time** (s)
Maximum likelihood unconstrained exhaustive search	2840.32
NCC MTM exhaustive search	568.92
GA (NCC) MTM based approach	260.94[a]
SPSO (NNC) MTM based approach	25.96 [b]
CSPSO (NNC) MTM based approach	20.26[c]

[a]Mean of 100 runs with std. err. of +/- 20.51 sec.; [b]Mean of 100 runs with std. err. of +/- 7.52 sec.; [c]Mean of 100 runs with std. err. of +/- 6.64 sec.

3.4.2 Circle Detection Problems

In this section, the circle detection problem is formulated as an optimization and is solved by the CSPSO-based approach. The idea is based on the three-edge-point circle representation method (Ayala-Ramirez et al., 2006), which can reduce the search space by eliminating unfeasible circle locations. Each circle *C* uses three edge points as particles in the algorithm. In this representation, edge points are stored as an index to their relative position in the edge array *V* of the image. This will encode an individual as the circle that passes through the three points v_i, v_j and v_k . Each circle *C* is represented by the three parameters x_o, y_o and *r*. With (x_o, y_o) being the (x, y) coordinates of the center of the circle and *r* being its radius. The equation of the circle passing through the three edge points can be computed as:

$$(x-x_0)^2+(y-y_0)^2=r^2 \tag{3.16}$$

with:

$$x_0=\frac{\begin{vmatrix} x_j^2+y_j^2-(x_i^2+y_i^2) & 2(y_j-y_i) \\ x_k^2+y_k^2-(x_i^2+y_i^2) & 2(y_k-y_i) \end{vmatrix}}{4((x_j-x_i)(y_k-y_i)-(x_k-x_i)(y_j-y_i))} \tag{3.17}$$

$$y_0=\frac{\begin{vmatrix} 2(x_j-x_i) & x_j^2+y_j^2-(x_i^2+y_i^2) \\ 2(x_k-x_i) & x_k^2+y_k^2-(x_i^2+y_i^2) \end{vmatrix}}{4((x_j-x_i)(y_k-y_i)-(x_k-x_i)(y_j-y_i))} \tag{3.18}$$

The shape parameters (for the circle, $[x_0, y_0, r]$) can then be represented as a transformation T of the edge vector indices i, j, k.

$$[x_{0,} y_0, r] = T(i, j, k) \tag{3.19}$$

where T being the transformation composed of the previous computations for x_0, y_0 and r.

In order to compute the fitness value of a candidate circle C, the test set for the points is $S = \{s_1, s_2, ..., s_{Ns}\}$, with Ns the number of test points where the existence of an edge border will be sought. The test point set S is generated by the uniform sampling of the shape boundary. In this case, Ns test points are generated around the circumference of the candidate circle. Each point s_i is a 2D-point where its coordinates (x_i, y_i) are computed as follows:

$$\begin{cases} x_i = x_0 + r \cdot \cos \dfrac{2\pi i}{N_s} \\ y_i = y_0 + r \cdot \sin \dfrac{2\pi i}{N_s} \end{cases} \tag{3.20}$$

Fitness function $F(C)$ accumulates the number of expected edge points (i.e. the points in the set S) that actually are present in the edge image. That is:

$$F(C) = (\sum_{i=0}^{N_s-1} E(x_i, y_i)) / N_s \tag{3.21}$$

with $E(x_\mathrm{i}, y_\mathrm{i})$ being the evaluation of edge features in the image coordinates and Ns being the number of pixels in the perimeter of the circle corresponding to the circle C under test. As the perimeter is a function of the radius, this serves as a normalization function with respect to the radius. That is, $F(C)$ measures the completeness of the candidate circle and the objective is then to maximize $F(C)$ because a larger value implies a better circularity. Here, for clarity, a measurement of the completeness of the candidate circle is defined as the percentage of the points on the candidate circle that are actually present in the edge image and this measurement is indicated by Cr:

$$Cr = N_t / N_s \tag{3.22}$$

where N_t is the number of points on the candidate circle that are actually present in the edge image.

Cr is a positive number ranging from [0.0:1.0], and a larger value of Cr implies a more complete circle.

To test the proposed CSPSO-based method, three test images have been generated, with randomly located circles (Figures 3.8, 3.9 and 3.10). Results of interest are the center of the circle position and its diameter. The algorithms have been run 100 times for each test. The species radius r_s is defined as the distance between each two circles' centers. For the three test images, the exact number of circles and the distances between their centers are known, and the species radius r_s was normally set to a value smaller than the distance between the two closest circles.

For comparison, SBS and SPSO were used as solvers at the same time. All the trial tests were coded in MATLAB and executed on an Intel (R) 3.0 GHz CPU with a 2G RAM desktop computer. The parameters in the setup, for the CSPSO and SPSO were: swarm size 120, inertia weight ω decreasing linearly from 0.9 to 0.2, cognitive coefficients $c_1 = c_2 = 2$, and maximum generation 5000. For the SBS, the parameters were: tournament size 3, mutation ratio reducing linearly each generation from 1.0 to 0.1, and the other parameter settings were the same as for CSPSO and SPSO.

The simulation was conducted by running CSPSO, SPSO and SBS 100 times. The minimal time, the mean time, the average value of Cr and the success rate are shown in Tables 3.10 and 3.11 and 3.12. From Tables 3.10 and 3.11, it can be seen that all the three methods, CSPSO, SPSO and SBS can achieve 100% success rate in locating all the circles, but the proposed CSPSO-based method takes less time than the other two methods, and gives higher *Cr* values in most cases. From Table 3.12, the advantages of the proposed CSPSO-based method are more obvious. The average run time of the proposed CSPSO-based method is less than half of the others. More importantly, it can take less time and have a 100% success rate, while the SPSO-based method can only achieve 70% and the SBS-based method can only achieve 75%. By using the CSPSO-based method, the average error for localization is 0.16 pixels and maximum error (the worst case) is 0.75.

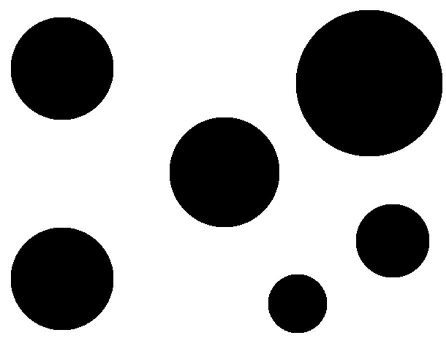


Figure 3.8 Six circles

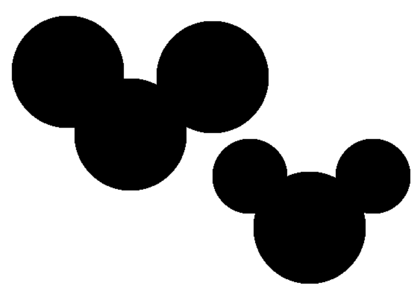


Figure 3.9 Merged circles

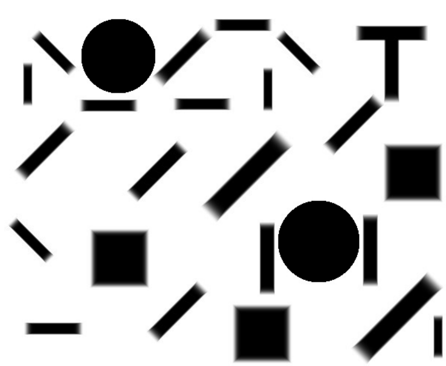


Figure 3.10 Two circles with other shapes

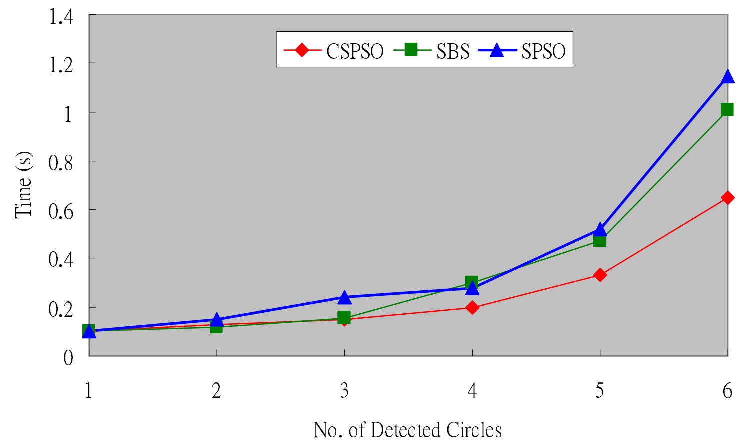


Figure 3.11 Mean search time against the number of circles being detected in the test image of six circles

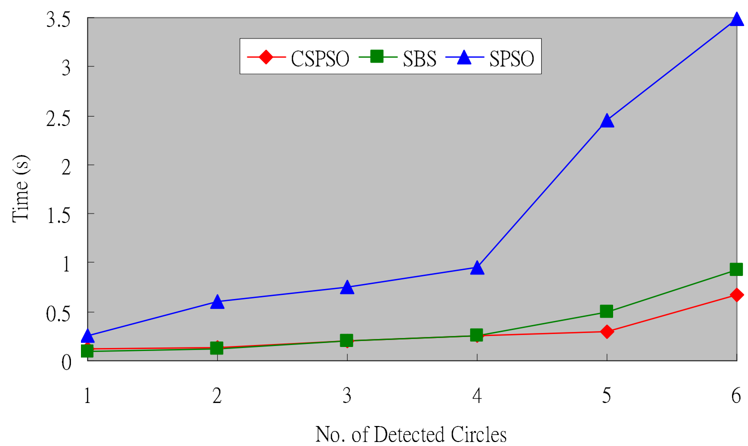


Figure 3.12 Mean search time against the number of circles being detected in the test image of merged circles

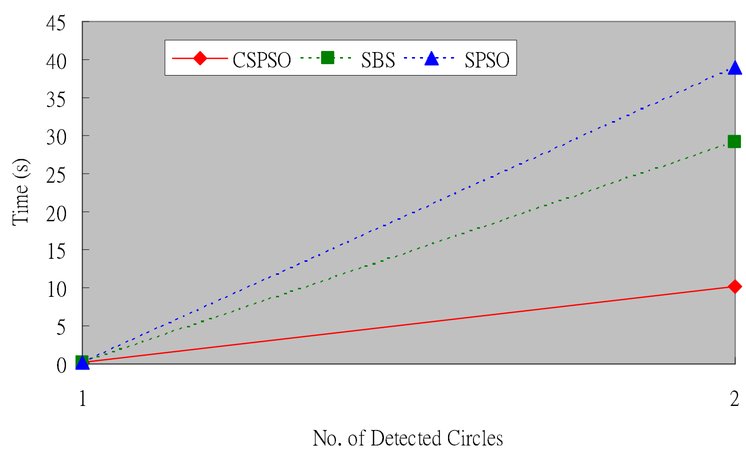


Figure 3.13 Mean search time against the number of circles being detected in the test image of two circles with other shapes

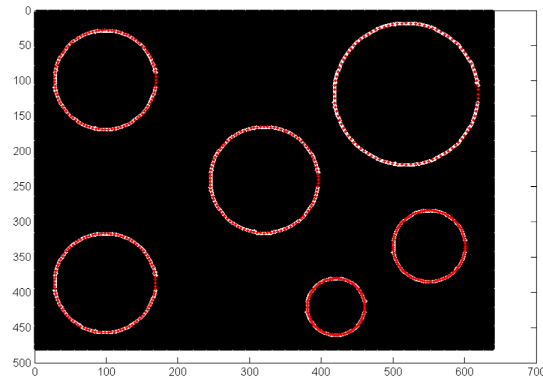


Figure 3.14 Detection result of the test image of six circles

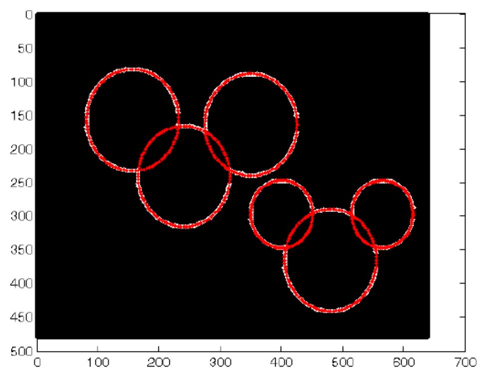


Figure 3.15 Detection result of test image of the merged circles

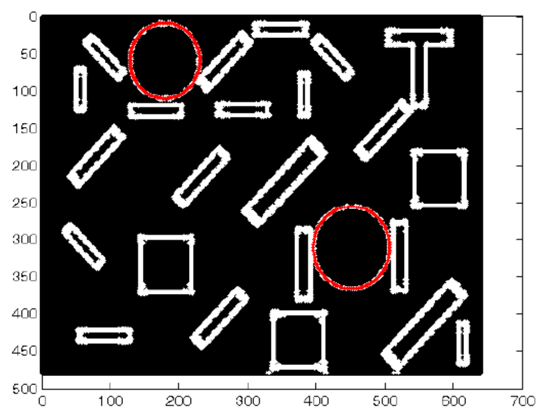


Figure 3.16 Detection result of the test image of two circles with other shapes

Table 3.10 Simulation Results on the Test Image of Six Circles out of 100 runs

Methods	SPSO	SBS	CSPSO
Time (mean & std. err)	1.15s±0.549	1.01s±0.376	**0.65s±0.131**
Time (minimum)	0.4630s	0.452s	**0.254s**
Cr (mean & std. err)	0.774±0.060	0.833±0.040	**0.830±0.047**
Success rate* (%)	100	100	**100**

Success rate means how many times that all of the six circles can be successfully located during 100 runs

Table 3.11 Simulation Results on the Test Image of Merged Circles out of 100 runs

Methods	**SPSO**	**SBS**	**CSPSO**
Time (mean & std. err)	3.48s±1.800	0.93s±0.377	**0.67s±0.269**
Time (minimum)	1.139s	0.515s	**0.313s**
C*r* (mean & std. err)	0.665±0.056	0.680±0.037	**0.521±0.022**
Success rate* (%)	100	100	**100**

Success rate means how many times that all of the six circles can be successfully located during 100 runs

Table 3.12 Simulation Results on the Test Image of Two Circles with Many Other Shapes out of 100 runs

Methods	SPSO	SBS	CSPSO
Time (mean & std. err)	38.92s±19.688	29.15s±20.055	**10.24s±5.462**
Time (minimum)	10.121s	4.202s	**1.254s**
C*r* (mean & std. err)	0.764±0.111	0.802±0.117	**0.742±0.096**
Success rate* (%)	70	75	**100**

Success rate means how many times that all of the six circles can be successfully located during 100 runs

Figures 3.11 - 3.13 also show the plots of the average search time against the number of circles being detected in all the test images. Results for the SPSO-, the SBS- and the proposed CSPSO methods are shown. As aforementioned, all the three methods can detect all the circles successfully in the first two test images but the proposed CSPSO-based approach is more efficient than the others. For the last test image, only the CSPSO-based approach has a 100% success rate. Neither the SPSO-based approach nor the SBS-based approach can detect both circles in all runs, which are represented by dashed lines in Figure 3.13. The simulation results of the last test image are also collected to perform the M^{c}Nemar test. When comparing the CSPSO method and the SBS method, the Z value obtained is 5.29. That means there is a 99% confidence level that the CSPSO method and the SBS method do not give equivalent results, and there is a 99.5% confidence level that the CSPSO method is better than the SBS method. When comparing the CSPSO method and the SPSO method, the Z value obtained is 4.80. This means there is a 99% confidence level that the CSPSO method and the SPSO method do not give equivalent results and there is a 99.5% confidence level that the CSPSO method is better than the SPSO method. Based on the simulation results and the M^{c}Nemar test result, it can be seen clearly that the proposed CSPSO-based approach is much faster and more effective than both the SPSO- and the SBS-based approaches. Thus, CSPSO can be considered as a possible means for solving multi-circle detection problems, and the detection results for the CSPSO-based method can be seen in Figures 3.14 - 3.16.

All the above test images have simple backgrounds, and that makes it easier for detecting circles, as there are less edge points and at the same time, all the circles under test have very narrow edges. However, in reality, the circumstances will be more complicated. The ‘circles’ may have wide edges and their shapes sometimes will not be that perfect. In order to detect circles correctly, an improved method, namely ‘tolerant radius’, is proposed based on the original formulation. This method requires that when the fitness value of an individual reaches a threshold (marked as Th_1), it is supposed that an imperfect circle is detected, and it gives the individual another two more chances to re-calculate its fitness value. This time, the method of ‘tolerant radius’ is used (Figure 3.17), which allows the corresponding radius of the candidate circle (the black circumference in Figure 3.17) to have a tolerance of 5 pixels, either by moving inside (decreasing the radius to the blue dashed line circumference in Figure 3.17) or by moving outside (increasing the radius to the red dashed line circumference in Figure 3.17). If a real edge point falls in the area of the circular zones, either formed by the original candidate circle with the radius r and the circle with the radius r-5 pixels (the green zone in Figure 3.17) or is formed by the ones with a radius of r and r+5 pixels (the pink zone in Figure 3.17), the corresponding point of the candidate circle is considered as effective. Hence, there will be another two fitness values re-calculated, and both will be no less than the original one. Then, another threshold (marked as Th_2) is set for evaluation. If either of the two re-calculated fitness values can reach Th_2, then the candidate circle under consideration is accepted.

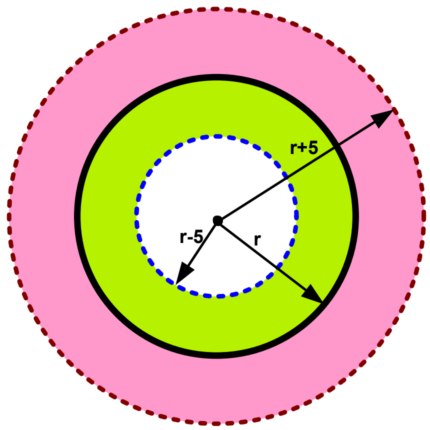


Figure 3.17 Schematic of the candidate circle with 'tolerant radius'

In addition to the searching power of the proposed CSPSO, the help of the 'tolerant radius' method proposed above can help in solving more practical circle detection problems based on the CSPSO-based approach. For simulation tests, one hand drawn sketch and one natural photo are used. The original images are shown in Figures 3.18 - 3.19 on the left, and the corresponding detection results are shown on the right. For each test image, the CSPSO with the 'tolerant radius' method was run 100 times, and the corresponding running times are shown in Table 3.13.

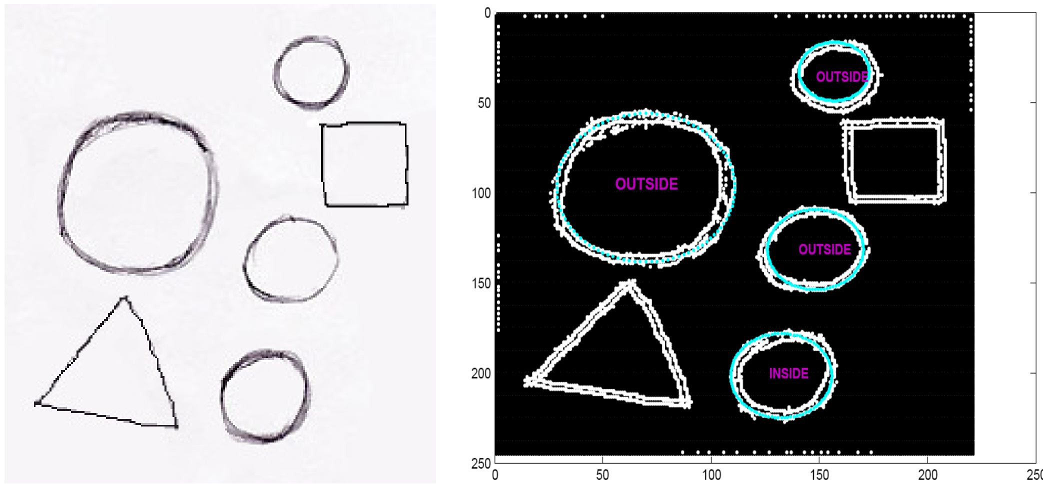


Fig. 3.18 Four-circle hand drawn sketch (on the left) and its detection result (on the right)

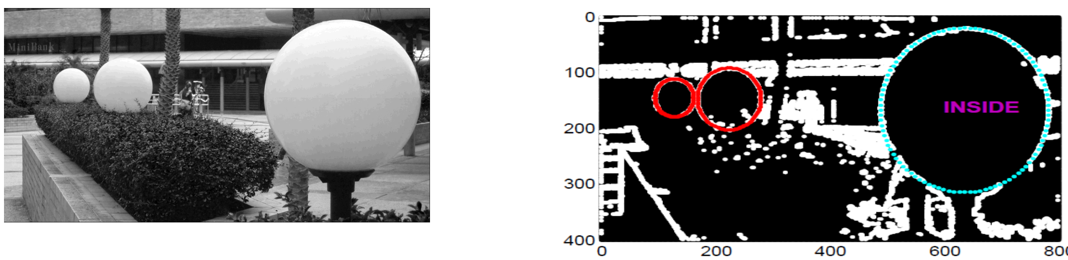


Figure 3.19 Natural image (on the left) and its detection result (on the right)

The test results of the hand drawn sketch that is shown in Figure 3.18 can fully illustrate the effectiveness of the proposed ‘tolerant radius’ method. The blue circles in the detection results are the accepted candidate circles that have a ‘tolerant radius’, and the corresponding moving directions of the radii (either INSIDE or OUTSIDE) are also shown. In the simulation tests using the natural image, the ability of the proposed method in solving circle detection problems in the image with complicated backgrounds can clearly be revealed. The effectiveness of the proposed method is fully illustrated by detecting a big imperfect circle (the one highlighted by light-blue in Figure 3.19). In addition, the satisfactory success rate and running time of the proposed CSPSO method are shown in Table 3.13. All these results fully prove the feasibility and effectiveness of the evolutionary circle detection method.

Table 3.13 Simulation Results on the Natural Images out of 100 runs

	Four-circle hand drawn sketch	**Natural image**
Time (mean & std. err)	2.48s±2.114	36.55s±7.285
Time (minimum)	0.392s	23.004s
Success rate* (%)	100	100

*Successful rate means how many times that all of the circles in the test images can be successfully located during 100 runs

3.5 Conclusive Remarks

In this section, CPSO and CSPSO are proposed by incorporating the chaos dynamic into the PSO algorithm. After a number of benchmark tests (numeric optimization problems) are chosen to compare the relative performances of the proposed algorithms and other algorithms, the proposed chaos-based PSO algorithms show promising performance in the tests. Two vision-based problems are then selected to test the feasibility of using the proposed algorithm as a solver. According to the problem nature, both the selected problems can be formulated as a multi-modal optimization problem. Therefore, CSPSO is used as the solver. For the first test, the CSPSO-based MTM method is proposed for solving a multiple PCB components detection problem. The proposed method has successfully formulated a multiple components detection problem into a multimodal optimization problem. Simulation results show that the proposed algorithm successfully located all the components in all runs, and in a shorter time than using other approaches. In the second test, the CSPSO-based circle detection method is also proposed for solving multiple circle detection problems. In order to correctly detect circles in practical circumstances, the ‘tolerant radius’ concept has been proposed to enhance the circle detection process. After proving its effectiveness through simulations on three artificial images, the CSPSO-based approach has been combined with the proposed ‘tolerant radius’ idea and successfully applied to solve multiple circle detection problems in the hand drawn sketch and in the natural image. All the results indicate that the chaos-based PSO algorithm can greatly reduce the computational time in solving the optimization problems.

In the two simulations, CSPSO has been proven to be an effective means in solving template matching and circle detection problems. The proposed method in template matching is useful in many areas such as the quality inspection of PCBs. On the other hand, the proposed circle detection method can address the drawbacks of the conventional circle detection method, such as the need for prior information on the radius range when using the Hough Transform-based method. The performance of the proposed algorithms has been demonstrated in benchmark tests and in simulation tests for template matching and circle detection, indicating that this approach could be deployed in other formulated vision-based and imaging problems for achieving the same success.

Chapter 4 Design of the Machine Vision Expert System (MVES)

4.1 Introduction

This chapter focuses on the design of MVES. It provides a systematic approach on how to construct a vision system for solving vision-based problems and enabling related information to be well managed and used in quality decisions making based on the infrastructural design of MVES and the chaos-based PSO algorithms.

The proposed system is equipped with an ‘efficiency information generating’ feature. This feature is used to enhance the utilization of the information, and to improve the quality decision effectiveness so that a better finished quality of products or WIP can be achieved. It also provides outlier signal detection functionality which makes it possible to provide automatic monitoring for the purpose of assisting the industrial practitioners. In the design of MVES infrastructure, chaos-based PSO algorithms play a core role in solving vision-based problems, which are formulated as optimization problems, using stochastic search power to find potential solutions. Apart from the chaos-based PSO algorithms, protocols for information handling are also incorporated for information generation, collection and integration, so that the information can be well indexed, stored and retrieved within the organization. In the following sections, the infrastructure of MVES is described in detail.

4.2 Infrastructural Design of MVES

MVES is designed to solve vision-based problems. MVES proposed is based on a typical machine vision system which tackles visual inspection tasks. In addition to solving inspection problems, one of the core functionalities of MVES is to manage all useful information systematically, so that useful information can be utilized and retrieved easily. For example, it can interpret outlier signals based on the control charts plotted to support quality decisions making. The infrastructural design of the system in this research is divided into four main modules: (i) Data Capture Module (DCM), (ii) Processing and Analysis Module (PAM), (iii) Information Storage Module (ISM) and (iv) Monitoring Module (MM). For illustration, the system infrastructural design suggested for solving visual inspection problems, is shown in Figure 4.1.

DCM is used for image acquisition and image pre-processing, which guarantees the captured image data are of the predefined quality based on requirement of the intended processes. PAM is used to solve vision-based problems. By taking the industrial automated inspection as an example, PAM performs quality inspection and/or geometric measurement, based on image features at various levels of complexity extracted from the formatted image data transferred from DCM. This module is very important because it ensures that a faulty item does not reach the downstream of stations or even customers. The vision-based problem handled by PAM has to be formulated as an optimization problem beforehand and solved by evolutionary approaches. The proposed chaos-based PSO algorithms support the functionality of PAM. ISM keeps track of the useful information transferred from PAM. ISM can be considered as an integrator which has a database to store all indexed and processed information. Thus, it enables easy retrieval and transfer of the information. MM aids in diagnosis of the state of a process by plotting control charts and interpreting outlier signals.

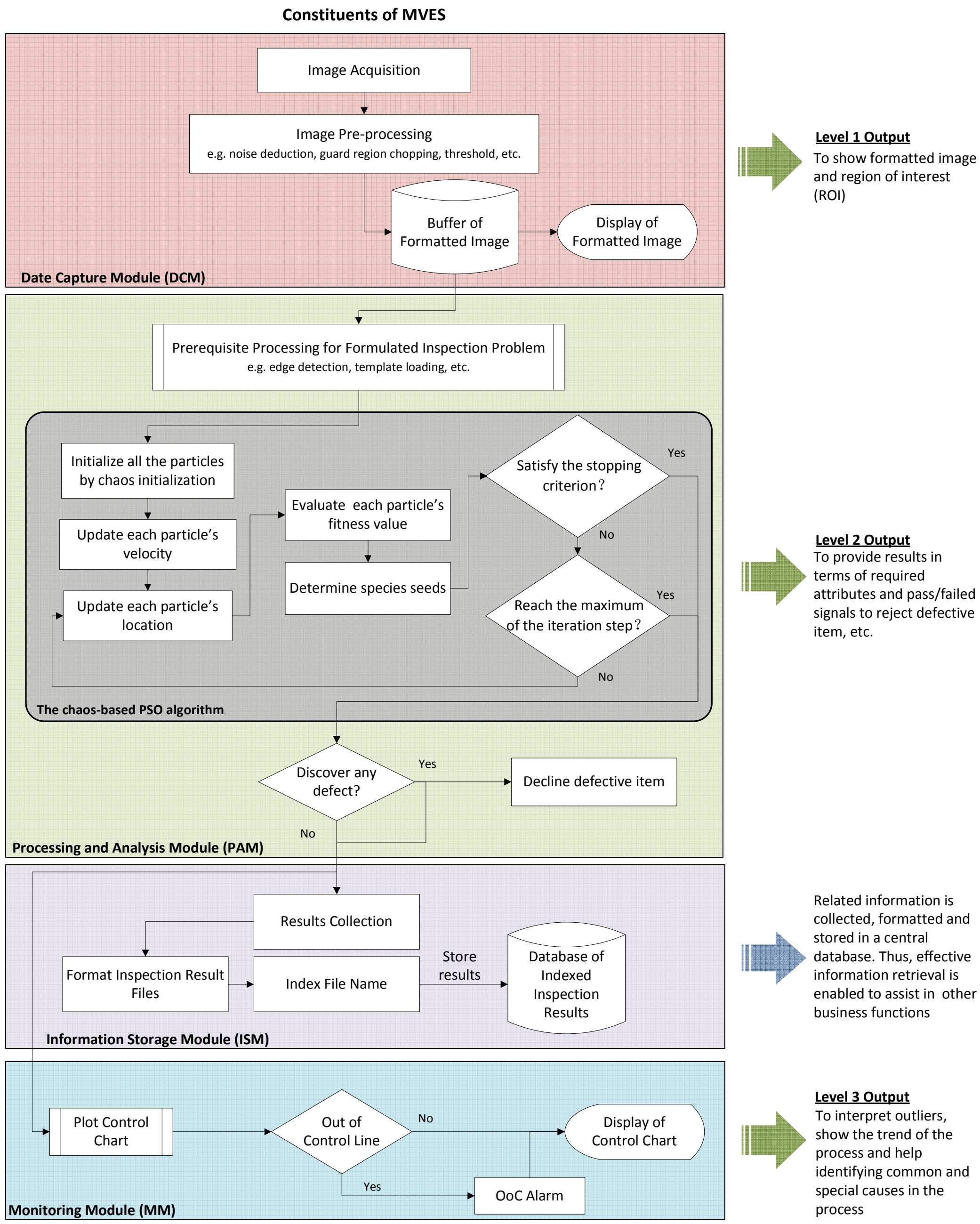


Figure 4.1 Constituents of Machine Vision Expert System (MVES)

4.2.1 Data Capture Module (DCM)

DCM can be considered as a data capture point of the characteristics of an object or a scene. It is an essential module of MVES and is responsible for capturing image data and pre-processing. Thus, the original image data captured is converted to the formatted image data for intended processes afterwards. The design requirement for a successful vision system heavily depends on the tasks to be accomplished, the environment, the speed, etc. Here, the system must be capable of performing quality verification such as differentiating between acceptable and faulty goods or parts, and identifying unacceptable variations and defects. Once the detailed requirements for tackling the problem are specified, an appropriate design can be created. For a normal inspection, the first consideration is to understand what kind of objects the system is going to capture in the inspection station. Thus, several issues, which are mainly related to hardware selection for image capturing, need to be considered in DCM:

1. Illumination – is a proper light source selected in order to acquire an image with an enhanced imaging contrast for inspection? Is the light intensity adequate in the inspection environment?
2. Field-of-view – how big is the object?
3. Resolution – how small is the smallest detail required?
4. Fixture – is a proper fixture used to hold the position?
5. Time – how much time is available to capture an image?
6. Trigger – how is the identification executed?

The aforementioned considerations assure that the captured image is suitable for the intended processes afterwards. In addition, perspective errors and lens aberrations may distort the captured image. Thus, ensuring the imaging setup so that the camera axis is perpendicular or nearly perpendicular to the object under inspection and knowing the types of distortion caused by the lens are very important. If the camera axis is almost perpendicular to the object and the lens distortion is negligible, simple calibration, which transforms a pixel coordinate to a real-world coordinate through scaling in the horizontal and vertical directions, is required. However, if the camera axis is not perpendicular to the object or the lens aberrations cause images, especially the region-of-interest, to appear distorted, perspective calibration and nonlinear distortion calibration is needed respectively. Thus, the imaging setup should be calibrated by defining a calibration template and a reference coordination system, and learning the calibration information. In most visual inspection tasks, the camera axis should be perpendicular to the object and the lens selected should have negligible distortion. Once the image has been captured, pre-processing of the image data must be conducted. This procedure is necessary before proceeding to conducting any subsequent analysis. The image data after preprocessing is known as a formatted image. Two tasks are involved at this stage, as described below.

Background noise removal

The median filter has been widely used to reduce background noise in digital images (Church et al., 2008) and other computer vision applications (Wang and Liao, 2002; Wang et al., 2005). It is a non-linear filter and is very good at preserving image detail when compared with linear smoothing filters. The main idea of a median filter is that it considers each pixel in the image. It first deploys a small mask template and the template operation can be calculated by either correlation or convolution (Wang et al., 2005). It then sorts the neighborhoods into order, based upon their intensities, and finally replaces the original value of each pixel with the median value based on the list generated. Replacing a pixel's grey level value with the median value of its neighborhood is expressed as follows:

$$G'(x, y) = \text{median}\ \{G(x1, y1) \mid (x1, y1) \text{ is in } N(x, y)\} \qquad (4.1)$$

where N(x, y) is the immediate neighbors of the pixel (x, y).

Contrast Enhancement

Histogram Equalization (HE) is one of the most frequently used methods to enhance the contrast of gray-level images. However, HE works on the entire image. If the images have finite number of gray scales, ideal equalization can be barely achieved. For example, HE may replace a number of pixels with originally different brightness values by a single value, hence some details are totally missed. On the other hand, adaptive HE is an alternative method. A histogram is determined and used to obtain a final value. The main drawback is that high peaks in the histogram lead to large values in the output image, because of integration. In addition to enhancing perception of contrast, using gamma correction and Contrast Limited Adaptive Histogram Equalization (CLAHE) can provide better results (Wang et al., 2005). In this contrast enhancement task, gamma correction is optional, unless underexposure is inevitably observed in the image captured, and is caused by the limitation of the imaging setup or illustration setup.

Firstly, gamma correction is a nonlinear brightness adjustment. By using it, brightness for darker pixels is increased but bright pixels remain almost unchanged. Thus, more details are visible.

Secondly, CLAHE works on small regions on the image, namely tiles. Each tile's contrast is enhanced so that the histogram of the output region approximately matches a specified histogram. Neighboring tiles are combined using bilinear interpolation to eliminate artificially induced boundaries after performing the equalization. In addition to reducing the noise produced, especially in homogeneous regions, optional parameters can be predefined to limit the contrast. Thus, the amount of contrast enhancement at each pixel is limited by clipping the original histogram to a limit (Wang et al., 2005).

4.2.2 Processing and Analysis Module (PAM)

PAM is responsible for performing image processing, classification and recognition. In most visual inspection tasks, PAM has to provide pass or fail decisions and the corresponding output data by computing a set of known features for the application domain from the formatted image received from DCM, and to reduce the number of features for decision-making. If the application is related to classification, more non-overlapping or uncorrelated features are considered in order to achieve better results (Oyeleye and Lehtihet, 1998). Since features depend on the application, there is no fixed set of features which fits all application needs. Some examples include size, position, orientation, quantity, contour completeness, and texture measurements on the regions. Such features can be identified, extracted and analyzed by statistical techniques or other computing techniques, including the proposed evolutionary approaches in this research for solving the vision-based problems. Thus, the computed features can be treated as the description of the formatted image. However, the number of computed features could be large, while the intrinsic dimensionality could be small. Thus, reducing the dimensionality of the feature space to the intrinsic dimensionality of the problem should be done before performing decision-making and the reduced feature set is further processed to come up with a decision (Malamas et al., 2003). The decision and the descriptions generated from the formatted image are application-oriented. Taking a visual inspection task in a manufacturing process as an example, PAM has to check whether the produced goods or WIP meet some predefined quality standards by matching a computed feature with a known model of the formatted image to be recognized. In the case of the above example, it is a model-matching approach and the decision-making process may involve low level and intermediate level image processing, such as thresholds, edge detection and circle detection.

In fact, model based approaches have been applied in a variety of application fields (Taylor et al., 1988). The basic idea of the decision-making process of PAM comes from a top-down procedural model approach, where the models are implicitly defined in terms of processes that recognize the images (Malamas et al., 2003). The top-down procedural model approach requires that the descriptions generated from the formatted image at different levels of specificity or detail be matched with one of possible many models of the various classes of images. Appropriate descriptions are generated with guidance, rather than descriptions being first generated and then matched with a model.

For the visual inspection tasks, the process of PAM can be further simplified because the original images are captured under controlled conditions of good lighting, and the formatted images have low noise levels. Thus, the descriptions can be constructed easily and are specifically based on the application needs. In addition, different inspection problems can be formulated as optimization problems and solved using the chaos-based PSO algorithms, hence, complex model matching process can also be avoided in some cases. Using known features from training results, PAM can identify the finished goods or parts being inspected and the features being matched, measured or analyzed. Solving the optimization problems, the features are further processed towards a decision for the inspection needs. Taking an inspection task which can be solved by the template matching technique as an example, the matching parameters of the vision system are inputted and a number of standard referencing images are loaded to produce the templates, so that the module can learn the important features of the referencing image. At the same time, the template generated from the referencing images will be saved. The matching process is performed automatically, based on the setting of the matching parameters previously defined in the interface. The module determines a pass or fail for each item based on the corresponding formatted image, and the ‘Pass/Fail’ indicator will be shown instantly on the display in the inspection station. If the item under inspection fails, the module is responsible for sending a signal to the corresponding motion module to reject the defective item from the conveyer or the production line.

4.2.3 Information Storage Module (ISM)

The Information Storage Module (ISM) is responsible for handling the output data from the participating inspection station. The inspection station, which encompasses DCM and IPM, does not have communication ability and only provides the required result files. For visual inspection tasks, the result files could be the output data and the resulting image. Data collection is done by a data collector which is a supplementary unit rather than a required functional unit. The data collector is responsible for connecting with the inspection station (or multiple inspection stations) in order to collect the result files. When the output data and the resulting image are collected, ISM will combine the output data, such as the inspection result, inspection duration, error type, unique identification number, with the resulting image by writing the data in the image’s Exchangeable Image File Format (EXIF) metadata, indexing the file name, and storing the combined file in the central database. However, Swanson et al. (1996) pointed out some drawbacks in storing the data in the metadata or a separate file. Firstly, the separate file requires extra storage space and additional file counts. Secondly, the metadata may be corrupted or changed in some situations, such as in format conversion or in an incomplete file transfer. Moreover, if a separate file which is used for indexing purpose, is lost, then the required file cannot be automatically retrieved, and searching and matching by a human operator is required. Thirdly, burning all the required information on an image may over-write the original pixel data. For example, any crash caused by the electrical system or human errors may damage the separate file, thus the link may be broken. It is obvious that the loss of the separate file or corruption of the metadata prohibits the retrieval of the useful information from the database. In addition to editing the metadata and indexing the file name, ISM enables users to embed the customized output data such as the date and time or unique identification number of the output data, into the image directly. These functions enable organizations to face the aforementioned inconvenience and unify the file format in the central database. When ISM needs to send the files to other entities in the network after receiving a request, the module identifies the appropriate files and the number of files required by cross-checking the data files identification. The procedure adopted by the system is presented in Figure 4.2.

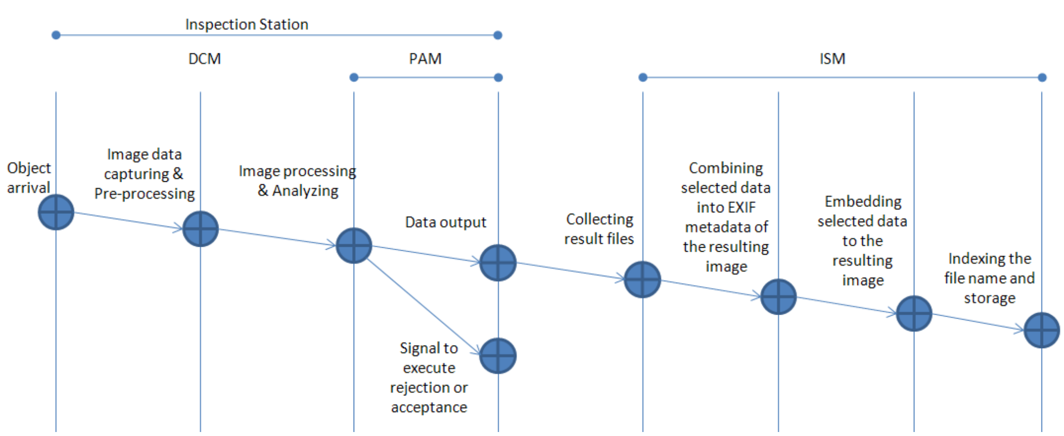


Figure 4.2 A workflow diagram of DCM, IPM and ISM

4.2.4 Monitoring Module (MM)

This module is used to plot control charts based on the output data. MM contains seven different types of control charts commonly used in industry. In general, the charts are broadly separated into two groups: attribute control charts and variable control charts. Attribute control charts control ‘attribute’ data such as number of defects, number of mistakes, etc. On the other hand, variable control charts control ‘variable’ data. For examples, length, strength, temperature, resistance, etc. MM provides a control chart selection guide, so the quality team can be able to select a suitable control chart for a particular application. The details of the selection guide are illustrated in next paragraph and the flow chart of the control chart selection is shown in Figure 4.3.

- Step 1: This is the first step to guide the user to choose a suitable control chart. If data collected in an application is based on counts, it is attributes data. In attribute data, there are binary data and count data. With binary data, it means distinct items are under inspection which results in yes/no or pass/fail (e.g. deliveries or invoices). With count data, an area where a defect has an opportunity to be found under inspection (e.g. number of scratches or dirt found on a component). Traditionally, c harts or u charts are used for count data. If the area is fixed from sample to sample (or fixed sample size), a c chart would be used; otherwise a u chart would be used. If variable data is used in the case, then it can be measured to any precision based on the requirement. If the data is based on counts, move to step 7, otherwise, move to step 2.
- Step 2: Variables data is chosen at this point. Two simple questions have to be answered in order to move to the next step. They are: how much data is there and how frequently is the data collected. Data may be collected on the percentage of inspection completed on each day. Thus, one value will be used to represent the day. If one in every five parts were inspected from a production line per hour and a critical dimension is measured, in this case, multiple values

will be used to represent each hour. If multiple values are used, move to step 3, otherwise, step 6.

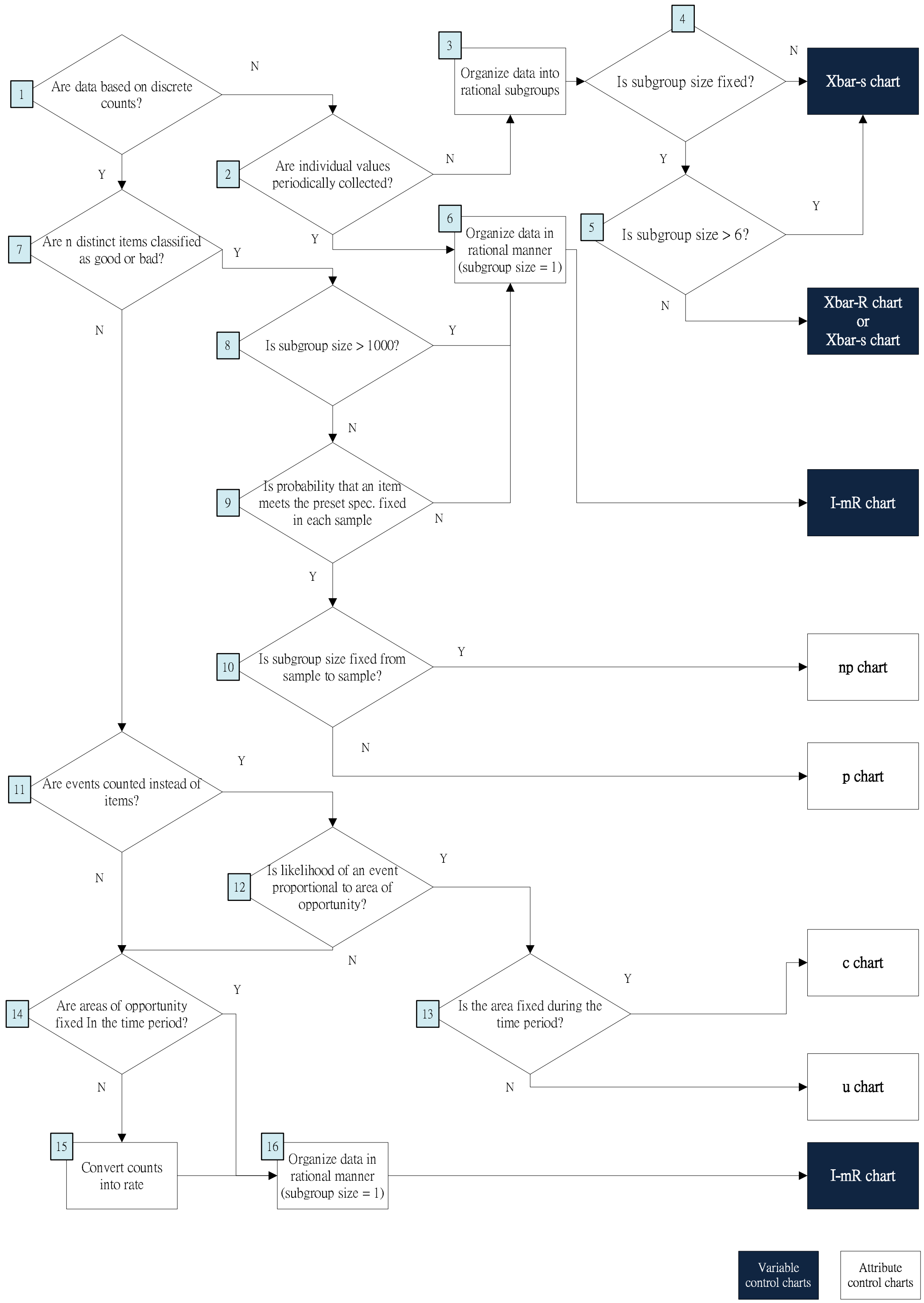


Figure 4.3 The control chart selection flow chart

- Steps 3, 4 and 5: If multiple values are collected at one time, rational sub-grouping is an essential sampling procedure. Samples should be selected in a way that obtains the most information from the data and explores the variation of interest to the users. The variation of interest might be shift-to-shift, day-to-day, hour-to-hour, batch-to-batch, etc. One suggested way of looking at control charts is that they are tested statistically to determine if the variation from subgroup to subgroup is consistent with the average variation within the subgroups. It is recommended to select the subgroups in such a way as to give the maximum chance for the measurements in each subgroup to be alike and to be different. The subgroups should have internal homogeneity (McNeese, 2005). If the subgroup size is variable and large (> 6), use a Xbar-s chart. If the subgroup size is fixed and small (< or = 6), use a Xbar-R shart. However, if the subgroup size is large, then a Xbar-s chart can also be used (Yeung, 2007).
- Step 6: If individual values are collected periodically, an I-mR chart would be helpful in exploring the variation users are interested in. An I-mR chart is the choice when only one value is used to represent the situation at a given time, say in daily bases or weekly bases, and all the values collected are organized in one subgroup only.
- Step 7: Data based on counts is chosen at this point. It requires the user simply to decide whether the target data is binary or count data. For example, the number of internal deliveries from the production line to the warehouse each day is the target and the decision is based on whether each was on time or not. In this case, distinct cases/items are inspected and classifying as good/bad or pass/fail (binary data). If the target data is of binary type, move to step 8, otherwise move to step 11.

- Step 8, Based on binary data such as yes/no or pass/fail, the thing to be determined is how many distinct cases or items are observed over a given time period. If the subgroup size (*n*) is >1000, move to step 6 and adopt an I-mR chart, otherwise, moves to step 9.
- Step 9: In many cases, the probability (*p*) that a single item meets the preset specification is assumed as constant for each of the *n* items. However, it is not always true (McNeese, 2005). For example, for internal delivery checking, the value of *p* is probably not constant for each transfer. If operator A transfers a pallet of finished goods by a hand pallet truck, the probability of that pallet being on time is most likely different from the rest being transferred using a forklift truck. If *p* is fixed from sample to sample, move to step 10, otherwise, moves to step 6 and use an I-mR chart.
- Step 10: If the number of items inspected is fixed in each time period, use an np chart, otherwise use a p chart.
- Step 11: Based on count data, there are two different types, including event counting and item counting. An event could be a lost time accident or near miss accident, while an item could be a surface imperfection or nonconformities found on an item. If the case is event counting, move to step 12. If it is item counting or is not sure, move to step 14.
- Step 12: At this point, a user needs to determine whether the likelihood of an event happening is independent on which part of an object or area is chosen as the area of opportunity. Take a lost time accident measurement in a factory as an example; it would be wrong to include two departments of different sizes in the data because the likelihood of a lost time accident may not be proportional to the department size, especially if the job nature of these departments is different.

If the likelihood is proportional, move to step 13, otherwise, move to step 14.

- Step 13: Again, a user needs to determine whether the area under inspection is fixed from sample to sample in the time period or not. By taking the aforementioned example in step 12, the area, meaning the factory, is the same all the time (assuming no major changes in the inspection period). However, if the number of scraps found in a particular production line divided by the number of total working days, then, the area is not fixed because the total number of working days worked varies from month to month. If the area is fixed, use a c chart, otherwise, use a u chart.
- Step 14: If the area is fixed, move to step 16, otherwise, move to step 15.
- Step 15: Assuming lost time accidents rarely happen and the control limits set on a c chart are not valid anymore, then, the data can be converted into a rate per period of time, such as days between accidents, and use an I-mR chart.
- Step 16: The same as step 6. An I-mR chart is used.

MM also interprets out of control signals based on the 7 common rules (Wortman, 2007), they are:

- 1 point beyond the control limit
- 2 out of 3 points in zone A (defined as the area between 2 and 3 times sigma)
- 4 out of 5 points in zone B (defined as the area between 1 and 2 times sigma)
- 6 or more consecutive points form a steady increasing or decreasing trend
- 8 points in a row on one side of the center line
- 14 points in a row alternating up and down (Systematic variation)
- 15 points in zone C (defined as the area between the center line and 1 times sigma)

4.3 Protocols to Information Handling

A protocol is a standard procedure for regulating data transfer from an inspection station or data capturing point to the central database. Three protocols are proposed to enable the best procedure for integration and transfer of the available result files to become useful information, and then stored systematically. In a real situation, the result files may be produced at distributed inspection workstations. These protocols generate, collect, integrate and store the result files. The details of the three protocols are described in following subsections.

4.3.1 Protocol A: Information Generation

Protocol A is implemented at DCM and PAM. In a typical visual inspection task on the factory floor, this protocol is used to capture the image of the object which is under inspection, to execute image processing procedures, to perform analysis, and to produce the output data and accept/reject signal. In general, DCM has machine intelligence via training by learning unique fiducial markers of the object's image for image registration and correcting camera distortion, if necessary. This training is important because it enables the inspection station to distinguish one object from another. If the application involves a conveyer, the training is also useful to set a uniform speed of the conveyer in order to synchronize with the capture time of the industrial camera in the inspection station. Some vision-based problems can be solved by standard machine vision techniques but some can be formulated as an optimization problem and solved by evolutionary approaches. In a usual industrial inspection, features of faultless objects which have a known class and orientation, are extracted. This information is then stored in PAM. In the recognition or interpretation process, the same feature information extracted from an incoming object is compared to the stored information. If the extracted feature information of the incoming object is the same as, or close to, the stored information and reaches the passing score, the incoming object is identified as a qualified one. On the other hand, some challenging problems are formulated as optimization problems and are solved by the evolutionary approach. Examples and more information can be found in the case studies described in the next chapter.

In general, the formulation of a vision-based problem to an optimization problem is problem dependent. That means, different vision-based problems can be formulated in different ways, but the common point is that selecting the fitness function which accurately quantifies the solution quality is a fundamental step. With a successful formulation, feature extraction and parameters tuning are also required as in other conventional machine vision techniques. No matter which approaches are adopted to solve a vision-based problem, the output data must be provided by the PAM with the resulting image following the Protocol A. Figure 4.4 illustrates the flow chart of Protocol A. For a usual inspection task, the protocol is constructed based on the following assumptions:

- An inspection station is responsible for one designated item type or scene.
- Definition of an inspection task, the technical setup, such as calibration and lighting control, techniques and algorithms selection, types of output data and control chart selection, is set before starting the inspection.
- Inspection stations (if more than one) are independent of each other
- Each inspection station can produce result files which include the output date and the resulting image. These files are saved in an internal buffer and sent to the data collector via communication lines.
- Output data must contain the required data (e.g. inspection result) which support

constructing the control chart, which is defined previously.

- Each output data and the resulting image have a unique identification number for better data management.
- If the inspection task cannot be completed by the inspection station in the first trial, e.g. the object cannot be recognized, a second trial will be made. If the task is still not completed, the inspection will be halted and a request signal for manual trouble-shooting will be issued.

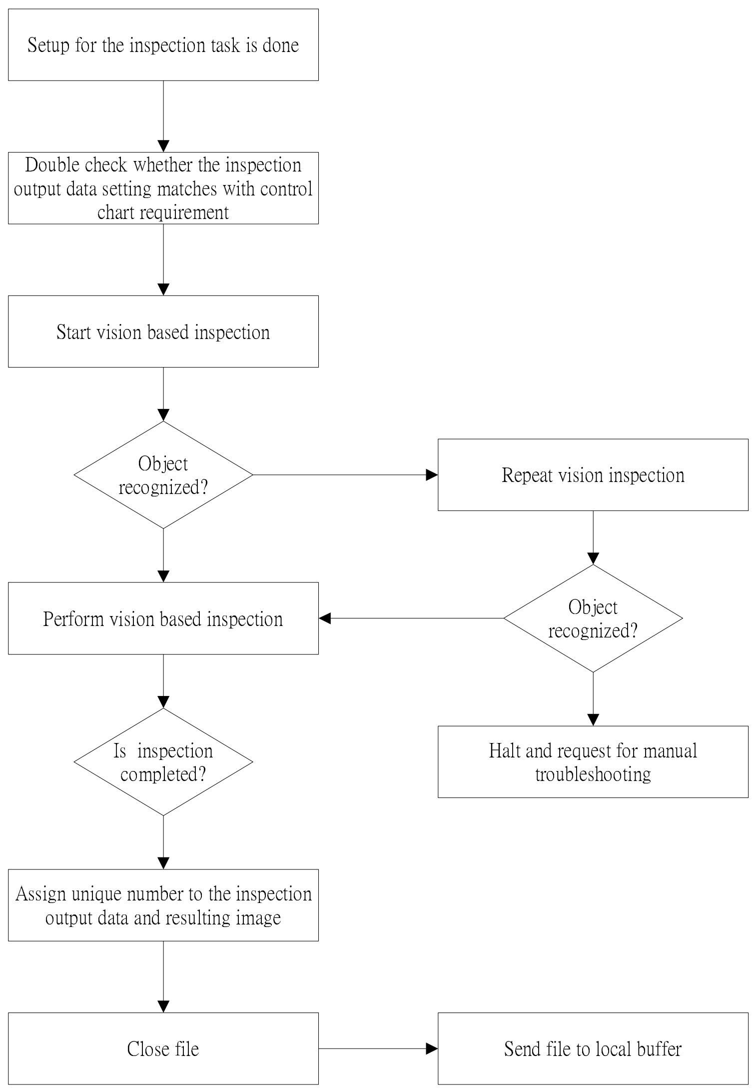


Figure 4.4 The flow chart of Protocol A for information generation

4.3.2 Protocol B: Information Collection

Protocol B is implemented at ISM to collect the output data and the resulting image which are generated by following Protocol A. Although DCM and PAM help in solving vision-based problems, just like many stand-alone machine vision systems, the lack of data communication makes them less effective and face an old problem found in machine vision: inspection tasks are separated and further isolated (Bradley, 1998). Obviously, local area networks and wireless networks have been widely used in society and are capable to transfer massive amounts of data in short periods of time. In addition, Fabbro (2002), Almadani (2005), and Wu et al. (2009a) proposed distributed image processing and image data transfer frameworks. Unfortunately, not all manufacturing sites and warehouses support such infrastructure. Consequently, they are most likely to experience network overload, communication delays, data redundancy and data missing problems when exchanging large volumes of data periodically. Thus, Protocol B is proposed to address the above issues. There are three different types of data collection schemes; a Flag based scheme, an Order based scheme and a Mixed scheme.

The Flag based scheme means the data collector will collect the output data and the resulting image when an inspection is done and a flag (signal) is sent to it. The data collector will check the file type of the result files. If they are authorized types (CSV text file format and JPEG file format), then it will receive the files from the local buffer of the inspection station. If the data collector is occupied, it opens a log and records the name of the requesting station and the time of the request. Once it is available, it will complete the task marked in the log file.

The Order-based scheme is usually applied to some situations in which the rate of output is slower than the time needed by the data collector to patrol through the whole network connecting with all participating stations in one loop. It is similar to a token-ring topology. By following this scheme, the data collector patrols the network connecting all inspection stations and checks for the presence of the result files in a non-stop manner until it detects them. It receives the files after the file types have been verified.

The Mixed scheme is a mixture of the aforementioned schemes. Its advantage is that it keeps a low traffic rate but provides a relatively prompt response to any urgent request. The flag in the Mixed scheme can be treated as a priority flag. The data collector keeps navigating the network. If the result files are ready for pick-up at a station, it receives the files, otherwise, it continues its patrol. If a priority flag is present during the patrol, the data collector halts and advances to the flag owner immediately. After file type verification, it retrieves the files and then resumes the patrol where it stopped.

The selection of a scheme is based on the existing infrastructure in the site, the output rate, the traffic rate, etc. Once the output data and the resulting image have been collected from the inspection station, it is necessary to further process it in order to have better storage and enable fast retrieval of the information for investigation in the future. Thus, Protocol C is explained in next section.

4.3.3 Protocol C: Information Storage

After following Protocol B, there are two strategies available to save the collected result files. They are central storage and distributed storage. A central storage is preferred with Protocol C for the following reasons:

- ISM is responsible to format the received files by integrating the output data with the resulting image to form a single file and indexing the file name systematically. It can also embed the customized data into the image by the digital watermarking technique, then the file is stored in the central database. File storing and tracing at a single storage location requires less time than storing and tracing at distributed storage across a network.

- Adding distributed storage means adding extra computers and storage units, for data storage.
- A distributed storage strategy needs a heterogeneous buffer system which requires developing a number of buffer management strategies. Thus, the technology and management costs are increased.

After the output data and the resulting image have been collected and stored in the buffer, Protocol C is used to assist in the file formatting processes for better storage, which supports efficiency retrieval from the central database in the future. An outline of the Information Storage Protocol is shown as follows:

- After ISM receives the output data and the resulting image, it stores these two files in the buffer and then combines the output data with the resulting image by writing the data to the image's EXIF metadata. Thus, two files become one image file, namely a record.
- Upon the successful integration, if necessary, the selected output data such as the date and time or unique identification number of the output data can be used to generate a digital watermark which will be embedded in the record directly.
- The record name is then indexed systematically with the 'date', 'inspection time', 'station name' and 'inspection result', e.g. the file name of the record contains an inspection result of a qualified item produced in inspection station A on 2010-09-20 at 13:30:25 is '20100920_133025_A_pass'.
- Before storing the record in the central database, the name of the new record

will be checked with the names of all existing records. If there is no duplication, the record will be stored in the central database, otherwise, a request for manual troubleshooting will be issued.

The functions and requirements of the protocols to information handling and their categorization, based on the three aforementioned protocols, are summarized as Figure 4.5.

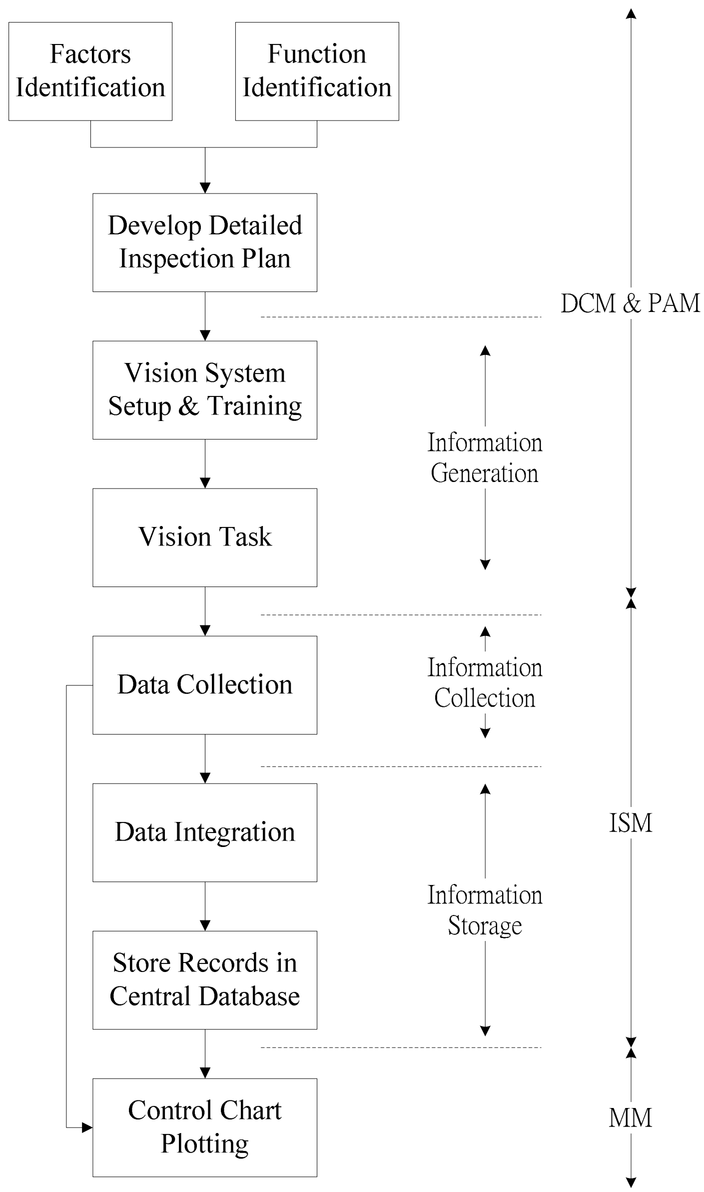


Figure 4.5 Overview of the logic of the protocols to information handling

4.4 Summary of the Design of MVES

In order to address the currently faced problems in deploying machine vision and in solving the emerging vision-based problems, MVEA has been proposed with the protocols for information handling which are incorporated for information generation, collection and integration. This chapter explains the functionality and features of each module and protocol, with more emphasis on tackling visual inspection tasks. It can be considered as a generic approach for solving different vision-based problems. In the next chapter, the first case study is a typical industrial inspection problem in a PCB assembly process. The integration of different technologies and functionality of different modules is revealed. The second case study concerns a monitoring problem in a logistics company. The flexibility and adaptability of the proposed approach is shown in providing a solution to the problem indentified in the second case study.

Chapter 5 Case Studies

5.1 Introduction

Nowadays, many Hi-Tech products and electronics manufacturers, and logistics companies in the mainland and Hong Kong have implemented integrated automation solutions since they understand that automated systems and integration can enhance quality and logistics in order to drive operational performance. Amidst this situation, vision systems are favoured for supporting online or real-time inspection, monitoring and quality control. At the same time, the amount of inspection data generated continues to expand, especially due to the increasing adoption of vision systems. Unfortunately, conventional approaches often separate the inspection tasks and further isolate them, without suitable technology to integrate the inspection information for future retrieval.

To evaluate the feasibility of applying MVES with the proposed evolutionary algorithms in solving vision-based problems effectively, and for effectively handling the corresponding data in order to enhance the quality decision making and operational performance, two case studies have been undertaken. The case studies concern PCB manufacturing and pick-and-pack processes. Although the case companies are classified as very mature companies in their respective areas, they are still searching for an appropriate way to improve their operation. This chapter provides brief industry backgrounds of the case study providers, their existing practices, the methods for applying MVES and the evolutionary approaches to solve the vision-based problems identified in the case studies, are proposed and discussed.

5.2 Case Study Selected from a Printed Circuit Board (PCB) Manufacturing Process

This case study is provided by Semin (Alias) limited, one of the independent manufacturers of PCBs, which was founded in 1983 as a technology-based company. Headquartered in Hong Kong, Semin is specialized in electronic and machinery design for the manufacturing industry. Several technological achievements have been appraised by industry experts as giving domestic leadership, reaching international level. Several products were honored in the 1997 and 2001 Hong Kong Awards for Industry. In 1988, Semin grew into a comprehensive enterprise with business covering product design to manufacturing in electronics and numerical control products. In 1993, the company expanded its business to China, where there are currently three manufacturing bases in Guangdong Province. Currently, Semin has more than 200 employees, forming a strong and professional team, and produces a wide variety of products, including PCBs, PCB modules, electronics, numerical control products, PCB drilling and routing systems, PCB testing machine, etc.

There are three main categories of manufacturers in the PCB industry. In terms of production volume, these three categories form a pyramid with the original brand manufacturers at the top and the local subcontractors, with their immense total volume, at the bottom. The three categories, from the top to the bottom of the pyramid are: The original brand manufacturers, such as Intel, Motorola, ASUS and Gigabyte; The large PCB suppliers who specialize in large scale production, some of which are original design manufacturers; the local PCB assembly subcontractors. To succeed in this ultra-competitive industry, PCB manufacturers continue to adopt increasingly higher levels of integration and are achieving higher levels of component density. In this situation, tolerances on PCB assembly become unprecedently tight, and hence automatic PCB inspection during manufacturing is critical, but difficult to implement. Most PCB manufacturing processes nowadays include surface mount technology. A surface mount device PCB assembly comprises three major processes, which are, in order, screen printing solder pasting on a PCB, component placement and then solder re-flow in a convection oven. There is an increased need for visual inspection in these three main tasks in PCB assembly. Correspondingly, they are solder paste inspection, component placement inspection and post-reflow inspection. These inspections are used to check for a range of possible errors that can be found in the manufacturing processes.

5.2.1 Existing Practice of the Case Example

The PCB assembly processes of single-sided SMT boards are presented in Figure 5.1. Applying solder paste to PCB pads is the starting point after which the surface mount devices will be placed on the PCB correctly. Finally, the board will be conveyed to a convection oven to complete the re-flow soldering step. Furthermore, double-sided reflow is more prevalent, which makes assembly become more complex. Double-sided boards, obviously, need the insertion of through-hole components and some of the designs have a few area-array packages. Surface mount devices on the reverse side require adhesive, and wave soldering must be applied.

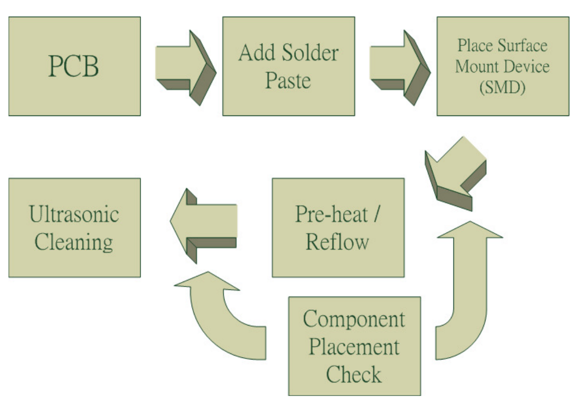


Figure 5.1 The general flow of PCB assembly process

5.2.2 Problem Description

Smaller components and greater component density are the two main elements affecting PCB inspection, but they are not the only ones. Speed always restricts the performance in completing an inspection task. Component placement is done by pick-and-place automation. Every small component from a type feed will be picked up by a vacuum nozzle and placed on the board. The "blowing" method for positioning a component on the board can cause a few problems. For example, too high a blowing power moves a component out of its correct position; too low a blowing power leads to failed component placing; minor X-Y mechanical alignment error may cause position offset problems. In general, missing components, misaligned components and rotated components are regularly found in the component placement stage.

Since the production rates for Hi-Tech industries are so high and the component densities on PCBs are becoming much higher, manual inspection is not a feasible option. Existing PCBs inspection systems used by the company are based on reference comparison methods which require a template that is created from a 'golden board' (faultless board). Then, the board under inspection is compared to this template. In the comparison process, direct subtracting of the template from the inspection image followed by an elimination procedure to locate the defects on a PCB, is the widely used approach. Based on this approach, the type of object detected and the difference in object numbers can be reported which can solve the missing components problem. However, problems in misaligned components and rotated components can hardly be solved. To address these issues, another inspection system provides NCC exhaustive search function for PCB components checking.

Although this method can tackle the component checking task, the run time is relatively too long.

In some situations, a batch of PCBs is inspected by multiple inspection stations. However, the inspection stations are stand-alone systems. Although each station is able to reject defective boards, inspection information, such as defect count, is stored individually, so the quality team has to collect the inspection data regularly, otherwise, they cannot integrate the inspection data for detecting any out of control signal and in making quality decision. Thus, this case study is aimed at finding a possible way to have an efficient approach to identify the three common problems in the PCB components placement process so that the inspection data can be managed in a better way to support the quality team.

5.2.3 The Solution to the Case Study by Adopting MVES

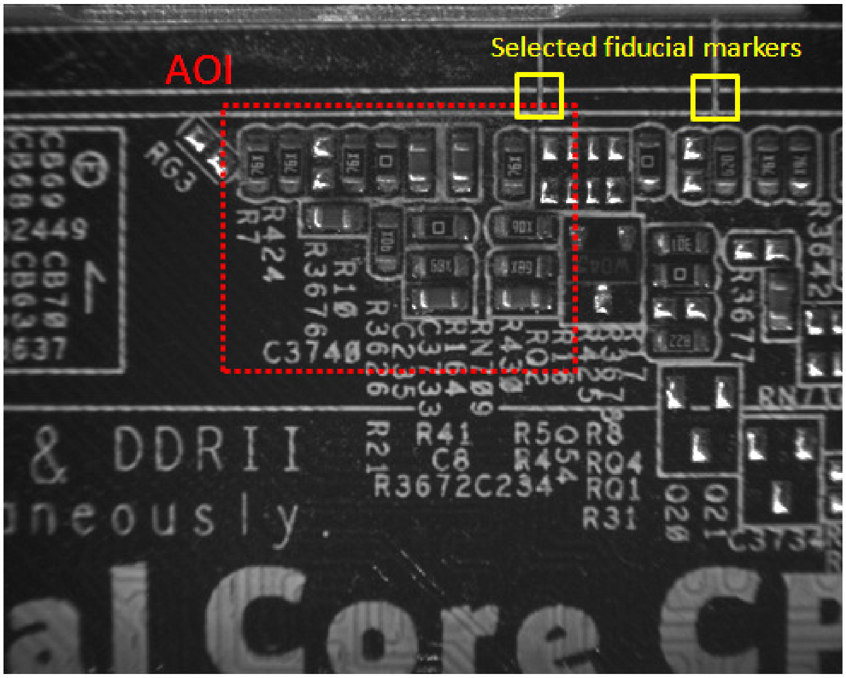
The general objective of MVES is to solve the PCB components inspection problem in the PCBs assembly process. With the help of the CSPSO algorithm and the Inspection Information Handling Protocol, a solution has been proposed to solve the problems found in the case study.

5.2.3.1 Formulation of the Inspection Problem and Preparation

Figure 5.2 (top) is a PCB source image showing different types of surface mount resistors. The quality check requirement is to extract the area of interest (AOI), and recognize and locate the ten labeled resistors located at the predefined position. If there is misaligned or missing component, the PCB is considered as a defective item. Note that a rotated component is acceptable in this case. According to the quality check requirement, the inspection problems can be formulated as a multi-modal optimization problem, being solved by the proposed CSPSO-based approach, which is mentioned in Chapter 3.

Totally, there are 40 PCB samples collected. 30 of them are faultless and 10 are defective. 10 faultless boards are selected to generate the templates of the surface mount resistors and provide definitions of the correct components. In order to solve the PCB inspection problem in the case study, based on this proposed system, capturing the PCB image is essential. Thus, a 3 axis CNC table with 1.5 ton granite platform is used as the inspection station. This granite table minimizes the effect of changes in temperature and reduces errors introduced by the environment. Panasonic AC linear servomotors of the Minas A4 series type and rated at rotational speed 3000r/min for movement precision up to 0.0001 cm are installed on the platform to control camera motion. To perform PCB inspection, there is a Prosilica EC1350 CCD industrial camera with a Navitar Zoom 6000 lens system. The lens system has 0.25X to 2.0X zooming power. A ShimaTec controllable red LED light source and Red (650nm) LED racks are mounted for illumination. After the setup of the inspection station, the raw images of PCB can be captured. The illumination has to be fine-tuned so that the markings on each surface mount resistor can be captured. Because of the nature of the template matching process, each AOI extracted must be aligned with respect to the one extracted from the 'golden board'. In other words, the local coordination system of the AOI extracted from a PCB during inspection must be matched with the one extracted from the 'golden board' which is used to define the correct number of components and the corresponding locations. Otherwise, the location of a component detected cannot be verified. The selection of a fiducial in the image is made manually by choosing a unique or recognizable pattern from its neighborhood to avoid false matches. Two corners of the printed lines on the PCB are used as fiducial markers for image registration. The fiducial selection is shown in Figure 5.2 (top). The size of the markers is 50 x 50 pixels (highlighted by a solid square) with a search region of 75 x 75 pixels surrounding the solid square. These corners are selected because the rotational angle and orientation offset of the image can be evaluated. Since all the images are taken by the same industrial camera and lens system, and the AOI is extracted in the middle part of the raw image captured, distortion errors in this case are neglected. With the help of the markers, each AOI extracted from an image has a zero datum (Figure 5.2 (bottom)), matched with the one extracted from the 'golden board'. The zero datum is the reference point of all the components' locations. Thus, the definition of correct components can be applied to check each detected component's label, location and orientation.

The components mounted on a PCB all have a fixed size and regular shape but not grey-level appearance because of the differences in the markings on the components and the non-uniform illumination. Thus, a generalized template, created by a set of template images for each component to be inspected, is adopted in the experiment. The generalized template is combined linearly by a set of template images to average the statistical variation. Figure 5.3 illustrates the formation of the generalized templates and the six templates used in this case study.



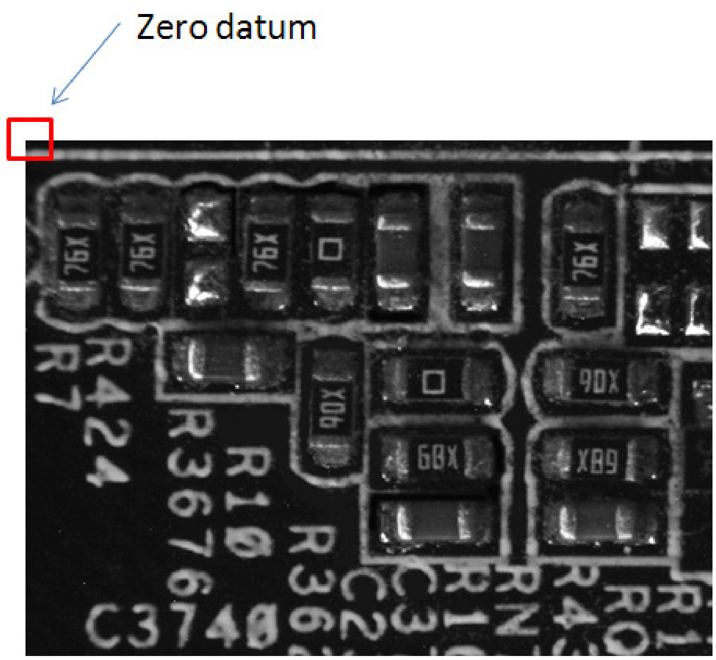


Figure 5.2 The raw PCB image (top); The formatted image for inspection (bottom)

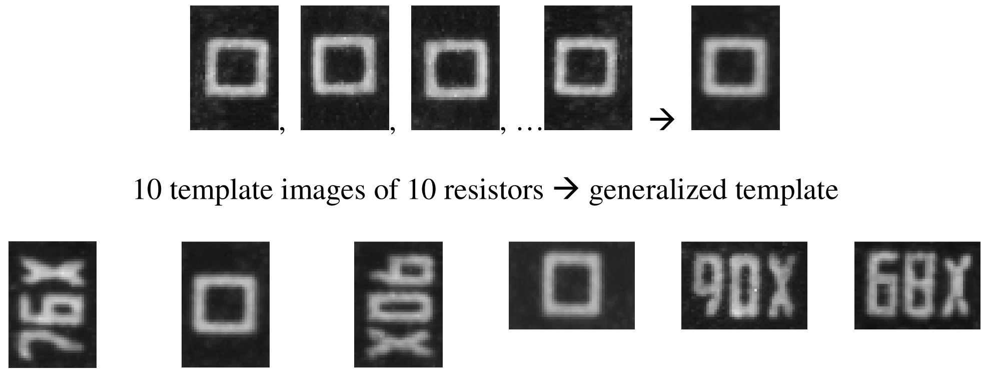


Figure 5.3 The formation of the generalized templates and the six templates created

5.2.3.2 Deployment of MVES with the CSPSO-based Approach

The protocols used in this study, as part of the Information Handling Protocol, are the Information Generation Protocol, the TCP/IP suite for the Information Collection Protocol, and the Information Storage Protocol. The deployment procedure of the solution based on the proposed MVES is as follows:

- The inspection station is setup. DCM is instructed to capture and pre-process the image obtained, including extraction, noise removal and contrast enhancement, in order to generate the formatted image.
- The PCB inspection problem is formulated and the preparation tasks are completed. The preparation tasks include generating the required templates, fine tuning of the CSPSO parameters in trial runs, and defining the inspection output data format. Thus, PAM can perform the required inspection tasks using the CSPSO-based algorithm and provide the required output data to MM and ISM.
- The preferred quality control chart is selected and historical data is provided to generate the control limits, so MM can plot the control chart based on the inspection output data from PAM. In this case, the np chart is selected for monitoring based on the control chart selection guide. The selection guiding process can be found in Appendix A.

- The inspection process begins after all the aforementioned preparation is completed. After inspection, PAM produces the inspection result files. The inspection output data will be used to plot the control chart.
- MM is responsible for plotting the selected control chart based on the data received from PAM and interpret outlier signal. If any outlier signal is detected, an alert will be displayed on the screen.
- The data collector collects the inspection result files from the inspection station through a local area network.
- After verifying the file type, ISM integrates the inspection output data, indexes the file name and stores the record in the central database.
- The central database, which is supported by a relational database management system, stores the record of each inspection. When necessary, the record can be retrieved and the related inspection output data and the resulting image can be reviewed.

The solution is built with the LabVIEW environment and consists of algorithms and programs written in MATLAB on three desktop computers, with an Intel(R) Pentium 4 3GHz CPU and 2G RAM (Figure 5.4). LabVIEW is a software tool used to assemble software constructions called virtual instruments (VIs). They look and act like real physical instruments (Kodosky and Dye, 1989). A VI display on a computer screen in a front panel shows the controls, such as knobs and switches, indicators, meters and lights. Everything in LabVIEW is graphically represented by icons with input and output terminals. To show connections, each icon is connected by wires created by using a mouse to indicate the flow of the data and to define the execution order of the subVIs. There are a number of pick-and-use subVIs in the drag-and-drop libraries that can be used for data acquisition, hardware communication, digital signal processing, numerical and statistical analysis (Poindessault et al., 1995). LabVIEW also affords researchers and developers an application prototyping workplace with a menu-driven interface. 'What-if' conditions can be explored on images before building the codes. Such graphical dataflow language enables completion of the application by generating ready-to-execute MATLAB and C++ codes. Thus, the concepts and functions of the proposed MVES can be illustrated by the suggested solution, which addresses the problems in the case study.

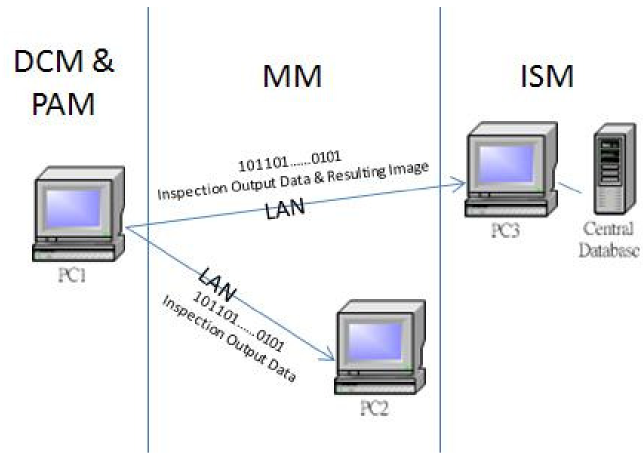


Figure 5.4 The illustration of the setup of the solution

5.2.4 Feasibility Test Results and Discussions

In this section, the proposed solution is tested in a laboratory in the Department of Industrial and Systems Engineering in the Hong Kong Polytechnic University to demonstrate the feasibility of solving the problems described in the case study. There are two objectives in the feasibility test. The first objective is to show how the proposed CSPSO-based algorithm can solve the inspection problem. A comparison of the performance of the proposed CSPSO-based MTM approach and the performance of the conventional NCC exhaustive search method is also conducted in order to reveal the possible advantages of the proposed method. The second objective is to demonstrate that the method can integrate the inspection data for better storage and easy retrieval in the future.

In this feasibility test, a scenario is assumed in which 30 PCBs are considered as a batch and there are 15 batches of PCBs for inspection. Since there is no conveyor in the setup, the 40 PCB images are captured by the inspection station before the start of the test. During the test, one of the forty images is randomly loaded from the local memory instead of real-time capturing. Totally, 450 inspections are conducted. These 450 inspections are then repeated using the conventional NCC exhaustive search method. Since the quality status of the PCB in each image is known, the True Positive (TP) rate, True Negative (TN) rate, False Positive (FP) rate and False Negative (FN) rate are also recorded in the test. Trial tests are conducted to determine the initial parameter setting before the test starts. It has been found and validated empirically that an NCC value of 0.97 is a good termination criteria for stopping the search after finding a template match, and the parameter settings for the CSPSO-based approach are a particle number of 50 and a r_s of 80, which match the optimal setting obtained in the simulation tests in Chapter 3. According to the test results, the proposed method is capable of performing the detection and location of all surface mount resistors. The average processing duration for detecting all ten resistors is 12.92 seconds. Figure 5.5 shows one of the resulting images. In the figure, all ten surface mount resistors are identified. Although the inspection does not require orientation checking, the proposed method can identify a rotated ‘76X’ resistor, which is highlighted by a dotted line in orange color. In Table 5.1, the average processing duration, TP rate, TN rate, FP rate, FN rate and success rate of the proposed CSPSO-based method and the NCC exhaustive search method are presented.

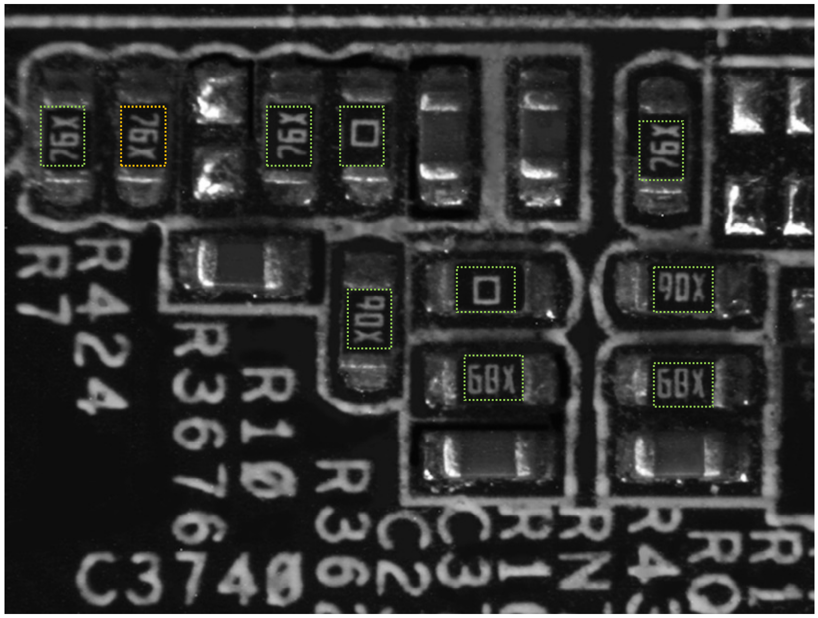


Figure 5.5 The inspection result of a 'passed' PCB

Table 5.1 Comparison between the CSPSO-based MTM Method and Conventional NCC Exhaustive Search Method

	Duration	True Positive Rate	True Negative Rate	False Positive Rate	False Negative Rate	*Success Rate
CSPSO-based MTM	15.92s ± 8.54s	100%	94%	0%	6%	98.89%
Conventional NCC exhaustive search method	450.62s	92%	78%	8%	22%	89.33%

*Success rate = (the total number of TP + the total number of TN) / the total number of inspection

From Table 5.1, the feasibility test results showed that the proposed CSPSO-based MTM approach for PCB components checking is better than the conventional NCC exhaustive search approach. Based on the same setup and configuration, the FP rate is zero when the proposed CSPSO-based MTM approach is used in the system. Although the proposed approach and the conventional approach give FN rates of 6% and 22% in respectively, the FN rate of the proposed approach is much lower, and more importantly, the run time for each inspection is much shorter than in the conventional approach. In general, it is 30 times faster than the conventional approach. All the FN cases produced by the proposed CSPSO MTM approach have been investigated. As aforementioned, the NCC value of 0.97 is set as the termination criteria for the search with a template match found. In fact, 0.97 is a relatively high value to accept a template which is matched, but it can guarantee that no FP case is produced, which is the most important criteria from the perspective of quality control. In this situation, the FN rate is still low when the FP rate is zero, and it ensures no defective item can be passed to next process or eventually to the customers. M^{c}Nemar test is conduction based on the test results obtained, The Z value obtained is 5.79. That means there is a 99% confidence level that the proposed approach and the conventional approach do not give equivalent results, and there is a 99.5% confidence level that the system adopting the proposed CSPSO-MTM approach is better than in adopting the conventional approach. According to Figure 5.6, the results also show that the proposed CSPSO-MTM approach produces lower mean time values as the number of resistors increases and, definitely, is a better approach for solving the problem.

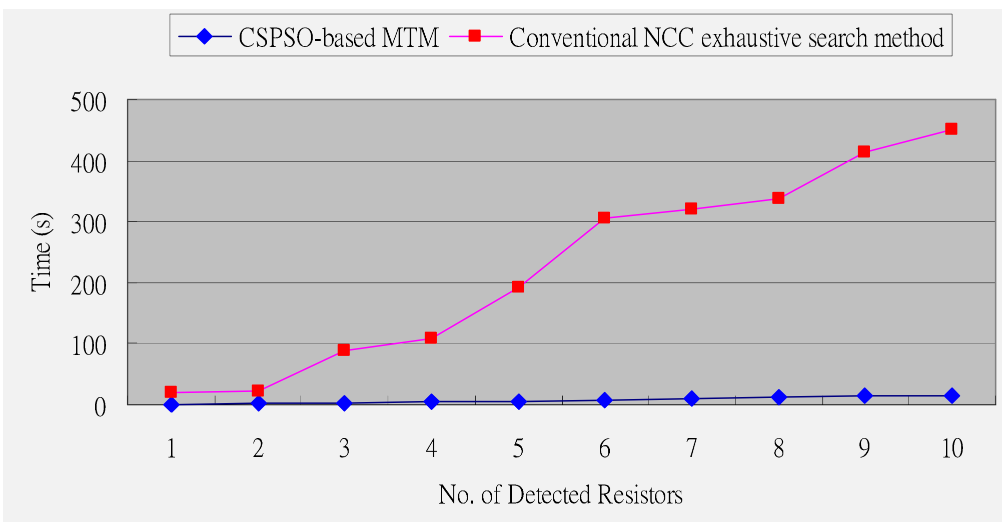


Figure 5.6 Mean search time against the number of objects being detected for both SPSO- and CSPSO- based approaches

After each inspection, two inspection result files, which are the inspection output data and the resulting image, are generated. The inspection output data is needed in order to plot the np chart in the MM. A snap shot of the control chart and monitoring process can be found in Appendix B. The two inspection result files are combined by following Protocol C which means two files are combined by extracting the inspection output data and writing the data to the resulting image's EXIF metadata. Thus, the two files become one file, namely a record. Basically, the record is a single image file with an indexed file name. In Figure 5.7, one of the records created, namely 'A1018_20101023_182556_p.jpg' is opened by a free EXIF reader (Yoshimoto, 2002). The name of the record is constructed by 'A1018' which means the inspection is done in inspection station A and it is the 18th sample in the 10th batch, '20101023' is the date – 2010/10/23, of the inspection, '182556' is the time – 18:25:56, of the inspection, and 'p' stands for passed. In this feasibility test, the inspection output data, including the inspection result, date and time, inspection station name, and the identification number of the record, can be found in the main information of the metadata of the image.

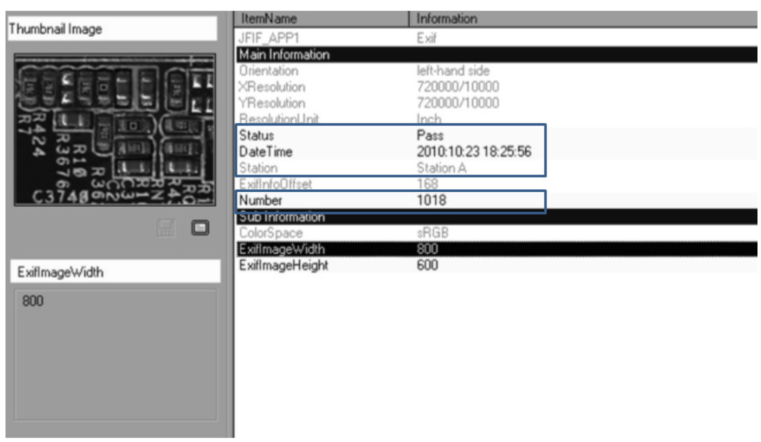


Figure 5.7 The inspection output data (highlighted by the solid lined rectangles) is written into the resulting image's metadata

On completion of the feasibility test, a design review was conducted in early November, 2010, to verify that the feasibility and the concept direction fit into the needs of the case study. Thus, a stakeholder group from the company, which provided the case study, was invited. The group included one supervisor and two members in the quality team and one in-house programmer. According to Malone

(2003), a simple design review checklist was compiled to facilitate the review process. In the review, the concept formation, system structure, enabling functions, significant characteristics and target users of the system in the proposed solution to the case study were considered. The discussed facts and comments are summarized in Table 5.2. Since the review was mainly based on the feasibility test, it does not include any issue from the standpoint of cost, production, hardware specifications and tolerance, and future maintenance.

Table 5.2 The Summary of the Feedback Collected in the First Design Review

Quality Team Supervisor	- The functions of the proposed system can address the PCB inspection issues mentioned in the case study which are commonly faced in the industry. - The structure of the proposed system is flexible. - The optimization engine, CSPSO, can be an effective solver as long as the inspection problem which can be formulated as an optimization problem. It limits the quick adoption of the system for other inspection tasks.
Quality Team Member 1	- In addition to official document announced from the QC department, the control chart selection guide can assist operator in confirming the use of a correct chart. - The maximum number of components can be matched in each time should be specified.
Quality Team Member 2	- The resulting images which contain the inspection date could be a good visual proof in tracing the root cause of quality problem. - The automatic monitoring by plotting control chart is essential to quality control and management.
In-house Programmer	- The inspection time is relatively too long. It is obvious that the inspection time can be greatly reduced to meet the actual application when the whole system is developed based on C++ and OpenCV.

The overall comments obtained from the stakeholder group were positive. Since solving inspection problems based on or assisted by evolutionary approaches is still in the development stage, it is a truth that the proposed CSPSO algorithm can be considered as a solver. It can solve an inspection problem when the problem is formulated into an optimization problem. It is foreseeable that more and more inspection problems and machine vision techniques will be solved and improved by adopting the evolutionary approaches. This case study is only a single case used to illustrate the feasibility of solving PCB components inspection problems effectively by the proposed MVES, which encompasses the proposed evolutionary algorithm, SPC charts and a better inspection information handling approach. The proposed system has a generic structure which can be extended to solve other problems, with suitable formulation.

5.3 Case Study Selected from a Pick-and-Pack Process

The feasibility of MVES was also tested in another case study provided by a logistics company - SFG Logistics Limited (Alias), where it revealed that it has sufficient flexibility to render it applicable in another vision-based problem involving monitoring. SFG is a logistics consultancy and management company which is proficient in providing warehousing and logistics services, such as pick-and-pack, order fulfillment, inventory management and transportation services. SFG has been certified by ISO: 9001. The quality management and operation in SFG have reached international standard. SFG has more than 300 workers in different sites and warehouses located in Hong Kong, China and the USA. SFG provides customers with different solutions such as enhancing supply chain visibility, improving delivery reliability and inventory control, etc.

Pick-and-pack is a part of a complete supply chain management process. It stands for picking ordered goods out of stock and packing them so all the goods in a same order can be effectively shipped to the customer. It entails processing small to large quantities and small to large varieties of goods. Nowadays, the usual pick-and-pack service includes breaking down pallet cases for case by case shipment, picking individual items from cases or storage for order fulfilment, and building new cartons of goods or re-packaged goods to fulfil customized orders or meet customer requirements.

In these pick-and-pack operations, the mobility of goods is very high, especially those logistics companies that offer high volume pick-and-pack services.

Goods are physical assets, and are tangible items, having economic and commercial value to a company. Compared with the fixed physical assets, movable ones are costly to a company. Thus effective physical assets management is important to most of pick-and-pack service providers, and helps to increase the visibility and efficiency within the supply chain and reduces the unnecessary expenditure due to goods gone missing or delayed.

Tracking the condition, quantity and location of goods is a necessary feature of physical assets management used by the pick-and-pack service providers, because a large amount of movable goods are commonly transferred from one place to another. Logistics companies which have better physical asset tracking systems usually perform better than their competitors in term of operational efficiency. The common practice of tracking the goods is to record their transfer history in a gateway by either writing manually or by keying into the computer database. However, differences between the actual information of the goods and the corresponding records in the database occur frequently since human errors are inevitable in all human intervened operations. One of the technologies used is the serially numbered asset tag technology, such as the barcode system, which is popular in warehouse applications for accurate identification. However, the barcode system cannot provide real-time tracking and still needs human intervention. The differences between the actual information of the goods and the corresponding records make the tracing and investigating process difficult when goods are stolen or lost, which in turn lowers the efficiency and profit of logistics companies.

5.3.1 Existing Practice of the Case Example

To reduce human errors, Radio Frequency Identification (RFID) technology, as an emerging and innovative technology, has been applied to track goods. RFID allows remote identification of goods using radio signals without orientation or line-of-sight requirements. RFID tags will be attached on each item that will check in or check out of a site, and the fixed or mobile RFID readers will be deployed in each gateway of the site. When the goods pass through the gateway, the data stored in the RFID tags will be read by the reader and the system will update the database. The identification process is real time and automatic, which minimizes the potential for human errors and reduces theft.

5.3.2 Problem Description

Normally, the RFID reader registers the tagged goods to achieve the tracking function when they cross the detection area of the gateway, but the system is actually tracking the RFID tags, not the goods. Consequently, a number of problems have arisen. For example, an end user could create a fake inventory by using valid RFID tags which have not been attached to the corresponding items. Furthermore, the RFID enabled system cannot effectively monitor the condition of the movable items since the data in the RFID tag will not be updated if the records remain unchanged in the backend database. Thus, it is difficult to trace back as to when and where an item is first damaged if no one notices or reports the damage earlier.

Real-time video devices, such as webcam or closed-circuit television (CCTV), are installed in the gateway to record the goods transfer scenes on tape or in databases. When the status of the goods does not match the actual condition, for instance, a goods pallet cannot be found in the warehouse, while the warehouse record indicates that the pallet has been stored, and there is no check-out record, then, the operators have to trace back from the video record to find out whether the cause of the unmatched condition involves human errors or not. This tracing process also helps to locate the missing goods and prevent theft. The tracing and searching processes, however, are expensive and time consuming because it is difficult to retrieve a specific section precisely, in such a large volume of video fragments for each day, or even for more than a week.

Since both data capturing by RFID and the video captured by webcam have their shortcomings, a more effective and securer tracking and tracing approach is highly desired for this case study.

5.3.3 The Solution to the Case Study by Adopting MVES

In the previous section, the feasibility test of MVES demonstrated how it can cope with the inspection problem in PCB assembly processes. The following solution illustrates how the proposed framework can be applied to solve a monitoring problem in the case study. The purpose of MVES is to incorporate with the RFID enabled system to meet the aforementioned challenges in tracking goods. MVES, with the help of the proposed CPSO algorithm and the protocols for information handling, is aimed at improving the current approach of recording the scenes of goods transfer recorded by a H264 webcam.

5.3.3.1 Formulation of the Monitoring Problem and Preparation

One of the main problems found in the case study is that the data captured by RFID is separated from the video record of the scenes of goods transfer. In order to strengthen the current goods tracking approach, the data in the RFID chip is embedded into the video record as a watermark when the tagged assets are passing through the gateway. In order to enhance the imperceptibility and robustness of the watermarking process for the video records, an evolutionary watermarking scheme is proposed based on the CPSO algorithm.

The H.264/AVC is the newest digital video compression standard jointly developed by ITU-T and ISO/IEC. H.264/AVC has achieved a significant improvement in the rate-distortion ratio compared to previous video coding standards. Ignoring the watermark embedding part of Figure 5.8, the basic structure of H.264/AVC encoder is demonstrated.

The input video frames are decomposed into macroblocks. Each macroblock is either intra or inter predicted based on the reconstructed samples, and the prediction error is transformed and quantized. A low computation cost integer DCT is adopted by H.264/AVC, which can be carried out with integer arithmetic using only additions, subtractions and shifts, after which the quantized coefficients are Zigzag reordered and entropy coded. The entropy-encoded coefficients, together with side information (prediction modes, quantization parameter, motion vector information, etc.) are passed to a network abstraction layer (NAL) for transmission or storage. A deblocking filter is also applied to the decoded macroblocks in order to improve the compression performance of the inter-coded blocks of future frames.

The new scheme embeds the watermark by modifying the quantized integer DCT coefficients of the I-frames' intensity components, and each I-frame is repeatedly embedded with the same watermark. As Figure 5.8 shows, the watermark scheme is incorporated into the encoder itself. In this way, the error introduced by watermarking will be compensated for future predictions and will not be propagated to P-frames and B-frames. More watermark bits can be embedded in the compressed video compared to the watermarking techniques that embed the watermark into the compressed video bitstream directly.

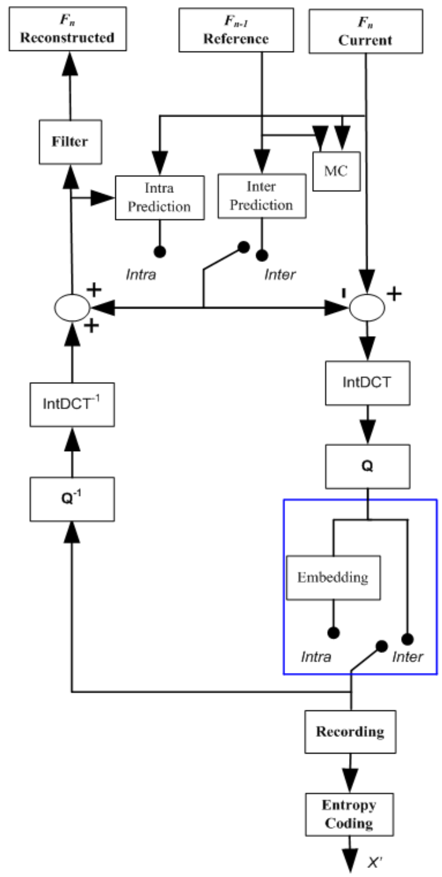


Figure 5.8 The basic structure of H.264/AVC encoding and watermarking embedding

Assuming the original input digital video is of size *M* x *N* and the watermark *W* is a binary image with $W(s,t) \in \{0,1\}$, then the H.264/AVC encoder will produce the number of *P* I-frames for the video *X*. One quantized integer 4 x 4 DCT block in an I-frame is denoted as *Y*(*s*,*t*) and the resulting 16 coefficients can be represented as:

$$Y_{(s,t)} = \bigcup_{k=0}^{15} \{Y_{(s,t)}(k)\} \quad 1 \le s \le M/4, 1 \le t \le N/4 \tag{5.1}$$

The elements in *Y*(*s*,*t*) are zigzag scanned so that a smaller *k* corresponds to low frequency components and a larger k corresponds to high frequency components. The terms *s* and *t* represent the position of each 4 x 4 DCT block. The goal is to select one coefficient, except the DC component $Y_{(s,t)}(0)$ in a block $Y_{(s,t)}$, to embed one single watermark bit $W(s,t)$ for $1 \le s \le M/4, 1 \le t \le N/4$, therefore, the maximum size of the watermark should also be $M/4$ x $N/4$. If necessary, one can resize the watermark to fit the host video first. Before embedding, a binary watermark image W is pseudo-randomly permuted with a predefined key, key_1 is required, in order to increase the security and robustness.

$$W_p = permute(W, key_1) \tag{5.2}$$

In the proposed algorithm, selecting the embedding location of the integer DCT coefficient in a block is based on PSO, and the embedding is based on dither modulation of the selected AC coefficient. Suppose that the watermark to be embedded is $W(s,t)$ and a coefficient $Y_{(s,t)}$(k) has been obtained by PSO in order to simplify the explanation of the dither modulation in the quantized integer DCT domain. The dither modulation embedding algorithm can be formulated as follows:

- Divide the $Y_{(s,t)}(k)$ axis into intervals A and B, based on the quantization step Δ. If the quantized watermarked coefficient $Y'_{(s,t)}(k)$ lies in the interval A, it indicates that the watermark bit 1 is embedded. If the quantized value $Y'_{(s,t)}(k)$ lies in interval B, it indicates that the watermark bit 0 is embedded.
- Calculate the integer quotient m and remainder r

$$m = \mathrm{floor}\left(\frac{Y_{(s,t)}(k)}{\Delta} + 0.5\right) \tag{5.3}$$

where floor() is the operation of rounding towards –ve infinity

$$r = Y_{(s,t)}(k) - m\Delta \tag{5.4}$$

- Quantize according to the sign of $Y_{(s,t)}(k)$ and the watermark bit $W(s,t)$, as shown in Table 5.3. The quantization step Δ controls the robustness and perceptions of the embedded watermark. It can be seen that the maximum quantization error is Δ from the Equation 5.3, according to the rules shown in Table 5.3. During watermark extraction, if *m'*, in Equation 5.5, is odd, the extracted watermark bit should be 0, otherwise, it should be 1.

Table 5.3 Combination of Quantization

$Y_{(s,t)}(k) \geq 0, \quad W(s,t)=1$	$Y'_{(s,t)}(k) = \begin{cases} 2k\Delta & \text{if} \quad m = 2k \\ 2k\Delta + 2\Delta & \text{if} \quad m = 2k+1 \quad \text{and} \quad r \geq 0 \\ 2k\Delta & \text{if} \quad m = 2k+1 \quad \text{and} \quad r < 0 \end{cases}$
$Y_{(s,t)}(k) \geq 0, \quad W(s,t)=0$	$Y'_{(s,t)}(k) = \begin{cases} 2k\Delta + \Delta & \text{if} \quad m = 2k \quad \text{and} \quad r \geq 0 \\ 2k\Delta - \Delta & \text{if} \quad m = 2k \quad \text{and} \quad r < 0 \\ (2k+1)\Delta & \text{if} \quad m = 2k+1 \end{cases}$
$Y_{(s,t)}(k) < 0, \quad W(s,t)=1$	$Y'_{(s,t)}(k) = \begin{cases} -2k\Delta & \text{if} \quad m = -2k \\ -2k\Delta & \text{if} \quad m = -(2k+1) \quad \text{and} \quad r \geq 0 \\ -2k\Delta - 2\Delta & \text{if} \quad m = -(2k+1) \quad \text{and} \quad r < 0 \end{cases}$
$Y_{(s,t)}(k) < 0, \quad W(s,t)=0$	$Y'_{(s,t)}(k) = \begin{cases} -2k\Delta + \Delta & \text{if} \quad m = -2k \quad \text{and} \quad r \geq 0 \\ -2k\Delta - \Delta & \text{if} \quad m = -2k \quad \text{and} \quad r < 0 \\ -(2k+1)\Delta & \text{if} \quad m = -(2k+1) \end{cases}$

$$m' = \text{floor}\left(\frac{Y'_{(s,t)}(k)}{\Delta} + 0.5\right) \tag{5.5}$$

where floor() is the operation of rounding towards –ve infinity

Based on the dither modulation embedding algorithm mentioned, a training scheme can be developed based on the proposed CPSO algorithm. Treat each 16 x 16 macroblock $M(u,v)$ with $1 \leq u \leq \frac{M}{16}, 1 \leq v \leq \frac{N}{16}$ as a separate CPSO training unit, and CPSO training is performed on a macroblock basis. As an example, one zigzag scanned block within a macroblock can be seen in Figure 5.9. One AC coefficient in a block and totally 16 coefficients in a macroblock are randomly chosen as the initialization of zero iteration for a particle in CPSO. However, the randomly selected coefficients might not ensure imperception and robustness. By applying

CPSO, the locations of the AC coefficients for all particles are updated after each iteration. The resulting CPSO selected locations represent the coefficients which hold higher video quality and robustness, subjected to some attacks at the same time. After a certain iteration time, 16 optimal locations will be obtained to embed a 16 bits watermark in a macroblock.

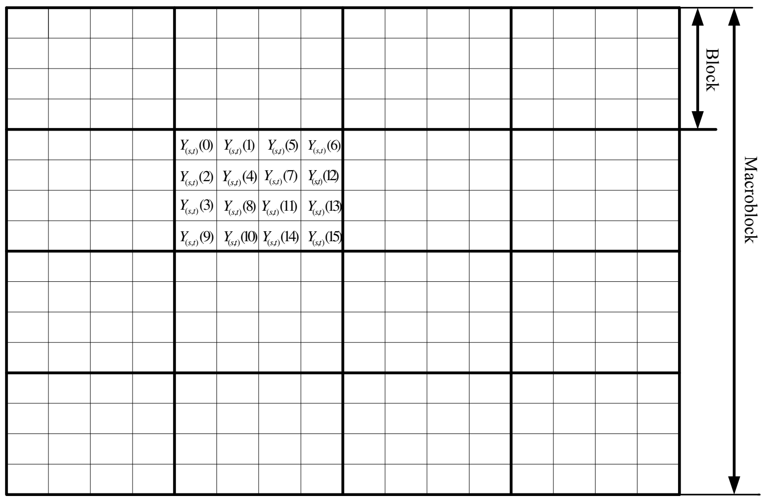


Figure 5.9 Illustration of blocks in a macroblock.

In order to formulate a fitness function in PSO, one should measure the watermarked video quality and robustness quantitatively in a macroblock. Huynh-Thu (2008) concluded that peak signal-to-noise ratio (PSNR) can be a good indicator of the variation of the video quality as long as the quality measurement is conducted in a single video content. Thus, the widely used objective video quality metric, PSNR, is chosen to represent video quality and the normalized cross-correlation (NCC) value between the original watermark and the extracted watermark indicates the robustness (Hsu and Wu, 1999; Sheih et al. 2004; Wu et al. 2011). The PSNR is defined as follows:

$$PSNR = 10\log_{10}(255^2 / MSE) \tag{5.6}$$

$$MSE = \frac{1}{256}\sum_{i=1}^{16}\sum_{j=1}^{16}(M_{(u,v)}(i,j) - M'_{(u,v)}(i,j))^2 \tag{5.7}$$

MSE denotes the mean square error between the original $M_{(u,v)}(i,j)$ and watermarked samples $M'_{(u,v)}(i,j)$ in the pixel domain, and NCC can be defined as:

$$NCC = \frac{\sum_{i=1}^{16} \sim [w(i) \oplus w'(i)]}{16} \tag{5.8}$$

where $w(i)$ is the original watermark and $w'(i)$ is the extracted watermark.

The term $\oplus$ denotes the XOR operation and ~ denotes the NOT operation. In this study, three common attacks, namely, Lowpass Filter, Median Filter and Gamma correction (γ) are employed in the scheme. Each attack corresponds to an NCC value. The fitness function can be defined as:

$$f = PSNR + \sum_{i=1}^{3}\lambda_i NCC_i \tag{5.9}$$

where λ_i is a weighting factor which balances the imperceptions and robustness of the embedded watermark.

A larger λ_i means a higher robustness and less imperceptibility, and vice versa.

Shieh et al. (2004) and Wu et al. (2011) devised flexible evolutionary schemes for image watermarking. A similar scheme is also adopted in this study for watermarking H.264/AVC compressed videos based on CPSO, as shown in Figure 5.10. Since attacks should be included in the scheme, the widely used attacks from Stirmark (Gonzalez and Woods, 1992), lowpass filtering, brightness and contrast adjustment, and γ correction, which represents one of the beautification attacks, are included in the training. Each particle is a 16 dimension vector representing the embedding locations in one macroblock. In each iteration, all the particles are updated according to the Equations 5.10 and 5.11. Assuming the total number is r

particles and the *i*-th particle in the *k*-th iteration is denoted as $P_i^k(j), j = 1, 2..., 16$, then the corresponding update velocity is denoted as $V_i^k(j), j = 1, 2..., 16$.

$$\begin{aligned} V_i^{k+1}(j) = c_0 V^k{}_i(j) + c_1 r_1(j)[Plocal_i(j) - P_i^k(j)] \\ + c_2 r_2(j)(Pglobal(j) - P_i^k(j)) \end{aligned} \tag{5.10}$$
$$\text{for } j = 1, 2, \ldots, 16$$

$$P_i^{k+1}(j) = \text{round}(P_i^k(j) + V_i^{k+1}(j)) \tag{5.11}$$
$$\text{for } j = 1, 2, \ldots, 16 \quad ; \text{constraint} : 1 \le P_i^{k+1}(j) \le 15$$

$Plocal_i(j),\ j = 1, 2, ...16$ are the local best locations for the *i*th particle in the previous iterations, which means that it outputs the largest fitness value among all previous iterations. $Pglobal(j), j = 1, 2, ..., 16$ are the global best locations for all *r* particles in all previous iterations. c_0, c_1 and c_2 are constant values and $r_1(j)$ and $r_2(j)$ are uniform random numbers between 0 and 1. The function round() means rounding locations to the nearest integer numbers, since the locations of coefficients must be integers. The constraint $1 \le P_i^{k+1}(j) \le 15$ means there are 15 AC coefficients in a block. Therefore, if $P_i^{k+1}(j)$ is larger than 15, $P_i^{k+1}(j)$ is assigned as a random number between 8 and 15, and if $P_i^{k+1}(j)$ is smaller than 1, a random number is assigned between 1 and 8. After a certain number of iterations, the optimal locations $Pglobal(j), j = 1, 2, ..., 16$ with higher *PSNR* and *NCC* will be obtained, and the coefficients can be quantized to embed the watermark in the macroblock. After that, they are passed to the next macroblock and embed the next 16 watermark bits through CPSO and dither modulation until all the watermark bits are embedded. When performing extraction, the locations of these dither modulated coefficients are also needed, and should be stored and the locations treated as another key, e.g. key_2.

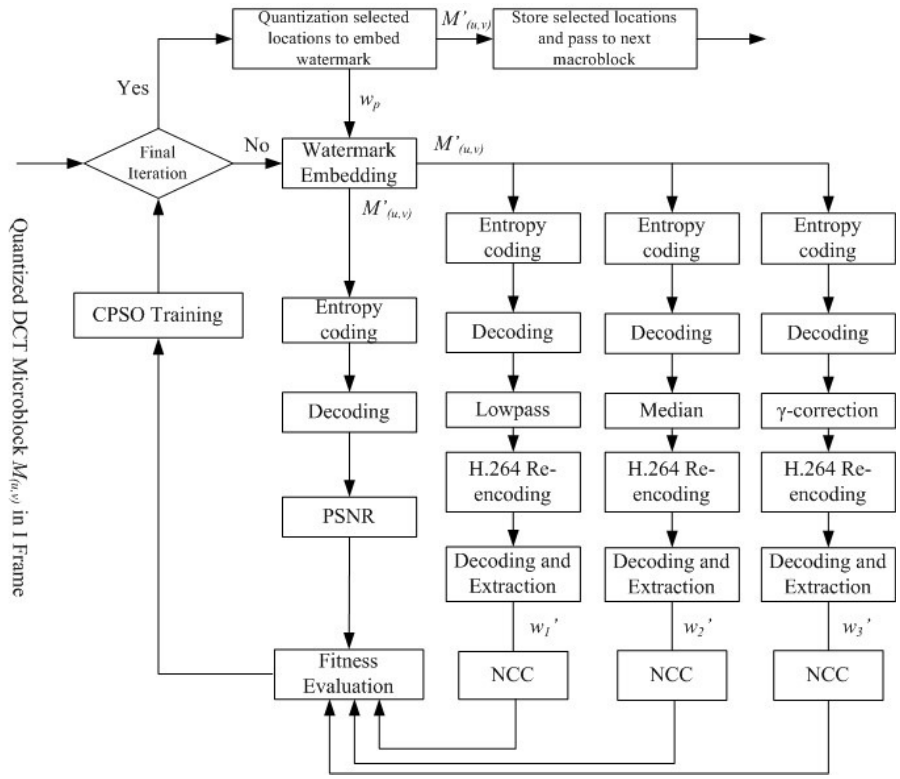


Figure 5.10 The CPSO training for the proposed watermarking scheme

5.3.3.2 Deployment of MVES with the CPSO-based Approach

The protocols used in this study are a modified Protocol A, the TCP/IP suite for the Protocol B, and Protocol C. Figure 5.11 illustrates the workflow of MVES applied to this case study.

Instead of images captured in an inspection station, the visual data captured in this study is H264 video using a H264 webcam. Therefore, no image pre-processing performed by DCM is required. DCM with the H264 webcam can be found in the gateway. DCM has nonstop monitoring and recording of the gateway scene. The video is in 320 x 240 (QVGA) H264 format, with 15 frames per second (fps) in the normal recording mode and the video is directly stored in the central database. When goods arrive, the received RFID signal triggers DCM to a higher resolution recording mode. The resolution of the video in the higher resolution recording mode is 352 x

288 and the frame rate is 30 fps. DCM captures the scene of the goods passing through the gateway. The captured video is then processed in PAM based on the CPSO training process in order to find the optimal coefficients for embedding the watermark. Since there is no checking or inspection tasks involved, PAM transfers the optimal coefficients and the H264 video to ISM, instead of the inspection output data and the resulting image. On the other hand, the data captured by the RFID enabled system is transformed and normalized to the Extensible Markup Language format by a middleware. The standardized data is sent to ISM. When ISM receives the standardized data, it generates a watermark which contains the standardized data, such as the date, time, Gate ID, and Goods ID. After receiving the optimal coefficients and the H264 video, ISM embeds the watermark into the corresponding H264 video and indexes the video name. Once the goods leave the RFID detection zone, the monitoring mode will switch back to the normal recording mode. In both recording modes, the video file name is indexed by the date and time. The video file stored in different portions of the database for further analysis (e.g. wrong delivery destination) and further applications (e.g. location tracking, condition tracking and tracing). As an example, users can obtain a specific video clip, which contains the scenes of a missing asset passing through the warehouse gateway, by querying the database. The data (e.g. date and time) of the target goods are firstly inputted into the query system. Then, the searching process will be started according to the video file names. Once a record is retrieved, the watermark in this higher resolution video record will be extracted for visual checking by the user. Finally, the required video clips are obtained. The file name could easily be altered by the user, but, not the embedded watermark. This double matching method can guarantee the retrieved

video record is exactly the one requested by the user. Figure 5.12 shows the query process of the video record.

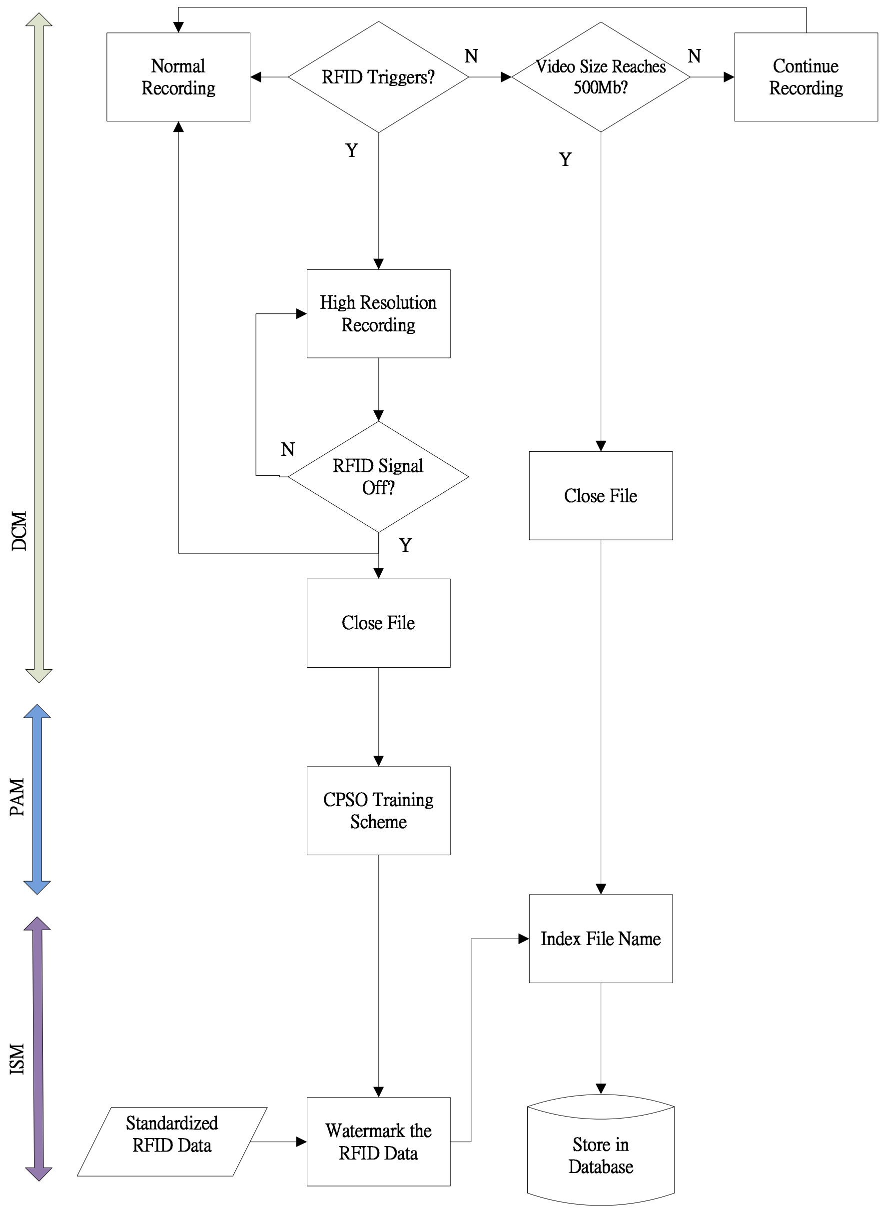


Figure 5.11 The workflow diagram of MVES

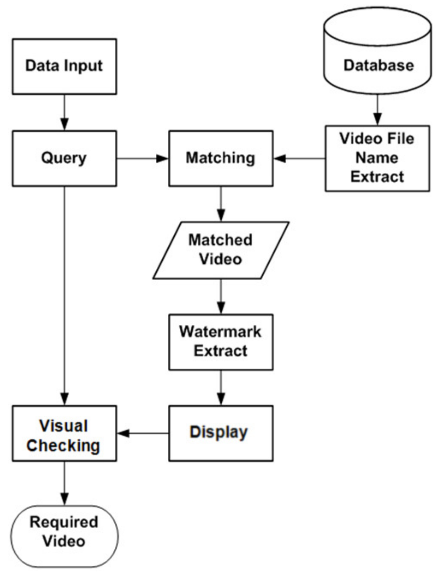


Figure 5.12 Illustration of the video record query process

When extracting the watermark, the original video X is not required in the algorithm. The watermarked video, however, may be subject to some intentional or unintentional attack, and the resulting video after attack is denoted by X''. The extractor is also inserted into the H.264/AVC decoder, as shown in Figure 5.13. When each entropy is decoded and reordered, the macroblock is passed into the watermark extractor, and each 16-bit watermark is extracted with the secret key, key_2, using Equation 5.5. After all macroblocks have been extracted and decoded, one can get the whole permuted watermark information W'_p. Then W'_p can be inverse permuted with key_1 to get the extracted binary watermark image W'. Since there are multiple I-frames in a video and all I-frames are embedded with the same watermark, one can combine all the watermarks extracted from all I-frames to get a final extracted watermark W_f. Each bit in W_f is determined by the corresponding bits in multiples of W' which have more occurrences.

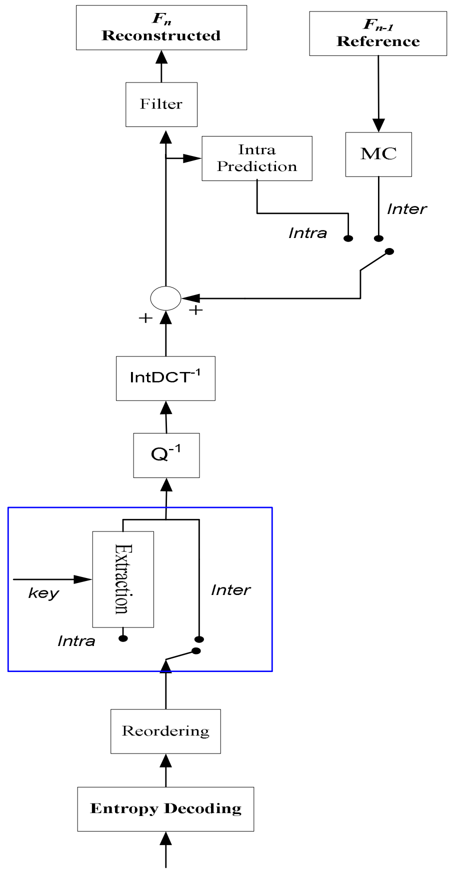


Figure 5.13 The basic structure of the watermark extracting system

5.3.4 Feasibility Test Results and Discussions

In order to test the feasibility of the proposed solution to the case study, feasibility tests are undertaken in a laboratory in the Department of Industrial and Systems Engineering in the Hong Kong Polytechnic University. Two experiments are included in the feasibility tests. Before conducting the experiments, the best location for the RFID tag is determined by the RFID Deployment Optimizer (RFIDDO) developed by Kwok et al. (2007). RFIDDO is used to identify the readability and performance of different RFID tag placement designs (such as location and orientation of the tag) while the tagged object is presented in the RFID interrogation zone in the normal operating condition. Through repetition with different locations and orientations of the sample tags, the optimal attachment location of RFID tags can be identified by comparing the analysis generated in RFIDDO. Based on the results comparison, the best location is either the left or right side of the goods, with the tag being placed vertically.

Once the best location and orientation of the tag attachment has been identified, the first experiment is to evaluate whether the indexed video corresponds to the movement of the goods on the trolley. Since the indexing approach relies on the captured RFID signal, therefore when the tagged goods pass through the gateway, the system will automatically be triggered in order to record the transaction, as well as to index the file name and watermark the video, which is recorded by the H264 webcam. If the reader cannot detect the tag, the system will then stop the high resolution recording mode. As shown in Figure 5.14, the RFID was recorded in the period from 22 Dec 2010 at 12:00 pm for a period of 42 seconds, and the video file, namely 10DEC22120000.avi, can be found in the database. To further test the repeatability of the proposed method, 10 different trials were run and then the content of these 10 indexed videos were examined and checked as to whether the videos can capture the entire transferring process on time or not. All the final results were satisfactory.

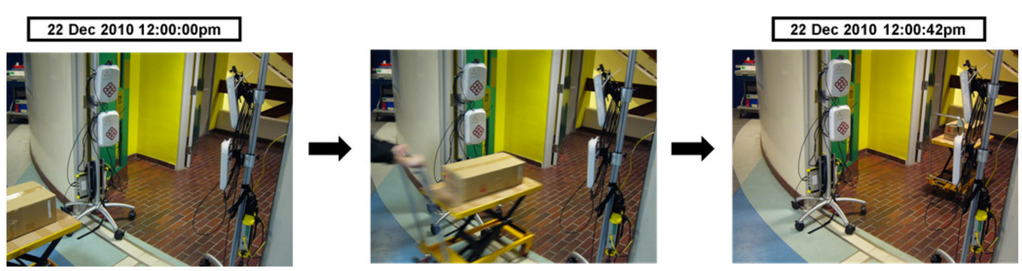


Figure 5.14 A scenario for indexing the video name with RFID data

After obtaining satisfactory results in the first test, the second test was conducted. Once the received RFID signal triggers DCM, a high resolution video is recorded. PAM optimizes the coefficients for watermarking and ISM embeds watermark of the corresponding RFID information into the I-frames of the video and indexes the video name.

In the experiments, the video of the goods passing through the gate with resolution 352 x 288 pixels, 1200 frames and compressed at 600 kps is used for testing. The binary watermark is generated based on the RFID data shown in Figure 5.15. Its size is 88 x 72 pixels so that each watermark bit is embedded into each non-overlapping 4 x 4 block in an I-frame of the video. Here, the free software codec X264 is used as the encoder, and the fixed I-frame mode is used, namely, setting one I-frame every 5 frames. Therefore, there are totally of 240 I-frames to be embedded with the same watermark. The test results of the chosen frame is captured and shown in this section.

The aforementioned watermarking attacks, low pass filter, brightness and contrast adjustment and γ correction are applied to evaluate the scheme. Since the *PSNR* value is much larger than the *NCC* value, the weighting factors are set, $\lambda_1 = \lambda_2 = \lambda_3 = 30$, based on numerous experiment results and validated empirically. If the weight is too large, the watermarked video may have a very low PSNR value and vice versa. Also, the modulation step Δ is set to 1. In the CPSO training process, a statistical analysis has been done with different parameter settings. It has been found that c_0 = 0.4 and c_1 = c_2 = 1.8 are good parameter settings for this optimization process. In order to reveal the visual quality, the watermarked frame with the proposed algorithm, is depicted in Figure 5.22. All the tests were executed 30 times on an Intel Core2Duo E8400 CPU with 2G RAM computer. The results are tabulated in Table 5.4 by comparing the average *PSNR* and *NCC* values with 50 and 100 particles respectively. Better performance has been achieved by increasing the number of particles and iterations. The comparison with the no CPSO training is shown in Table 5.5, namely, the embedding locations are randomly generated in all 30 runs. In Table 5.6, simulation results of the watermarking method, where the GA selection proposed in Shieh's work (2004), is used instead of the CPSO training, are shown. According to the results, it can be seen that there are observable improvements on both *NCC* and *PSNR* values after applying CPSO training. Using the CPSO training is better than using the GA selection because both the resulting fidelity and the robustness of the CPSO-based approach are higher and with fewer iterations.

Table 5.4 Testing Results of the Chosen Frame with CPSO-based approach

Particles	**Iteration**	**Average** *PSNR* (dB)	**Average** NCC_1 (LPF)	**Average** NCC_2 (B&C)	**Average** NCC_3 (γ)
50	1	40.26	0.7922	0.7310	0.8685
	50	40.34	0.9465	0.8740	0.9403
	100	40.36	0.9600	0.8900	0.9510
	150	40.38	0.9620	0.8985	0.9525
100	1	40.30	0.8101	0.7359	0.8783
	50	40.38	0.9562	0.8893	0.9461
	100	40.40	0.9663	0.9040	0.9496
	150	40.42	0.9690	0.9106	0.9525

Table 5.5 Testing Result of the Chosen Frame without CPSO Training

Average *PSNR* (dB)	**Average** NCC_1 (LPF)	**Average** NCC_2 (B&C)	**Average** NCC_3 (γ)
39.02	0.6345	0.7318	0.7803

Table 5.6 Testing Results of the Chosen Frame with GA Selection Adopted in Shieh's Method with 200 Iterations and Weights = 30

Average *PSNR* (dB)	**Average** NCC_1 (LPF)	**Average** NCC_2 (B&C)	**Average** NCC_3 (γ)
40.01	0.9300	0.8978	0.8952

The extracted watermarks (Figures 5.16 to 5.18) of the proposed system are fully recognizable manually for matching during the query process. The first row of the watermark is the date, the second row is the time and the third row contains the gate I.D (G01) and goods I.D. (PAK01). The comparisons, without using CPSO training, are shown in Figures 5.19 to 5.21.

Figure 5.15 The original watermark

Figure 5.16 The watermark extracted after low-pass filter

Figure 5.17 The watermark extracted after brightness & contrast adjustment

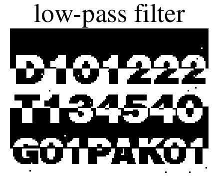


Figure 5.18 The watermark extracted after γ correction

Figure 5.19 The watermark extracted after low-pass filter without CPSO Training

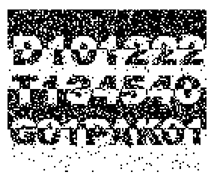


Figure 5.20 The watermark extracted after brightness & contrast adjustment without CPSO Training

Figure 5.21 The watermark extracted after γ correction without CPSO Training

(PSNR: 40.42)

Figure 5.22 The original frame (right); The watermarked frame (left)

The experiment was also conducted with compression only in order to reveal the reduction on PSNR caused by watermarking. The resulting *PSNR* value of the selected frame, after compression without watermarking, was 40.99. Therefore, applying the watermarking scheme with CPSO training caused only a more or less 0.57 drop in term of the *PSNR* values. Since the typical quality requirement is in the range of 30-40 dB, satisfactory result can already be achieved by applying the proposed watermarking scheme with 50 particles and 50 iterations. The watermarked frame is illustrated in Figure 5.22, which is obtained by applying CPSO for 100 particles and 150 iterations.

After the feasibility test, a design review was conducted in late December, 2010. The intent of the review was to verify that the feasibility and the concept direction fit into the needs of the case study. Thus, a stakeholder group related to the logistics company, which provided the case study, was invited to participate. The group included one supervisor and one operator, who are responsible for the pick-and-pack operation, and one solutions engineer who supports the RFID enabled system used in the logistics company. Similar to the previous case study, a simple design review checklist was made to facilitate the review process. In the review, the concept formation, system structure, enabled functions, significant characteristics and target users of the system in the proposed solution to the case study are considered. The facts and comments discussed are summarized in Table 5.7. Since the review was mainly based on the feasibility test, it does not include any issues from the standpoints of cost, production, hardware specifications and tolerance, and future maintenance.

Table 5.7 The Summary of the Feedback Collected in the Second Design Review

Supervisor	- The company can enhance the visibility and accuracy in tracing the goods or inventory with the proposed solution. - The structure of the proposed system is adoptable to the existing RFID enabled system. - The key is an important element to the watermark extraction process. Who should keep it?
Pick-and-Pack Operator	- The video record can be treated as a good delivery proof in each transfer. - The searching process of a video record is much faster than the existing one. - Matching the data of the watermark can be treated as double-checking procedure to make sure the retrieved video is the correct one.
Solution Engineer	- Why the watermark embedded in I frames only?

The general comments obtained from the stakeholder group were positive. The proposed solution combines visual data and RFID data to monitor and record the location and condition of the goods. The company can benefit from the improved visibility and accuracy in each goods transfer through the gateways. With the aid of MVES, the personnel workload and human error related to the track-and-trace operations can be diminished. Previously, a stock keeper could inquire about the overall stock level and availability only, but the goods condition can be monitored by applying the suggested solution.

When an item is lost or damaged, a visual record of the condition of the goods at different stages can be retrieved from the database immediately in order to find out when and where this occurred and who was involved. In addition, the watermark hides sensitive information, such as the gateway ID and goods ID, etc., in the video. The original, hidden information is robust to normal image attacks and can be retrieved even if the video images are attacked or edited. Furthermore, stock will not be lost and operations staff will pay more attention because records are created automatically and every transfer process in the gateway becomes visible. Based on these two facts, the theft rate and damage rate can be reduced.

In actual situations, it is suggested that the supervisor or the operator who is responsible for the video record retrieval process, holds the keys. The keys must be kept in a secure location to prevent from misuse. The decoding process will only be conducted by the supervisor or the operator if he or she wants retrieve a video record and check the goods status at that moment. In addition, it is not necessary for each I frame to be evaluated by the CPSO training process in the proposed watermarking scheme, otherwise the method would be too time-consuming. It has been found, and validated empirically, that evaluating one I frame out of every three I frames is a good criteria for the solution.

5.4 Summary of the Case Studies

Through these two case studies, the proposed MVES and the proposed evolutionary algorithms have been successfully applied to solve the PCB components inspection problem and the goods transfer monitoring problem. CSPSO has been applied to solve the PCB components detection problem based on the MTM approach. This method has successfully solved multiple components detection problems as multimodal optimization problems. Test results showed that the algorithm successfully located all the components in all runs, and in a shorter time than using other approaches. CPSO has been applied to optimize the digital watermarking process during information integration. The test results were satisfactory and no recognizable artifacts and missing processes were detected when replaying the records in the tests. This approach, which can improve the tracking and tracing processes of the goods, can be applied to any workshop, warehouse and organization which needs to manage moveable physical assets. The two case studies have been used to confirm the flexibility and applicability of MVES and the proposed algorithms.

In the first case study, the functionality of the 4 modules of MVES has been revealed. DCM is used for image acquisition and image pre-processing, PAM is used to solve PCB components detection problem with the support of the CSPSO algorithm, ISM keeps track of the inspection output data transferred from PAM, and MM aids in diagnosis of the state of a process by plotting a control chart. In the second case study, the flexibility of the 4 modules of MVES has been fully demonstrated. Since the case company has applied Radio Frequency Identification (RFID) technology to track goods, the main problem faced by the case company is how to combine the RFID data and the video records. Thus, MVES including DCM, PAM and ISM has been proposed to solve the goods tracking problem, MVES with 3 modules has been proposed with the deployment of CPSO based digital watermarking techniques in order to provide an innovative data enrichment solution and enhance the traceability of data records. On the other hand, the power of the chaos-based PSO algorithms has been revealed based on the test results. The chaotic PSO based approach in vision applications and image processing is still untapped. These two case studies can be considered as a stepping stone in applying evolutionary algorithms, machine vision, SPC and digital watermarking techniques to provide integrated solutions for tackling different vision-based problems such as visual inspection and monitoring problems. Future research can further investigate other possible applications based on the proposed infrastructure and algorithms.

Chapter 6 Discussion

6.1 General Discussion of MVES

In today's competitive environment, the need for quality and fewer factitious errors has led to a rapid growth of automated technology in manufacturing and in logistics. Many Hi-Tech products and electronics manufacturers, and logistics companies become more automated in order to reduce waste, improve the quality of their products and to increase the efficiency of their operations. Currently, machine vision is the most desired approach in quality control and monitoring.

It is now possible to buy the necessary hardware and use existing image processing tools to build a monitoring solution or system quickly. This 'assembly approach' makes the technology accessible even to someone who has little machine vision knowledge, as each standard tool is capable of solving a specific problem. Without integrating the suitable tools together, it is difficult to build a full solution for solving practical problems. By using this assembly approach, the inspection tasks are usually separated and further isolated. Furthermore, the importance of handling the corresponding information, such as inspection results and resulting images, is neglected in this type of approach.

In this research a schema is proposed for the design of MVES. This schema is based on the core concept of machine vision with the evolutionary approach. The infrastructure of MVES is followed by the assembly approach. This leads to effective solutions with more flexibility than is provided when only the standard tools are used. MVES also takes advantage of evolutionary computation, SPC charts and digital watermarking technology to facilitate the solution development in solving vision-based inspection and monitoring problems. In MVES, the useful data is used to generate control charts, hence outlier signals can be detected. This provides automatic monitoring for the purpose of assisting the industrial practitioners. In the infrastructure of MVES, chaos-based PSO algorithms are important components which help in solving formulated vision-based problems. The chaos-based PSO algorithms can be treated as solvers to tackle the emerging problems using an evolutionary approach. More importantly, the proposed MVES addresses on the question of information handling. This feature is useful for enhancing the utilization and storage of useful information, and for improving the effectiveness of decisions regarding quality. These decisions require historical information retrieval, and have as their ultimate aim the achievement of better quality and operational performance. An innovative approach for using digital watermarking is also proposed to combine different sources of data into an integrated record for efficient storage.

6.2 Implications for Industrial Practitioners

Machine vision is successfully applied to various industrial inspection problems. It helps industry obtain that which is unobtainable using human operators. For example, the vision system can work throughout the day without becoming exhausted. Furthermore, some applications require high precision and consistency which is hard to achieve when employing an ordinary human inspector, but which is easy to achieve using machine vision. Also, certain industrial applications may have a negative impact on human beings whereas they will not affect the vision system. Ultimately, it allows industry to detect defects, leading to repeatability of inspection results, reliability in products or WIP and to consumer confidence and satisfaction.

In the global trend towards 100% inspection, vision systems are becoming increasingly important. New applications for these systems are being reported every day. Therefore, the future direction of vision systems is being transformed from solving shop floor inspection problems using standard tools to advanced and integrated solutions which inspect, solve, record, document and store. The emphasis of vision systems is now on assisting in effective quality decision making and proactive quality control. MVES can provide three main functions and steps to enable industrial practitioners to address this new emphasis: (i) solving challenging vision-based problems; (ii) automatic statistical quality monitoring and outlier monitoring; (iii) providing systematic information handling and storage.

Clearly, there are significant advantages associated with the use of evolutionary algorithms and other emerging technologies. The important issues in MVES are brought into focus when the inspection problem can be solved effectively by adopting an evolutionary approach and when the resulting data are integrated and stored systematically for future retrieval. MVES gives a quality team the opportunity to move back to the beginning of a chain of procedures to indentify the key reasons and characteristics leading to failure, thus, proactive action can be taken to prevent any failure in future processes. This automatic control which charts functionality and information handling protocols, can greatly reduce the workload and processing time. This saving means that decisions regarding quality can be made more efficiently and the focus can be extended to the monitoring of other aspects of the process. It is foreseeable that with the use of the proposed approach at the managerial level the inspection data can be transformed into integrated information, to aid in solving quality problems. In addition, the flexibility of the generic structure of 4 modules is illustrated in the case studies. MVES has been proposed to solve the PCB components detection problem with DCM, PAM, ISM and MM. MVES has also been proposed to enrich video data with identification in a goods tracking problem.

Since quality monitoring is not necessary in the second case study, only 3 modules, DCM, PAM and ISM, have been involved. Thus, the flexible infrastructure of MVES can be used to solve monitoring problems and aid in enhancing the operational performance based on different industry requirements.

6.3 Limitations of the Research

In this research, chaos-based PSO algorithms are proposed and the focus is on solving vision-based problems. These algorithms are designed to be applied in cases where the vision-based problem cannot be fully solved by ordinary machine vision techniques and image processing tools. If the inspection problem is not properly formulated, the evolutionary approach is inappropriate and may reduce the accuracy and reliability of the results. In general, there are multiple concerns in an inspection task. The design and application approaches can be slightly varied case by case. However, if the inspection task is simple and the problem dimension is low, solving the formulated problem using the chaos-based PSO algorithms is not suggested because a simple method using the ordinary techniques and conventional approach can meet the requirements.

The particle number (swarm size) used in the CPSO and CSPSO algorithms can vary, so the species radius in the CSPSO algorithm needs to be adjusted accordingly. In order to provide adequate searching ability to find the optimum while maintaining a reasonable computation loading, the recommended range of particle numbers is 50 to 150. The chaos-based PSO algorithms can be modified in the future by allowing for the swarm size and species radius (for CSPSO) to be adaptively adjusted. Furthermore, the determination of the required image pre-processing and processing tasks by relying on the knowledge of experts in the professional development team is quite time-consuming and subjective. Another useful technique based on artificial neural networks, which remembers previous system settings and then derives a suggested setting automatically, is recommended in order to enhance the deployment of the proposed system.

6.4 Discussion of MVES in Two Case Studies

To test the feasibility of the infrastructure of the proposed system, two case studies, provided by two separate companies, have been conducted. These have been described in previous sections.

The supervisor who is in charge of the PCB manufacturing process pointed out that the most common type of inspection that has been done for years on the assembly lines involves sorting out the defective items from the acceptable ones. However, this is a method of creating quality by inspection rather than an effective quality control approach. Using this approach, the rejects are only considered as scrap or are sent to be re-worked. Although this assures that only the up-to-standard products or parts reach the next stage, it does not address the cause of the failure nor the status of the process (whether it is stable or not). Thus, sorting out failures can be considered as an inefficient method to get good quality goods. In addition, many inspection data are not recorded or collected from the inspection station. In some cases, the data is collected manually, which introduces human error such as duplication or incomplete data. It makes it hard to perform a systematic analysis and makes it hard to store the data in such a way that it can be retrieved for tracing back in the future.

Another supervisor in the logistics company pointed out that if there is lack of monitoring a company can never identify where most problems occur in a process and so the cause of problem can never be discovered. At the end of a process, the inspection can only give a final decision of whether or not the items are good. No investigation can be done afterwards. Also, it harms the company in that it creates an acceptance of a certain level of failure. This acceptance subtly creates an atmosphere of accepting failure at every stage of every process undertaken by the company.

It is obvious that a company has to maintain an awareness of developments in quality control by deploying appropriate technology to maintain and enhance not only the quality of the goods produced by the company but also the operational performance. Therefore, there is a need to provide a systematic approach to tackle vision-based problems and handle the corresponding data in order to achieve efficient quality decision making and proactive action.

There are two implications of the proposed schema and the feasibility tests conducted in the case studies. Firstly, the schema offers a novel approach, which combines machine vision, evolutionary algorithms and SPC to deal with emerging vision-based inspection problems existing in the PCB assembly process that are time-consuming and hard to solve using traditional approaches. This new approach paves the way for future research along this line of attempt. Secondly, it demonstrates that a simple and flexible infrastructure can be applicable to solving different types of vision-based problems in electronics manufacturing and logistics areas such as the components inspection problem in the first case study and the monitoring problem in another case study. The problem identified in the second case study is not purely inspection-oriented, it relates to enhancing the quality related to the goods being transferred and to the information handling issues. This is a feasibility test in applying the proposed system with the evolutionary based approaches, but it offers some proof that it is feasible to provide effective solutions beyond visual inspection.

Effective inspections can be conducted at intermediate stages in the process. These inspections give statistical information necessary for monitoring the process and for determining the cause of the quality problem, so that failures can be prevented in the future. Also, the integrated information can be retrieved easily for further investigation or track-and-trace. More research along these lines is necessary if a suitable technique or approach is to be found to achieve further enhancement in quality control and operational performance in an organization.

Chapter 7 Conclusions and Future Work

7.1 Summary of the Research Work

In recent years, attention has been focused on automated vision-based inspection systems which have shown great promise in supporting quality inspection. However, there are still two major obstacles to deploying vision systems because they are designed to separate and isolate the inspection tasks and do not consider the integration of inspection information. Thus, existing systems usually create quality by careful inspection so as to maintain a quality level rather than support quality decision making and quality monitoring. The aim of this research is to propose a schema for designing MVES using evolutionary approaches. The proposed MVES incorporates machine vision, the proposed chaos-based algorithms and other technologies to overcome the challenges of an environment where every company seeks for high quality output and high operational performance. The principle and infrastructure of MVES, featuring the incorporation of DCM, PAM, ISM and MM have been designed and proposed in order to conduct feasibility tests based on two case studies provided by an electronics manufacturer and a logistics company, thereby providing solutions to address the problems identified in the cases. The unique features of MVES focus on solving emerging vision-based problems using a systematic approach for handling the output data so that the organization can subsequently retrieve useful information for further investigation or data mining. Thus, MVES provides not just an inspection function but aims at providing a way to solve challenging vision-based problems and to maintain the standard of quality at the same time.

7.2 Contributions of the Research

This research provides a generic approach to the design of MVES with an ability to handle the corresponding information systematically in order to support proactive quality control and quality decision making. This will also help to develop an innovative approach for solving emerging vision-based problems in other areas. Some contributions, as a result of this research are summarized below.

(i) This research proposes a new schema for establishing cooperative linkages among machine vision, evolutionary computation and other technologies to create an integrated system to support quality decision making and to enhance operational performance. The unique features of MVES are the provision of support for solving vision-based problems, managing output data, plotting control charts, and integrating useful data for efficient storage and retrieval. Thus the concept of inspection (sorting out failures) can be extended to support quality decision making and to improve operational performance.

(ii) The performance of the proposed chaos-based PSO algorithms has been fully illustrated in Chapter 2. In the benchmark tests, CPSO and CSPSO can be considered as more stable and effective approaches to solve single modal and multi-modal optimization problems. Consequently CSPSO has been proven to be an effective means in solving the template matching problem and circle detection problem. The proposed method in template matching is useful in many areas such as the quality inspection of PCBs. On the other hand, the proposed circle detection method can address the drawbacks of the conventional circle detection method, such as the need for prior information on the radius range when using the Hough Transform-based method.

(iii) The performance of the proposed algorithms has been demonstrated in benchmark tests and in simulation tests for template matching and circle detection, indicating that this approach could be deployed in other vision-based and imaging problems for achieving the same success. The CSPSO algorithm has been applied to solve the PCB components detection problem. The proposed CSPSO-based MTM method is 30 times faster than the conventional NCC exhaustive search method and it also gives a zero FP rate and a higher success rate. The CPSO algorithm has been applied to solve the video data enrichment problem. The proposed CPSO-based DCT digital watermarking method can give very satisfactory results in terms of fidelity and robustness. The proposed chaos-based PSO algorithms provide an opportunity to solve the other vision-based problems, which cannot be fully solved or cannot be solved efficiently by the standard approaches, and can fulfill different industry requirements.

(iv) The protocols for information handling are essential for generating, gathering, integrating and storing the data from single or multiple inspection stations. Missing data or redundant data may add extra cost to a company in passing, processing and retrieving the data. The proposed protocols enable efficient data collection with three different schemes for selection based on the existing infrastructure available in the workplace or factory floor. This is a contribution to managing the data systematically, integrating the data and storing the information for future retrieval and investigation. So, improvement opportunities of the quality control and operational processes can now be identified more effectively than previously.

(v) This research has led to the development of MVES, which encompasses the evolutionary algorithms and chaos theory, and embraces machine vision and SPC to support efficient quality decision making and achieve operational performance improvement. Testing of the feasibility of MVES in the PCB components inspection problem and in the goods tracking problem, through the demonstration in two case studies, have been successful. This indicates that evolutionary approaches can be used to solve vision based problems, as well as tackling real world problems in the industries. Also, this may indicate that the approach has the potential to be deployed in other industries for achieving the same kind of successful outcome.

7.3 Suggestions for Future Work

Some of the characteristics of the proposed algorithm and system to be investigated in future research are as follows:

(i) The feasibility of the proposed system has been studied and demonstrated in case studies from PCB manufacturing and logistics. However, the principles and techniques can be further extended to different industries, with modifications, for solving new vision-based problems. In order to obtain accurate and reliable results, the proposed system still requires experienced programmers and a professional development team to formulate the problem and setup the vision system.

(ii) The proposed chaos-based algorithms basically consists of two major parts. In the first part, the chaotic dynamics is incorporated into PSO algorithms, so that the search behavior can be enhanced. As the tent map shows, it has outstanding advantages and higher iterative speed, so it is more suitable for the uniform distribution function in the interval from zero to one. Thus, chaos variables are generated using the tent map for initialization in this research. Besides the initialization, the inertia weight of PSO algorithms affects the performance. The chaotic map could be useful in determining the inertia weight of PSO algorithms. Along this line, the challenges lie in how to select the appropriate chaotic map so that the performance of PSO algorithms can be further enhanced in accordance with the specific problem context of domain applications.

(iii) In the second part, the challenges lie in how to select the most suitable parameter for the species radius of the CSPSO in accordance with the specific problem context of domain application. For example, in the multiple template matching process the best way could be to determine a suitable radius adaptively during the process. To do this the effects of interaction between the radius parameter, image size and template size need to be studied.

(iv) In the matter of choosing protocol alternatives and required image pre-processes and processing tasks, a knowledge-based module can be developed to select and suggest suitable ones. Since each alternative has its own advantages and disadvantages, the module can be used to select the appropriate alternative to use in a given situation with the aid of an artificial neural network which remembers previous successful system settings.

(v) Further research on the infrastructural configuration of the proposed system is required in order to further provide its benefits to different areas. In general, this research work paves the way for a new approach to dealing with vision-based problems such as inspection and monitoring. It does this by using evolutionary approaches with machine vision technology, digital watermarking techniques and SPC. It is recommended that researchers utilize the untapped evolutionary algorithms to solve other emerging problems, with the aim of supporting quality decision making and improving operational smoothness. Ultimately, this can help companies to maintain an awareness of new developments in quality control and operational performance.

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Appendix A- The Control Chart Selection Guide

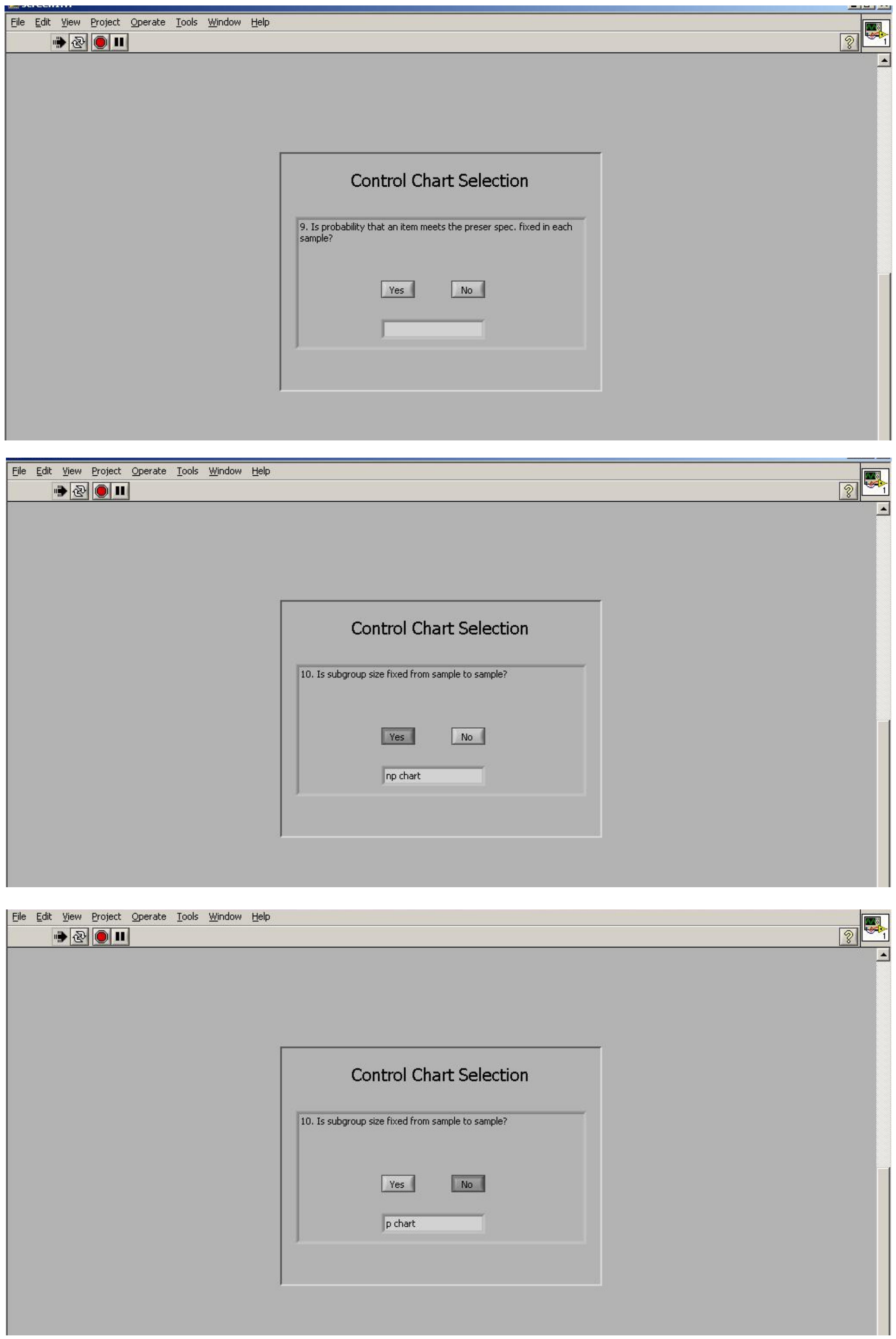
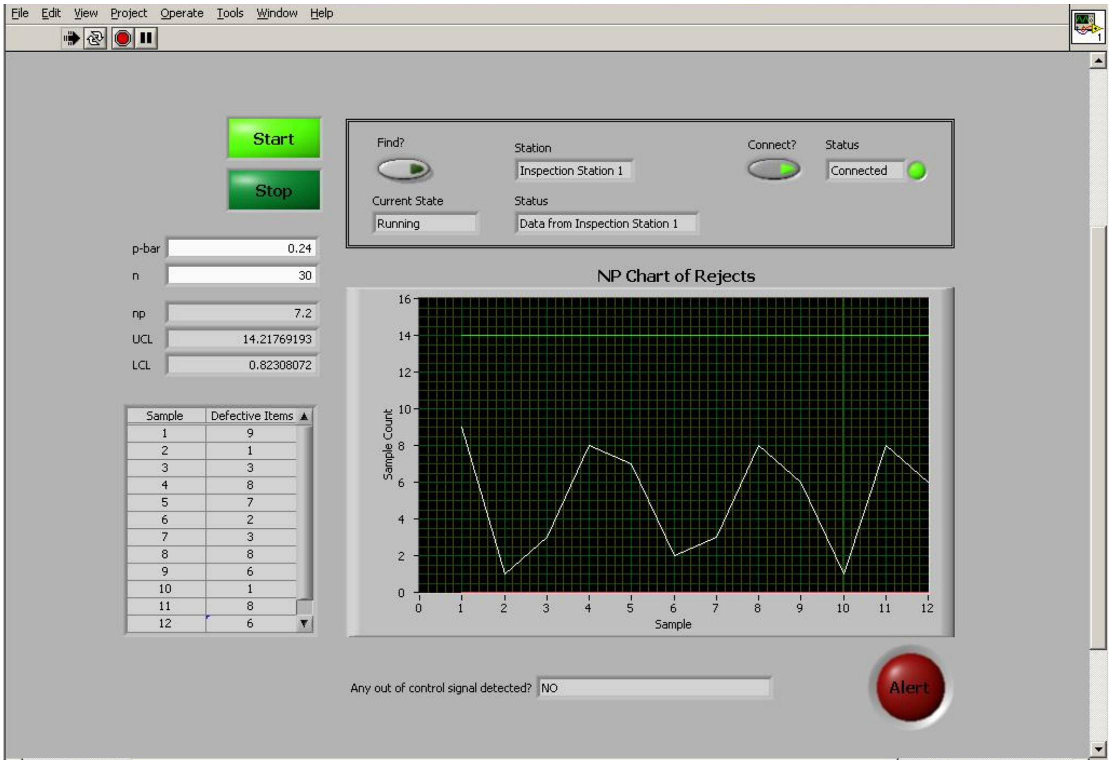


Figure A.1 Snap shots of control chart selection

Appendix B- The Snap Shot of the Control Chart and Process Monitoring



Sample	Defective Items
1	9
2	1
3	3
4	8
5	7
6	2
7	3
8	8
9	6
10	1
11	8
12	6

Figure B.1 The snap shot of a np chart