# COLLABORATIVE FIXTURE DESIGN AND ANALYSIS SYSTEM WITH ROBUSTNESS FOR MACHINING PARTS


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# Summary


Reducing the product lead time and improving the product quality are the two main strategies of a manufacturer to compete in the global dynamic markets. In this research, a distributed collaborative design environment with web services and web ontology has been developed for improving the product design efficiency, while robust design approach is adopted for improving product quality. In this thesis, fixture design application domain has been developed to illustrate the concept.

A distributed collaborative framework is first proposed for the fixture design and analysis system in order to enable designers across the geographical boundaries to collaborate seamlessly to complete a design. This system is developed using Web-Service-based service oriented architecture (WSSOA). The benefits of using WSSOA for the system are interoperability, platform-independence and language neutrality of web services and service-oriented architecture. Using the developed fixture design system, fixture designers can be guided to arrive at a fixture design with heuristic rules, and this design can be evaluated by collaborators with fixture analysis module. This system also provides flexibility for expert designers to design complicated fixtures.

Ontology models are then developed for knowledge representation in the domain of fixture design. The following ontology models are developed to facilitate the fixture design process: 3D parametric feature-based geometric model, manufacturing related setup planning, fixture synthesis, and FEM-based fixture analysis. The ontology models are developed using the Web Ontology Language (OWL) to facilitate the

exchange of information among applications in a dynamic environment. Web ontology enables not only seamless integration of various applications in a distributed collaborative platform, but also effective information exchange between upstream applications and downstream applications, viz. fixture design and fixture analysis.

A robust fixture localization approach is first developed using Taguchi's method to explore the effects of surface tolerances, which arises due to dimensional and geometrical variations, on optimal location of a workpiece. Fixture-workpiece models and evaluation criteria are also developed for robust fixture design. In these models, workpiece surface errors, setup errors, deformation at contacts and fixture elements deformation errors are considered as source input. The evaluation criteria measure the product quality based on sum square of point deviation or directional point-wise manufacturing error. These evaluation criteria are frame-invariant, which means the value does not change with the change of coordinate system.

In addition, two optimization methods, a modified genetic algorithm and a modified particle swarm optimization, have been developed for the robust fixture design process. Both developed algorithms can be used to explore the 3D surface space and the clamping force range to search for optimal points and force values for robust fixture design. These developed algorithms are also deployed in the developed system.

A case study to illustrate the developed collaborative fixture design and analysis (CFDA) system is finally presented. In this case study, the collaboration between fixture designer and fixture analyst is realized through the developed CFDA system. Meanwhile, the developed ontology model facilitates information exchange in the system and the developed robust design module helps a user select fixturing contact points.

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# List of Abbreviations

| | |
|---|---|
| CAD | Computer Aided Design |
| CAFD | Computer Aided Fixture Design |
| CORBA | Common Object Requesting Broker Architecture |
| CSG | Constructive Solid Geometry |
| DCOM | Distributed Component Object Model |
| DL | Description Logics |
| DTD | Document type definition |
| FAC | Fixture Analysis Control file |
| FBC | Fixture boundary condition file |
| FD | Fixture Design |
| FEA | Finite element analysis |
| GA | Genetic Algorithm |
| GCS | Global Coordinate System |
| HTML | HyperText Markup Language file |
| FDC | Fixture design configuration file |
| CFDA | Collaborative fixture design and analysis |
| J2EE | Java 2 Platform, Enterprise Edition |
| JNI | Java native interface |
| JVM | Java virtual machine |
| KPC | Key Product Characteristic |
| MC | Model compression |
| MSE | Mean Square Error |
| OA | Orthogonal array |
| OCC | Open Cascade |

| | |
|---|---|
| OWL | Web Ontology Language |
| PCL | Patran command language |
| PSO | Particle Swarm Optimization |
| RD | Robust Design |
| RDF | Resource Description Framework |
| RDFS | Resource Description Framework Schema |
| RMI | Remote Method Invocation |
| SOA | Service oriented architecture |
| SOAP | Simple Object Access Protocol |
| SQL | Structured Query Language |
| STEP | Standard for the Exchange of Product model data |
| Sts | Status file |
| TopoDS | Topology descriptor |
| UDDI | Universal Description, Discovery, and Integration specification |
| VMC | Vertical Machine Centre |
| W3C | World Wide Web Consortium |
| WCS | Workpiece Coordinate System |
| WSDL | Web Service Description Language |
| WSSOA | Web-Service-based Service-Oriented Architecture |
| WWW | World Wide Web |
| XML | Extensible Markup Language |

# Chapter 1 Introduction

> *"We are definitely pressured to get to design release more quickly in order to keep up with the competition. We need to get to market first to win market share. We're turning to simulation to minimize our testing phase of product development."*
>
> -- *Jay Abrams, Elgin Sweeper Company*

The advent of dynamic markets, customer demands and product development competition point towards a need for lower cost, shorter product lead time in the fiercely competitive global industry. In response to this pressure, manufacturers are following two main strategies: *improving product performance or quality* and *improving development efficiency* [1]. Physical prototyping is still widely adopted for product testing and verification in the traditional product development process. However, building and testing physical prototypes is expensive and time consuming, and could slow down the product development process. Thus, computer simulation and analysis is becoming more and more important in product development processes in helping designers understand the physical behaviors of the product, improve product quality and make decisions especially at the early stage of product development.

In order to improve development efficiency to cater for the faster and higher demand of new and customized products, companies are required to collaborate with each other to gain competitive advantages. Distributed collaborative design and manufacturing environment helps globally distributed manufacturing organizations with different expertise to join together to design and manufacture a product rapidly.

Fixtures are extensively used in every stage of manufacturing for holding the workpiece during machining, assembly and inspection operations. One of the primary reasons for the emphasis on fixturing is that it plays an important role in product quality control in the product developing and manufacturing process. According to the statistical report on the American automotive industry, about 73% of variation problems from pre-production to the production phase were caused by fixture related problems [16]. In extreme case, 20-60% of the total machining errors were caused by setup error in which the major part is the fixture error [124]. Therefore, improvement in fixturing and the fixture design will reduce product faults in manufacturing.

In this research, robust design approach is adopted for improving product quality while distributed collaborative design framework is used for improving the development efficiency. In this chapter, Section 1.1 introduces what the fixture is, fixture design approaches and problems current fixture design is facing. Section 1.2 presents robust design approach and why it is utilized in fixture design. Section 1.3 discusses the reasons why distributed collaborative systems are required and the issues that need to be addressed to facilitate distributed collaborative systems. The first three sections provide background and motivation of this thesis and Section 1.4 presents an overview of the organization of the thesis.

## 1.1 Fixture Design

Fixtures are devices which are designed to repeatedly and consistently maintain the orientation of a workpiece during machining, assembling, welding, inspection, *etc*[73].

As they hold and properly locate a workpiece during machining, they also ensure that all the work produced using the same fixture will be identical within acceptable tolerance ranges, even with unskilled workers. They are an essential part of manufacturing production. The primary components for a typical machining fixture are a baseplate and a number of locators, supports and clamps. Locators and supports are passive fixture elements used to position the workpiece and restrict movement of the workpiece in static equilibrium. Supports in this thesis are referred as vertical locators. Clamps are active fixture elements to provide clamping forces onto the workpiece so that they can resist external forces generated by the machining operations. Figure 1.1 shows a typical machining fixture system with a workpiece and fixture elements.

Figure 1.1 A machining fixture system (source: www.hohenstein-gmbh.de)

Fixture design is a highly complex process because it must consider the workpiece, the cutting tools, the machining environment and the components that interact with each other. Senthil Kumar *et al.* [96] illustrated all factors considered in fixture design that are categorized into three basic constraints, including technical, economical and resource availability. As part of manufacturing tooling, fixture design not only makes significant contributions to the production time and cost in daily production, but also plays an important role in product quality control.

In general, a machining fixture design should meet the following essential requirements [35]:

- **Accurate position**: A workpiece must be located accurately in a fixture with respect to the machine coordinate system and the workpiece coordinate system.
- **Total restraint**: The fixture must hold and restrain the workpiece from the external force, e.g. cutting force.
- **Limited deformation**: When a workpiece is under the action of cutting forces and clamping forces, additional adjustable-locators or adjustable-supports are needed to reduce deformation of the workpiece.
- **No interference**: None of the fixture elements should interfere with any of the machining operations. At the same time, interference among fixture elements should be avoided.

In general, there are three phases involved in the design of a fixture: problem description, fixture analysis, and fixture design synthesis [6]. Extending integration of these phases will improve the computer-aided fixture design (CAFD) system and help designers explore the design space more efficiently and effectively.

## 1.2 Robust Design

Traditionally, fixture designers have relied heavily on experience and expertise in designing the most suitable fixture for a workpiece. This approach lacks efficiency as manual fixture design is starting to be time consuming, where the product lifecycle is getting shorter. Hence, computer aided fixture design techniques began to develop extensively during the 1980's, followed by a series of deterministic studies, to expedite the process of fixture design, as well as to improve the quality and efficiency of fixture design. Nonetheless, much research work was focused on the automated generation of locating schemes for fixtures [43, 50, 93], and neglected various dimensional and geometrical variations during the mass production. This research aims to address such variations through the application of the robust design technique to improve the quality of designed fixtures.

In order to improve product performance or quality, uncertainty is an important factor for designers to consider when making decisions regarding design specifications. For managing the sources of uncertainty discussed above, two main approaches are available. One approach is to reduce the uncertainty itself. This is only feasible when a designer has large amounts of data or complete knowledge of a system. The other is to design a system to be insensitive to uncertainty without reducing or eliminating it in the system, and such a process is called robust design. In other words, robust design is used to make the system response insensitive to uncontrollable system input variables, thus improving the quality of a designed product.

## 1.3 Collaborative Design Environment

In industry, development of new fixturing solutions for complex workpieces is still based on designers' experiences and involves manual prototyping and testing. This leads to higher costs and longer lead-times, especially when ineffective fixture designs have to be iteratively improved, prototyped and re-tested.

In today's product development context, part of product design activities are sub-contracted out to other firms in order to rapidly design the product and reduce design lead time. As a consequence, this enables the companies to maintain competitiveness in a fiercely competitive global industry. Meanwhile, this also creates a scenario where the designers and manufacturing engineers may be globally dispersed. Therefore, to realize a collaborative functional fixture design system, care must be taken such that the design activities can be performed on the internet.

On the other hand, a successful fixture design always involves multi parties' participation, including fixture designer, process planners, shop schedulers, machining engineers, analysts etc. When developing new fixturing solutions for complex workpieces, fixture designers are required to pass the initial design to the analyst for verification and validation. The analyst evaluates and simulates the performance of the current fixture design using computer simulation method, e.g. finite-element method (FEM), and then feeds back results to the fixture designers. Fixture designers can then adjust the design based on simulation results. This creates a collaboration scenario.

In order to facilitate a distributed collaborative design environment, a number of issues need to be addressed:

- *Compatibility problems*: In today's product development environment, team members from different companies work together to realize a product. However, the use of different software may cause a compatibility problem.
- *Collaborative platform for the fixture design process*: This will ensure timely information sharing, maintain data consistency and enable globally distributed organizations to effectively collaborate and finalize the fixture design
- *Managing information exchange in the fixture design process*: Product design data and knowledge are not only managed by the design and production activities, but also required in the downstream applications of the product development process to carry out their tasks. Meanwhile, upstream applications need feedback information from the downstream applications for

validation or optimization.

Therefore, the main objective of this research is to develop a collaborative fixture design and analysis (CFDA) system incorporating the robust techniques.

## 1.4 Organization of the Thesis

This chapter has discussed the underlying motivation of this research and presented approaches adopted by this thesis. The rest of this thesis is organized as follows.

Chapter 2 conducts reviews on the distributed collaborative design systems, ontology modeling and related research on robust fixture design. Based on the literature review, the objectives of this thesis are identified.

Chapter 3 presents the application framework for the distributed collaborative fixture design system.

Chapter 4 describes the information model not only for enabling distributed global enterprise to reach collaboration effectively, but also for integrating disparate phases and sharing knowledge through the fixture design process.

Chapter 5 studies fixture locating with robust design approach by combining Taguchi method and Monte-Carlo statistical method in order to increase quality of final machining workpieces, so that the layout could be robust and insensitive to the errors.

Chapter 6 introduces a robust design method with genetic algorithm to minimize point-wise manufacturing errors on the machining features and thus to improve product quality by simulating locating process with Monte-Carlo statistic method.

Chapter 7 presents the development of robust fixture design considering clamping forces and contact deformation using a hybrid of particle swarm optimization and genetic algorithms.

Chapter 8 presents a case study to explain in detail the developed system.

Chapter 9 concludes this thesis by presenting the research contributions. It also discusses the potential of future works, both in terms of how the current fixture design system could be enhanced, and the directions in which this thesis could lead to future research.

# Chapter 2 Literature Review

## 2.1 Distributed Collaborative Design Systems

Product design is typically a highly iterative activity involving a group of designers. It is ideal to have all the collaborating designers at the same geographical location within the enterprise. However with the advent of Internet technologies and evolution of electronic design tools, companies often outsource engineering activities to rapidly design and prototype the product and hence reducing product design lead times. This enables the companies to maintain competitiveness in a fiercely competitive global industry. Thus in a global manufacturing scenario, there is a need to maintain data consistency across heterogeneous systems and to enable effective communication among collaborators.

When a product is designed through the collective and joint efforts of many designers, the design process may be called collaborative design (it may also be called co-operative design, distributed concurrent design and inter-disciplinary design) [114]. In order to realize the collaborative design, a collaborative CAD system is required. Such a system needs two kinds of capabilities and facilities: distribution and collaboration. Physically the former separates CAD systems as being geographically distributed but expands them to support remote design activities. Functionally, the latter associates and co-ordinates individual systems to fulfil a global design target and objective. Distributed technology is fuelled by the development of IT technologies such as Java, Java, .Net, Web, XML and Web service technologies, and collaboration is driven by the design and development of effective collaboration mechanisms to facilitate human-to-human/human-to-computer relationships. Although these two facets (distribution and collaboration) have different focuses, they are closely inter-related and complementary. A collaboration mechanism needs a specific design of a distributed architecture of a system to meet the functional and performance requirement. Different collaboration scenarios have been discussed below

### 2.1.1 Collaboration Scenarios

Different scenarios for collaboration are shown in Figure 2.1, *i.e.* common access to design information, collaborative visualization, co-design, and concurrent engineering (CE) based collaboration. They are described as follows.

- *Common access to design data* – This is achieved by sharing product data [20, 86]. There is no real time visualization of component and the data is downloaded from the centralized information system.
- *Collaborative Visualization* – This enables real time visualization of 3D geometric model between designers [99, 134]. These are primarily web based light weight collaborative systems using formats such as VRML, X3D, etc. The models are for visualization only and cannot be modified. System infrastructure is usually built using Java 3D, since it is widely used to realise 3D programming environment in many systems. To enhance the communication between different collaboration tools such as white board, net-meeting and discussion forums are used.
- *Co-design* – This approach allows geographically distributed systems to visualize and modify the product. For example, Su *et al* [103] proposed a system where the designers work together with the same solid model in a

commercial CAD system. Normally server side programming or hybrid client server architecture is widely used. Collaboration tools such as Net-meeting, white board is commonly used. Main challenges for effective collaboration include efficient data management to optimise data sharing, transmission and management. Also effective strategies need to be developed for proper team organization, coordination and negotiation.

- *CE-based collaboration* – Figure 2.1(d) shows a simplified example of CE-based collaboration. CE-based collaboration facilitates communication and data transfer between upstream design operations and downstream manufacturing activities. Within CE, a designer can consider and evaluate downstream manufacturing processes of the product life-cycle in the initial design phase. Web services and multi-agent systems are popularly used for system integration and co-ordination. Examples in this category include agent-based virtual prototyping environment developed by Xiang *et al* [128]. In [128] the virtual prototyping agent was developed for fluid power system development. It consists of Domain agents (DAs), which represent for components and control agents (CAs), which is for facilitating communications and activities of Das. Rodriguez and Al-Ashaab [89] developed remote simulation systems for collaborative mould design to provide efficient response to markets for higher markets. In the systems, simulation tools for mould manufacturability are embedded for on-line invoking. Current research is based on improving the infrastructure in terms of flexibility, adaptability and extensibility.

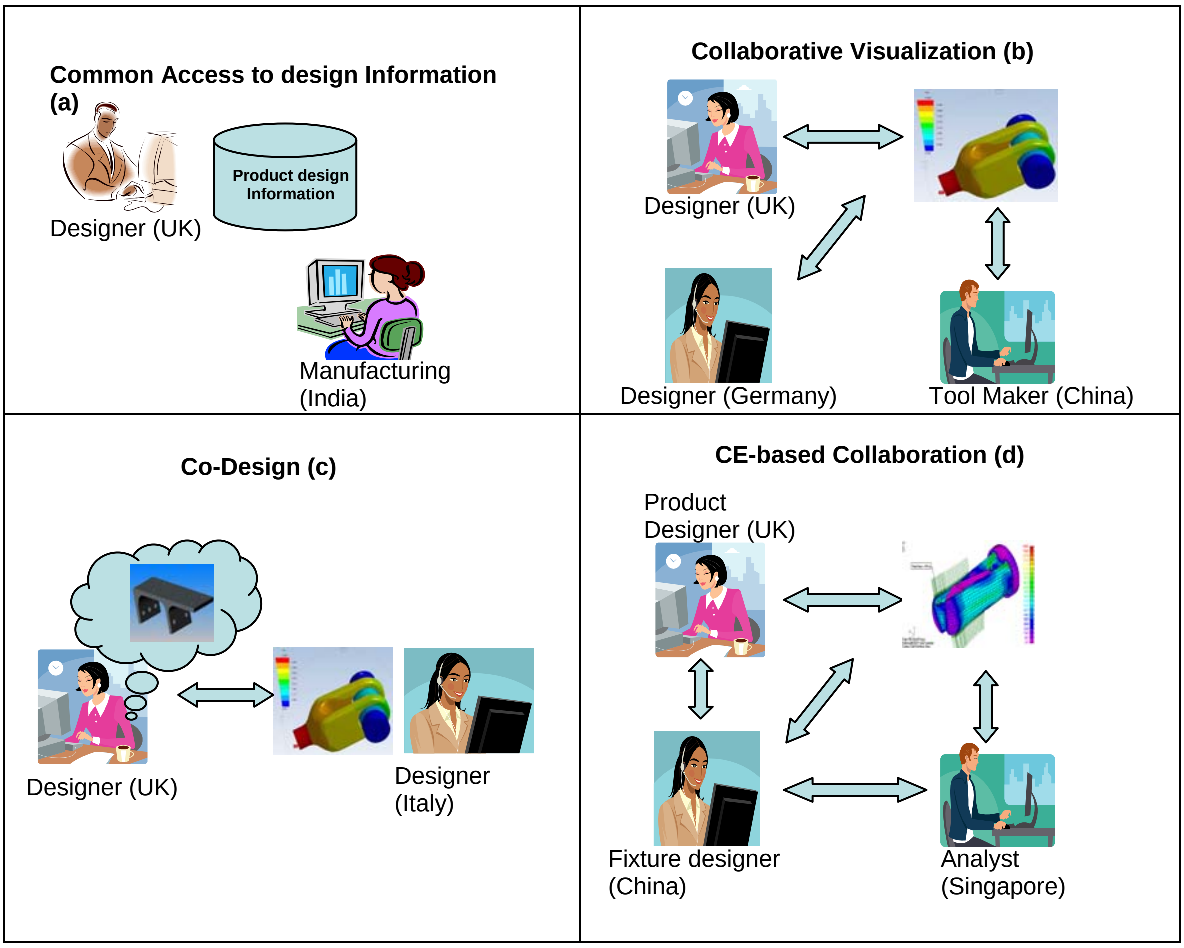



Figure 2.1Distributed collaborative design approaches

### 2.1.2 Distributed Systems Architectures

Various distributed collaborative applications have been reported for different engineering domains using various system architectures. The architecture of collaborative systems can be divided into three types based on the coupling degree of visualization and geometry kernel, as well as system openness and extensibility. These three types are tightly coupled structure, middleware based coupled structure and loosely coupled structure.

In the first type, the whole geometry kernel is put in each client and the central server plays as an information agent and exchanger to broadcast CAD model and commands generated by one client to other clients [21, 72, 76, 82, 87]. The tightly coupled structure is simple and easy to realize. Standard CAD systems can be conveniently distributed through this mechanism. However the interfaces between systems must be customized and the communication protocols are to be strictly matched. Any change will lead to re-compiling and re-deploying of all program modules.

Middleware, in general, is a set of layers that sit between application and commonly available hardware and software infrastructure in order to make system structure more flexible and more extensible. In the middleware-based structure, the geometry kernel and the models reside in server and clients are light-weighted interface used to display visualization model only [5, 30, 49, 55, 60, 65, 112]. Some of the data processing logic is enclosed in the middleware, which makes the coupled systems more independent. In this way, data consistency is easily kept since the primary models are created and maintained in the server. Some recent technologies like CORBA, Java RMI, and Microsoft's DCOM are used to implement a distributed collaborative system. Mervyn et al [65-66] used the middleware approach for developing an integrated product and process design (IPPD) system. However, the incompatibility of interface and communication protocol among the technologies has become the main barrier of collaboration among heterogeneous systems. Therefore, a loose-couple system is developed to overcome the problems.

In the loose-coupled system, the components are not fully dependent on or have minimum interaction with each other. Peer-to-peer system, agent-based system and service-oriented architecture (SOA) system are in the scope of this system. The peer-to-peer (P2P) collaborative design systems provide avenues for the users to share and manipulate collaborative engineering applications. Inventor collaborative tool[1] support the sharing of services or modules of a system manipulated by other systems based on the P2P architecture. Aziz et al. [4] employed the semantic web initiative format RDF to manage knowledge in a peer-to-peer design environment using JXTA.

In an agent-based collaborative design system, agents have mostly been used for supporting co-operation among designers, providing semantic glue between traditional tools, or for allowing better simulations. Most agent-based system use P2P architecture. Development of various agent-based systems have been reported and includes process coordination [64], system interoperability [131], knowledge collaboration [105], and conflict management [18]. Shen et al. [100] provided a detailed discussion on issues in developing agent-oriented collaborative design systems and a review of its significance. However, in a distributed environment, an agent system typically has some pitfalls: lack of scalability, robustness and security [122].

SOA separates functions into distinct service units. These application services are loosely coupled, independent, and can be distributed across a network. They can be combined and reused to create business applications. SOA can be implemented using several technologies, but the most common choice today is the use of web services. Web services provide a standard means of interoperating between different software applications, running on a variety of platforms and/or frameworks [113]. The main technologies of web services like SOAP, WSDL and UDDI are all based on XML that forms the basis of web services' platform-independent and provides language-neutrality. Thus, web services show undoubted advantages in addressing heterogeneity.

[1] http://www.autodesk.com

There are many advantages of web-service-based SOA (WSSOA) for distributed collaborative applications, such as flexibility, scalability and reusability. A loosely coupled architecture allows you to replace components, or change components, without having to make changes to other components in the architecture/systems. This means businesses can change their business systems as needed, with much more agility than if the architecture/systems were more tightly coupled. With this degree of independence, components are protected from each other and can better recover from component failure. If the SOA is designed correctly, the failure of a single component should not take down other components in the system. Thus, loose coupling creates architectures that are more resilient.

The most crucial advantage of WSSOA is widespread interoperability, which means clients and loosely coupled services can communicate with each other regardless of the platform being used. This characteristic can be of great use in distributed collaborative applications, since it aims at supporting team members from different domains to accomplish the design task using the heterogeneous platforms. Based on the current main frameworks supporting web services, J2EE and .NET, the software development industry has provided several SOA platforms, such as IBM's WebSphere [120] and Microsoft's BizTalk [69].

However, the integrated platforms mainly involve in e-bussiness and e-government, and do not have the specialized characteristics for engineering domain. So far, only few research works have employed web-service-based SOA for distributed collaborative design & manufacturing. Shen et al [101-102] proposed a service oriented integration framework used to establish a dynamic collaborative environment for manufacturing resources sharing based on software agents and web services. Dong et al [25] also proposed a web-based extended manufacturing resource service for product development with SOA. In order to facilitate design and manufacturing process integration and coordination, Kim and Chung [45] presented a framework to support design & manufacturing process collaboration using web ontology and web services.

## 2.2 Ontology Modelling

In order to seamlessly integrate different modules and applications in an integral distributed collaborative environment, the information model should be represented at knowledge level. This is because a knowledge model helps us to clarify the structure of intensive knowledge and information processing tasks. In other words, a knowledge model provides a specification of data and inference processes required by the system. Moreover, one of the major challenges in the distributed collaborative environment is the communication among applications. In content level, this communication language is required to be platform independent, programming language neutral and machine interpretable. In order to enable intelligent decision making, this language needs to have enough expressive power to formally encode a wide spectrum of knowledge ranging from design constraints to design axioms.

In this research, an ontology representing domain knowledge in fixture design process is developed. This ontology is encoded using the Web Ontology Language (OWL) [2], a formal language representing knowledge and reasoning. An ontology is a taxonomy of concepts and their definitions supported by a logical theory (such as first-order predicate calculus). An ontology is originated primarily for the purpose of knowledge sharing [31].

[2] http://www.w3.org/TR/owl-features/

OWL developed by the Semantic Web group at World Wide Web Consortium (W3C)[3] is currently the most expressive language for explicitly representing, specifying, publishing and sharing ontologies. Like other languages of the Semantic Web, such as eXtensible Markup Language (XML)[4], Resource Description Framework (RDF)[5], *etc*. OWL possesses the same features: explicitly expressing information meanings, machine processible and interpretable, and easily exchanging and integrating information on the Web. OWL supports more vocabularies and semantics than XML, RDF, and RDF-S[6] and thus has greater ability in interpreting the content on the Web by machines. OWL provides three sub-languages – OWL Lite, OWL DL, and OWL Full – to support different levels of expressiveness. OWL Lite only supports simple constraints and classification hierarchy, while OWL Full provides the maximum expressiveness but do not guarantee the completeness (all conclusions are Therefore, OWL DL is employed in this work because it supports the maximum expressiveness and retains computational completeness and decidability.

OWL DL is so named due to its correspondence with Description Logics (DL) [7], which is a mathematically rigorous representation and forms the formal foundation of OWL. As a family of logic-based knowledge representation formalisms, DL enables ontologies to perform reasoning, including classification, query, checking consistency, concept equivalence, *etc*.

Many research groups have contributed to ontology modeling in engineering design and manufacturing. NIST developed Process Specification Language (PSL) [32] as an

[3] http://www.w3.org
[4] http://www.w3.org/XML
[5] http://www.w3.org/TR/2002/WD-rdf-concepts-20021108/
[6] http://www.w3.org/TR/2002/WD-rdf-schema-20021112/
[7] http://dl.kr.org/

interlingua for different manufacturing process applications to enable exchange of information. It focuses on only manufacturing related information data, thus the information model related to fixture design cannot be directly represented with it. Kim *et al* [44] developed an assembly design (AsD) ontology representing engineering, assembly and joining relations. The AsD ontology processed queries about assembly information and acted as a medium for selective assembly information sharing. Udoyen and Rosen [109] used DL concepts to describe archived FEA models and build expandable classification hierarchies for automatic retrievals. In their ontology, FEA models are represented through their distinguish characteristics such as components, structure, load and material. In order to improve the precision of search results, a classification-based search approach was developed using the DL-based classification service.

In the domain of fixture design, Mervyn *et al.* [68] tried to propose an information model of fixture design in an integrated product and process development but he failed to capture the information model at knowledge level. Hunter *et al.* [37] presented an approach for the partial reusing of a knowledge model for the fixture design process. This approach provided a way to reusing the knowledge defined in the different knowledge groups that integrate a model for fixture design. Similarly, Fan and Senthil Kumar [26] presented a model for the knowledge representation of fixture design. This model was used for implementing an Internet-based fixture design system with case-based reasoning (CBR). These two knowledge representations were diagrammed using Unified Modeling Language (UML)[8], a standard modeling language that is widely adopted by software communities to model application

[8] http://www.uml.org/

architecture, behavior, business process, and data structure. However, UML lacks logical foundation as ontology. In order to deploy an agent-based system in distributed environment, Ameri and Summers [2] introduced a formal ontology, called FIXON, for representation of the knowledge on the fixture design process. The proposed ontology supported knowledge reuse and seamless information exchange among machine agents. The work in this chapter shares the same research scope with them. However, our work is motivated by the ultimate goal of knowledge sharing and decision making between fixture synthesis and analysis.

Based on the system evaluations, Pehilivan and Summers [77] have concluded that the information flow to integrate disparate design phases should include: geometry information, locator information (number, type, orientation and position), material properties, machining information, applied forces, tolerance requirements and displacement information.

The design can be arrived with the distributed collaborative platform and ontology models for fixture processes, but robustness is not guaranteed. This will be addressed in Section 2.3.

## 2.3 Robust Fixture Design

Fixture design is a process to design a fixture for a given product and for a specific manufacturing operation with many manufacturing-related criteria and considerations. Usually, fixture design process involves with fixture analysis and fixture design synthesis. Fixture analysis involves the relational models among design variables, kinematic and dynamic constrictions, and performance evaluation; while fixture synthesis involves finding an optimal/feasible solution for a given workpiece during its machining with certain search strategies. Without exception for robust fixture design, optimization methods are used to search the best solutions for robustness and fixture-workpiece system models provide the criteria for performance evaluation.

### 2.3.1 Optimization Methods

With the wide applications of optimization methods in industry, fixture design optimization has gained more interests in recent years. Many research works have been conducted in searching for feasible or optimal solutions for fixture layout and/or configuration using certain technique, e.g. expert system [80, 95], case-based reasoning [96], generic algorithms (GA) [123], nonlinear-programming [3], etc.

However, some methods mentioned above still have some difficulties reaching automatic fixture synthesis. For example, the rule-based expert system is strictly limited to the initial rules created, which are static and serve as the primary means of reasoning, while the solutions from non-linear programming depend on the initial feasible fixture layouts and are sensitive to these initial layouts. Therefore, the trials on evolutionary algorithms (including GA) have provided a viable alternative. In this approach, fixture design is generally regarded as a complex multi-modal and discrete problem. Wu and Chan [123] applied genetic algorithms (GA) to the fixture configuration optimization: based on the information provided by the verification system, a genetic algorithm approach carries out the evaluation process to determine the most statically stable fixture configuration among a large number of candidates.

Krishnakumar and Melkote [50] presented the use of genetic algorithms in arriving at optimal fixture layouts. A finite element approach was used to evaluate generated fixture layouts. Vallapuzha *et al.* [110] used spatial coordinates to encode in the GA based optimization of fixture layout. They also presented the methodology and results of an extensive investigation into the relative effectiveness of the main competing fixture optimization methods, which showed that continuous GA yielded the best quality solutions [111].

Kaya [43] proposed an application of genetic algorithm to optimize the location of locator, support and clamp elements. In this study GA has been used to find the optimal locator and clamp positions in workpiece. The GA code has then been integrated with a FEA solver. In addition to optimizing fixture element layout for the entire tool path, the algorithm also considers chip removal effect during machining. However one of the main concerns while using GA is that computational cost can be very high since remeshing for the workpiece is required for every chromosome, therefore distributed computation in a local area network should be used to reduce computational time. Also this method has only been developed for simple 2D cases.

Mervyn *et al.* [67] developed an automatic fixture design system for modular fixture layout and configuration design using evolutionary search algorithms. In this research, modular fixture elements are used in fixture configuration and fixture solution is represented as tree-based structure. However, this method can only get feasible solution for fixture design.

Padmanaban and Prabhaharan [75] compared GA and ACO (ant colony optimization) techniques for optimization of fixture design layout. They concluded that ACO technique is better than the GA in the context of the elastic deformation of the workpiece and the convergence rate.

Deng and Melkote [22] presents a model-based framework for determining the minimum required clamping forces that ensure the dynamic stability of a fixtured workpiece during machining. The clamping force optimization problem is formulated as a bilevel nonlinear programming problem and solved using the Particle Swarm Optimization (PSO) technique featuring computational intelligence.

As the optimized fixturing scheme does not guarantee the least sensitivity to the variation of locators, robust fixture design for machining parts was conducted in consideration of both performance and robustness. In robust design, only few research works were conducted in this area of machining fixture. Under the assumption of deterministic location, Cai et al. [10] and Wang [115] formulated fixture model and optimized fixture layout design. Cai et al. [10] developed simulation software called RFixDesign for robust fixture configuration design. In order to minimize the result errors (position and orientation errors), however, only surface errors and fixture setup errors (source errors) are considered. Non-linear programming technique was employed in this work. However, non-linear programming is sensitive to its initial value to reach the optimal solution. Wang [115] developed an sequential optimization approach for fixture layout problem with a point set on the workpiece surface. This approach focused on increasing locating accuracy by maximizing the determinant of the Fisher information matrix (D-optimality), which is the inverse of the sensitivity matrix. However, the measurement of product quality is the positional error of workpiece rather than features to be machined on the workpece.

### 2.3.2 Fixture Design Model for Robustness

Fixture design models, as a part of fixture analysis, can provide the necessary tools to evaluate and measure how well a fixture achieves its functions. This is useful in not only verifying a designed fixture but is also useful in guiding search approaches in fixture synthesis.

In the context of tolerance analysis for workpiece location, Rong et al. [91] developed tolerance zone definitions and fixturing coordinates system for locating error analysis. Choudhuri and De Meter [19] presented an analysis based on a modeling of variations on the geometry of spherical tip locators. Geometric errors of the workpiece datum surfaces were also analyzed for positional, profile, and angular manufacturing tolerance cases.

In consideration of location accuracy analysis for rigid parts, Asada and By [3] defined the concepts of deterministic location that the workpiece is uniquely positioned when moved into contact with the locators. The kinematic problems for deterministic localization were characterized by analyzing the constraints on the surface of the workpiece by fixturing. Xiong et al. [129] built up a mapping model between the error space of locators and the workpiece locating error space. In this model, deterministic localization, over deterministic localization and under deterministic localization were studied. Similar study has also been studied by Qin et al. [83, 85]. Chaiprapat and Rujikietgumjorn [17] developed a mathematical model to predict geometrical variation of a resultant-machined surface within the specified tolerance of the datum feature. Nonetheless, there is a lack of robustness in the model, as users were not able to determine which parameters to control in order to achieve a locating scheme, with the least machining errors.

For deformable parts, Camelio et al [12] and Li et al [54] studied the impact of fixture design on the sheet metal assembly and Cai et al [9] established the “N-2-1” principle for sheet panel locating. Based on previous work [10], Cai et al [11] optimized pin layout for sheet metal locating.

Cai *et al.* [10] began studies on robust fixture design, which minimizes workpiece positional errors caused by locating surfaces and fixture set-up errors. Wang [115, 117] formulated fixture model of localization accuracy for a workpiece based on deterministic localization. Carlson [14] and Liu and Wang [59] presented a second order analysis of the localization error. Cao et al. [13] presented the deterministic and variation analysis algorithm for rigid workpiece positioning. The workpiece positioning variations due to locating errors are quadratically approximated using the method of moments. However, all these researches focus on workpiece positioning accuracy instead of geometric features to be machined.

Wang [118] analyzed the impact of localization source errors on the geometric errors of machined features. It showed the importance to consider the overall error among the multiple critical points on the machining features in fixture layout design. Zhou et al [132] and Loose et al [61] developed state-space modelling techniques for dimensional variation propagation of multistage machining processes with general fixture setup schemes. The machining feature errors are also used for final product quality measurements considering fixture error, datum error, machine geometric error, and the dimensional quality of the product. In their work, however, the feature errors are calculated using either deterministic source errors or the worst case scenario.

## 2.4 Problem Statement and Research Objectives

The various reported research work can be summarized in a single table as shown in Table 2.1. From the reported research, it is clear that there is no single collaborative fixture design system with analysis and robustness presented.

Table 2.1 Comparison of fixture design systems

| Researchers | Methodology | | | | | | | | | | | | | Application Focus | | | | | | Goal | | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Analysis | | | | | | Synthesis | | | | | | | | | | | | | | | |
| | GM | FBM | ST | MA | FEM | NLP | CAD | AM | RBR | KBS | CBR | GA | ANN | Stability | Interference | Accessibility | Clamp force | Deformation | Accuracy | Robustness | Optimization | |
| Nnaji and Alladin [74] | | | | | X | | | | X | | | | | | | | | | | | | |
| Pham and Lazaro [80] | | | | | | | | | X | | | | | | | | | | | | | |
| Senthil Kumar et al [95] | | X | | | | | X | | X | | | | | | | | | | | | | |
| Fuh et al, [29] | | | X | | | | | | X | | | | | | | | | | | | | |
| King and Lajaro [46] | | | | | | | | | | X | | | | | | | | | X | | | |
| King and Ling [47] | X | | | | | | | X | | | | | | | | | | | | | | 2.5D |
| Willy et al. [121] | X | | | X | | | | | | | | | | X | X | | | | | | X | Boolean algebra |
| Sun and Chen [106] | | | | | | | | | | | X | | | | | | | | | | | |
| Perremans, [78] | | X | | | | | | | X | | | | | | | | | | | | | |
| Lin et al. [57] | X | X | | | | | | | | | | | | X | | | | | | | | |
| Rong and Bai [90] | | | | | | | | X | | | | | | | X | | | | | | | |
| Cai et al, [10] | | | X | | | X | | | | | | | | | | | | | X | X | X | |
| Lin and Huang [58] | | | | | | | | | | | GT | | X | | | | | | | | | Group Technology |
| Wu *et al.* [125-126] | X | | | | | | | | | | | | | X | | X | | | X | | | |
| Roy and Liao, [94] | | | X | | | | | | X | | | | | X | | X | | | X | | | Blackboard architecture |
| Senthil Kumar et al. [97] | | | | | | | | | | | | X | X | | | | | | | | | |
| Ma et al. [62-63] | X | X | | | | | X | | | | | | | | | X | | | | | | |
| Krishnakumar and Melkote, [50] | | | | | | | | | | | | X | | | | | | | | | | 2D |
| Senthil Kumar et al. [98] | | | | | | | X | | | | | | | | X | | | | | | | |
| Kakish et al [42] | | | | | | | | | | X | X | | | | | | | | | | | |
| Wang and Pelinescu, [116] | | | | | | X | | | | | | | | | X | | | | | X | X | |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Li and Melkote [53] | | | X | | X | | | | | | | | X | | | X | SQP |
| Hou and Trappey [36] | | | | | | X | | | | | | | | | | | |
| Subramaniam et al. [104] | | | | | | | | | X | X | | | | | | | Multi-agent |
| Zhang et al. [130] | X | | | | | | | | | | | | | | X | | |
| Li et al. [56] | | | | | | | | X | | | | | | | | | |
| Mervyn et al. [65] | | | | | | X | | | | | | | | | | | Internet-enabled |
| Cecil [15] | | | | | | X | | | | | | | | | | | IDEF0 |
| Krishnamachary and Reddy [51] | | X | X | | | | | | | | | | | | | | Gauss Elimination Method |
| Mervyn et al. [67] | | | | | | | | | X | | | | | | | X | |
| Hamedi [34] | | | | X | | | | | X | X | | | X | X | | X | |
| Kaya [43] | | | | X | | | | | X | | | | | | | X | 2D workpiece |
| Boyle et al. [7] | | | | | | | | X | | | | | | | | | Axiomatic design |
| Hunter et al. [38] | | | | | | | X | | | | | | | | | | IDEF0, UML |
| Wang et al. [119] | | | | | | | | | | | X | | X | | X | X | |
| Wu et al. [127] | | | X | | | | | | | | X | X | X | | | | Linkage mechanism |

GM- Geometry Method
FBM – Feature-based Modeling
ST – Screw Theory
FC – Form Closure/ Force Closure
MA – Mechanical Analysis
FEM – Finite Element Method
LP – Linear Programming
NLP – Non-Linear Programming
CAD – Computer Aided Design
AM – Analytical Method
RBR - Rule-based reasoning/Expert system/
KBS - Knowledge-based system
GA – Genetic Algorithm / Evolutionary Algorithm
CBR – Case-based Reasoning
GT – Group Technology
ANN – Artificial Neural Network
BBA – Black Board Architecture
SQP - Sequential quadratic programming

### 2.4.1 Problem Statement

*2.4.1.1 Collaborative environment for fixture design*

An ideal computer-aided fixture system should support the integration of every fixture design phases and the collaboration of design and simulation as well. In order to support distributed collaborative design and manufacturing applications effectively, a number of issues need to be addressed:

- *Collaborative environment for fixture design process*: In order to avoid software compatibility problem during enterprise collaboration, the collaborative environment is required to be platform-independent, flexible and scalable. Web-service-based SOA (WSSOA) is well suited for these requirements. However, WSSOA mainly involve in e-bussiness and e-government, and does not have the specialized characteristics for engineering domain. So far, only few research works have employed web-service-based SOA for distributed collaborative design & manufacturing. The collaborative fixture design framework and the fixture design process in the collaborative environment have not been sufficiently addressed yet.
- *Managing information exchange in the fixture design process*: Product design data and knowledge are not only managed by the design and production activities, but also required in the downstream applications of the product development process to carry out their tasks. Meanwhile, upstream applications need feedback information from the downstream applications for validation or optimization. To the author's knowledge, applying web-service-based SOA to the application of fixture design and analysis needs addition efforts, such as information support for designing a fixture, which is crucial in computer-aided fixture design. Such an information model that facilitates the

integration of the fixture design phases in a collaborative environment is not reported.

- *Knowledge representation for fixture design process:* In order to seamlessly integrate not only disparate fixture design phases but also fixture design with other applications, the fixture process model is required to be represented at knowledge level to helps users to clarify the structure of intensive knowledge and information processing tasks. Moreover, the communication language for distributed applications is required to be platform independent, programming language neutral and machine interpretable. In order to enable intelligent decision making, this language need have enough expressive power to form design knowledge. Although a few research works [2, 37] represent fixture design at knowledge level, none of them focuses on the design process, especially fixture analysis.

*2.4.1.2 Robust fixture design*

In order to develop robust fixture design, two research efforts, *viz.* (i) fixture-workpiece system modeling and (ii) optimization method, should be accomplished.

- *Fixture-workpiece modeling for robustness*: As discussed in previous sections, few fixture-workpiece system models have been developed incorporating positional accuracy. However, most of them measure product quality by focusing on point-based accuracy or the whole workpiece position. Machining feature-based accuracy for measuring product quality is not well addressed.
- *Optimization method*: In order to increase product quality and keep the fixture design performance insensitive to changes in conditions and source errors, fixtures are required to be designed in a way not only with optimization but

also with robustness. In order to realize this, robust design methodologies and optimization techniques must be developed.

### 2.4.2 Research Objectives

This thesis aims to solve the problems presented in Section 2.4.1 by developing a collaborative design and analysis application. In order to realize a collaborative environment for integrated fixture design and analysis, a good knowledge representation scheme, robust fixture design methodologies and relevant optimization techniques must be developed. The specific objectives of the thesis are:

- To develop a distributed collaborative environment for the collaboration between fixture design and fixture analysis.
- To develop a knowledge representation scheme to seamlessly transfer information among different modules in the system.
- To develop robust design techniques to make the fixture design insensitive to workpiece variations.
- To develop optimization techniques to explore the design space to identify the best possible solution.

However, every study has its own limitation. The study in this thesis is limited at:

- The distributed collaboration is focused on two parties: fixture design and fixture analysis;
- The fixture design is constrained at designing a fixture for a single machining workpiece in a setup.

# Chapter 3 Fixture Design System Framework

This chapter presents the architecture of the developed fixture design system, and gives an overview of the functionality of the system. Section 3.1 presents the architecture of the distributed collaborative fixture design system with serviced-oriented architecture (SOA). Section 3.2 shows the process for fixture synthesis in the integrated fixture design and analysis environment. Section 3.3 describes the fixture analysis process, including pre-processing, solving and post-processing and a summary is carried out in Section 3.4.

## 3.1 Service-Oriented Architecture

The developed CFDA system addresses collaborative fixture design and uses a web service based SOA approach. SOA is one of the promising concepts to have emerged in enterprise architecture circles of late, presenting an approach for building distributed system that delivers application functionality as service to end-users. SOA separates functions into distinct service units. These application services are loosely coupled, independent, and can be distributed across a network. They can be combined and reused to create business applications. These services communicate via a standardized, platform-independent protocol that hides the underlying implementation details of each service. A service can be implemented either in Microsoft .net or J2EE, for example, and the application consuming the service can be on a different platform or language.

SOA can be implemented using several technologies, but the most common choice today is the use of web services. Web services provide a standard means of interoperating between different software applications, running on a variety of platforms and/or frameworks [113]. The main technologies of web services like SOAP, WSDL and UDDI are all based on XML that forms the basis of web services' platform-independent and provides language-neutrality. Thus, web services show undoubted advantages in addressing heterogeneity.

There are many advantages of web-service-based SOA (WSSOA) for distributed collaborative applications, such as flexibility, scalability and reusability, the most crucial one is widespread interoperability, which means clients and loosely coupled services can communicate with each other regardless of the platform being used. This characteristic can be of great use in distributed collaborative applications, since it aims at supporting team members from different domains to accomplish the design task using the heterogeneous platforms.

Figure 3.1 shows the overall architecture of the developed integrated fixture design and analysis system. CFDA is designed as a distributed system with a three-tier structure. It consists of a presentation layer that provides thin-client user interface to various users including designers and analysts, an application layer that performs functional services for engineering processes, and a resource layer that maintains the storage of fixture design and analysis data.

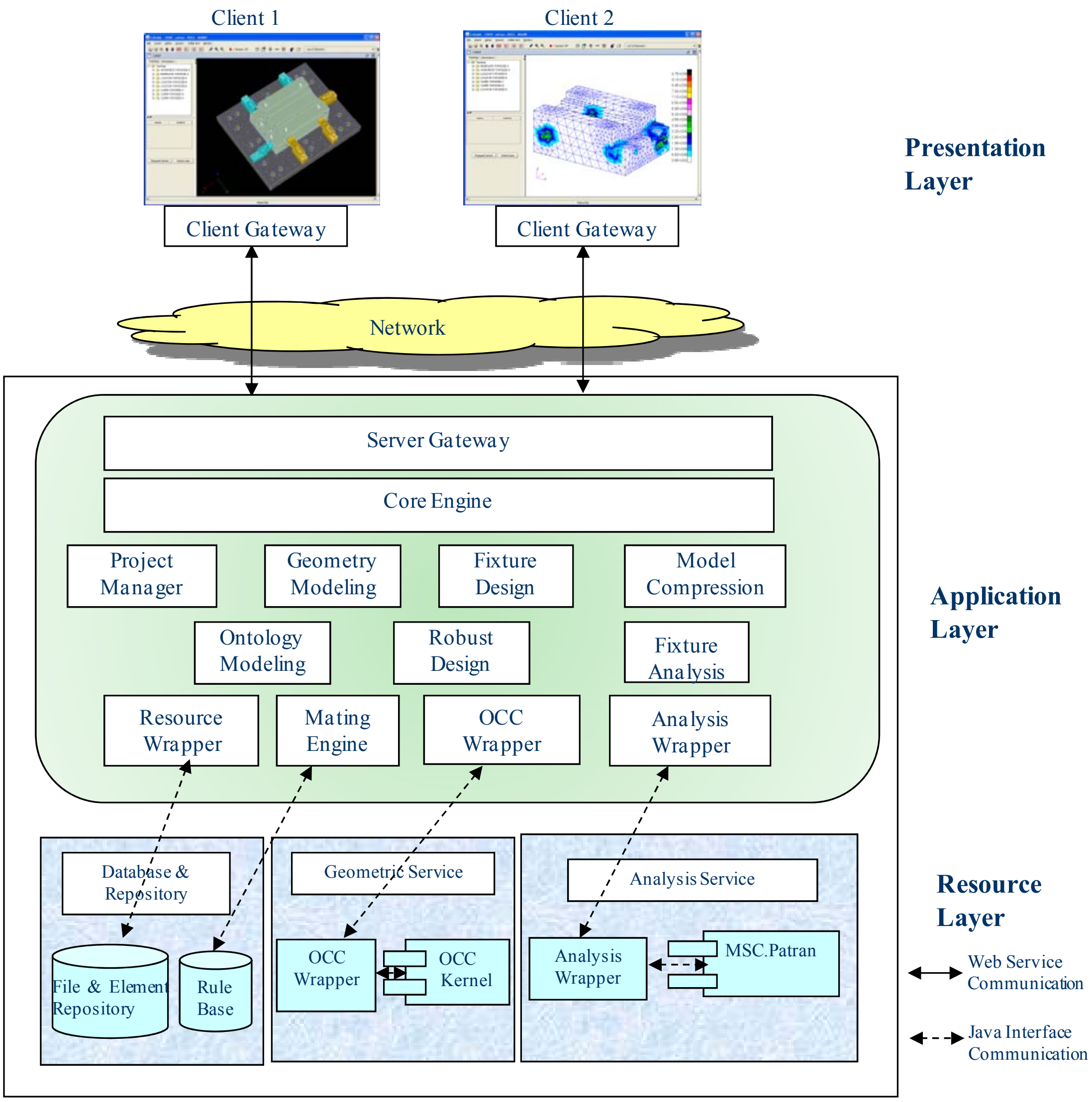



Figure 3.1 The system architecture based on Service-Oriented Architecture

### 3.1.1 Presentation Layer

This is a swing user interface using Java3D Canvas for fixture design and analysis. Each client has a web service client called "Client Gateway" that is interfaced to "Server Gateway" on the server side. This enables the users to access the system services to perform fixture design and analysis. The gateways maintain the user session and dynamically invoke the functional services from the server.

### 3.1.2 Application Layer

Functional services and business logic represent the application layer. The business modules include "Server Gateway", "Core Engine", "Project Manager", "Geometry Modeling", "Fixture Design", "Fixture Analysis", "Robust Design", "Ontology Modeling" and "Model Compression".

"Server Gateway" includes the service endpoints that expose the functions for the end user and is responsible for communication and message passing between the server and clients. The "Core Engine" has a service handler, a controller and a component interface handler. The service handler handles all requests and responses from and to user. The controller is responsible for delegating a user request and the component interface handler integrates the different modules with the main system.

"Project Manager" module manages the user and sessions. Project structure management and user management are common processes for creating a project, adding a user, deleting a user, creating a group, joining into the project, etc. Session management mainly includes three operations: Create-session that starts a new session for one user in the collaborative design; Kill-session that closes the opened session after finishing a related design; Join-session that allows the current user to join in an existing session for co-visualization.

"Ontology Modeling" is used to access to other modules to retrieve information and then to create OWL instance file using Jena2 API [23]. Jena2 is a Java framework for building Semantic Web applications and it provides programmatic environments for RDF, RDFS and OWL. The developed ontology models for fixture design process will be discussed in Chapter 4.

"Robust Design" module contains algorithms (including the developed GA and PSO) for robust fixture design. Since these algorithms are coded with Matlab, in order to integrate with other Java modules, Matlab Builder$^{TM}$ JA[9] is deployed to convert the codes into Java classes by generating Java wrappers around the Matlab functions. The details of the developed algorithms for robust fixture design will elaborated in Chapter 6 and Chapter 7.

"Fixture Design" contains algorithms that handle assembling fixture elements with the machining parts. The rules are managed by a rule engine which is implemented with JBoss Rules [40], an open source and standards-based business rules engine. JBoss Rules is employed in the deployment as it adds flexibility to the SOA implementation.

The "Fixture Analysis" module deals with FEM pre-processing and retrieves the feedback from FEM post-processing. It connects with "ontology modeling" module to generate fixture analysis ontology files. "Fixture design" module is responsible for interactive fixture design processes. "Geometric modeling" module connects to Open Cascade (OCC) solid modeling kernel and provides not only essential CAD query and manipulating functions for a fixture design process, but also Constructive Solid Geometry (CSG) and feature-based modeling capabilities.

In order to improve system performance and reduce transmission time, facet visualization data are compressed using the Edgebreaker algorithm [92] that provides a compact representation for the visualization of the CAD model in "Model Compression". The detailed implementation of this algorithm for data compression can refer to [28].

[9] http://www.mathworks.com/products/javabuilder/

### 3.1.3 Resource Layer

Resource layer consists of the database, rule base, file repositories, geometric service, and analysis service. The database holds user details, project information and session management data using MySQL. There are three repositories viz., STEP file repository, CFDA file repository and fixture element library. STEP file repository holds all the STEP files designed by the user. The CFDA file is a OWL-format application file for fixture configuration and the fixture element library stores the various fixture elements [39] used for designing a fixture. The rule base contains various rules for designing a fixture.

In the developed system, the Open Cascade solid modeling kernel has been utilized to carry out the manipulation of product models from geometry modeling module at application layer. Since OCC kernel is written in C++ language, OCC wrapper is needed to utilize the modeling functions. Java Native Interface (JNI) allows Java application running in the Java virtual machine (JVM) to operate with application or libraries written in different languages. Thus, JNI is employed for OCC wrapping and geometric modeling at application layer.

Analysis service is responsible for the design analysis to perform pre-processing, solving and post-processing using FEM. MSC.Patran is utilized for pre-processing and post-processing and MSC.Marc for solving. The Patran commands are wrapped through C language, thus similar to the OCC kernel and the analysis module can carry out the operation of FEM via this analysis wrapper.

## 3.2 Fixture Design Process

In this work, the fixture design is a sequential workflow that consists of following tasks: importing workpiece, baseplate selection, determining the locating, supporting, and clamping elements and saving the configuration. Figure 3.2 shows the sequential workflow of the interactive fixture design. Solid lines represent the interaction between processes, and dashed lines show the interaction between the various processes and the client gateway. The procedure for designing a fixture is explained in detail in [65]. Each process interacts with a unified interface, the client gateway, to communicate with services at the server side. Since saving a design is independent with other tasks, it is not shown in Figure 3.2. One of the key features of SOA development is that the business processes are transparent. That is, when a user is operating with the fixture design process, he/she does not know where the services come from and only interacts with the user interface to complete the job.

Figure 3.3 shows the interaction sequence among the components in CFDA during a fixture design process. When a user requests for a fixture design (FD) process, e.g. loading a baseplate, the client gateway requests for the baseplate service and sends in the required input parameters like, the type and size of the baseplate to be loaded. Once the functional web service gets the request, it delegates the request to the FD component. With the necessary input details, the baseplate STEP file is retrieved from the repository and then generates TopoDS objects via the Open Cascade kernel. A tessellated mesh of the model is created by invoking a functional call on the OCC kernel. The meshed data are then formatted and compressed with the model compression (MC) module. The compressed mesh data are encapsulated into a XML file, and it is then sent to the client.

Received by the client gateway, the XML file is parsed and then de-compressed. The mesh data are then rendered in Java3D canvas for user visualization and manipulation. This process is repeated until all the necessary elements are loaded and the design of a fixture is completed.

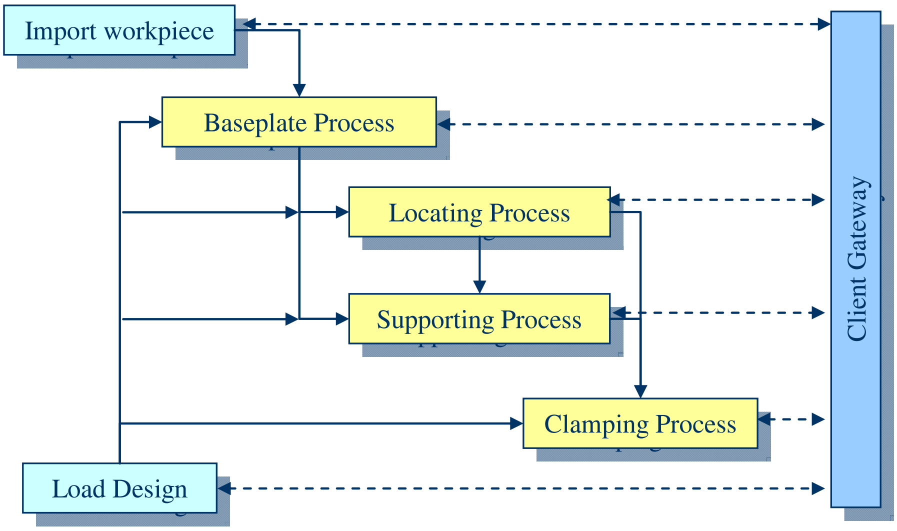



Figure 3.2 Fixture design sequential workflow at client side (solid line represents the interaction between processes, and dash line the interaction between processes and client gateway)

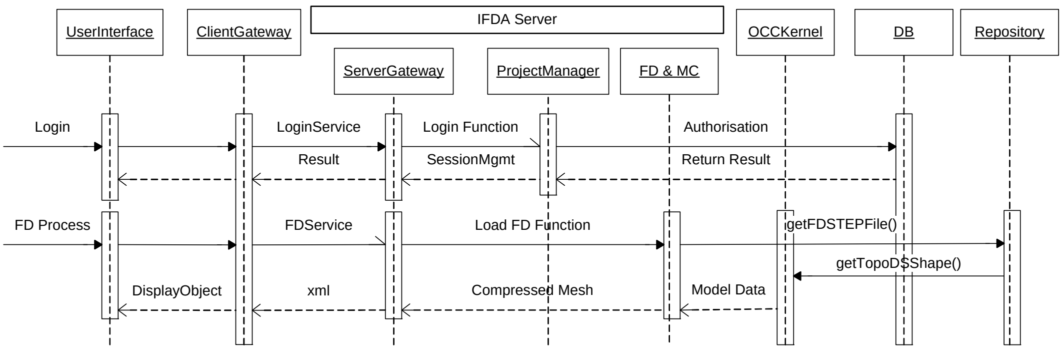



Figure 3.3 Iterative diagram for fixture design process

## 3.3 Fixture Analysis Process

This section describes the various stages involved in fixture analysis and the fixture analysis process in a CFDA environment.

### 3.3.1 Steps in Fixture Analysis

In the analysis phase, CFDA uses FEM to analyze the model under the simulation of external forces due to the machining of the work piece. A key fixture analysis requirement is to predict the minimum reaction forces at the fixture contacts under the external cutting forces and moments. This will facilitate the designer to analyze and ensure that the designed fixtures are able to perform their task under a given manufacturing condition. Thus fixture analysis serves as a feedback to study the feasibility and the performance of a given fixture design.

Fixture and workpiece contact is modeled as deformable elements interacting with each other with friction. The machining process is simulated using the cutter tool path. The workpiece boundary condition is defined by locators and clamps and the clamping force is considered as an external load.

The various steps involved in the analysis are pre-processing, solving and post-processing. A key element in pre-processing a fixture element model is contact analysis. Since a fixture model consists of several bodies (e.g., clamps, locators, etc) in contact with the workpiece, defining a proper relationship model between these different bodies is necessary. This ensures that the fixture elements are in contact with the workpiece without any penetration or separation before the machining commences. The whole model is then meshed and boundary conditions such as clamping force, material properties, etc are applied. The output from the preprocessing file is a finite element data file which is stored in the server database.

The solving step involves the model computation on a FEA solver. The FEA solver generates a result which is stored in the database for post processing. After the solver generates the result file, the various reaction forces, displacement of the workpiece is plotted and stored in the database as a report. This report file helps the fixture designer to judge the quality of the design.

### 3.3.2 Fixture Analysis in an CFDA environment

In order to seamlessly exchange information and knowledge between fixture design and fixture analysis, Web Ontology Language (OWL) is used to express fixture design configuration file, analysis control file and analysis result file. The fixture design data file contains information about the workpiece and the fixture elements and the orientation of the fixture elements in the X, Y and Z direction in the global coordinate system. The analysis control file contains the details of input deck to be applied to the fixture design for analysis. The input deck for the fixture design contains loading forces such as clamping pressures, cutter tool path, material properties, relationships between fixture elements and workpiece, and boundary conditions. All these data are used for automating the pre-processing tasks within FEM. The analysis result file contains necessary information and data extracted from FEA results for fixture analysis. These data returned to designers can help them to evaluate the quality of the designed fixture. The details of representation can be referred to Chapter 4.

To integrate fixture design with analysis, the client gateway on the client side is provided with a user interface with which the client interacts with the FEM module. Commercial FEA software MSC.Patran and MSC.Marc have been used for fixture analysis. Patran command language (PCL) is utilized to automate a fixture analysis process on the server side. The interaction of the client with the fixture analysis is described in detail in the case study.

Figure 3.4 gives a summary on how the client interacts with the CFDA system in the fixture analysis process. It can be seen that once there is a user request for fixture analysis, the client gateway requests for the fixture analysis service and sends in the required input parameters like the STEP file, FDC file (fixture design configuration file) and the FAC file (analysis control file for fixture analysis). The FDC and FAC files in conjunction with the fixture design STEP file serve as an input for automating the FEM procedures such as pre-processing, solving and report generation tasks.

Once the functional web service gets the request, it delegates the request to the analysis component. With the necessary input details, the analysis component generates the batch and the session files (used for automating the pre-processing and the solving tasks) and also retrieves the fixture design files (STEP + FDC + FAC) from the repository. A functional call for executing the batch file is then given by the analysis component and the analysis procedure starts. The status file generated by FEM is encapsulated into an XML and sent to the client. Received by the client gateway, the XML is then parsed and decompressed to display the status file.

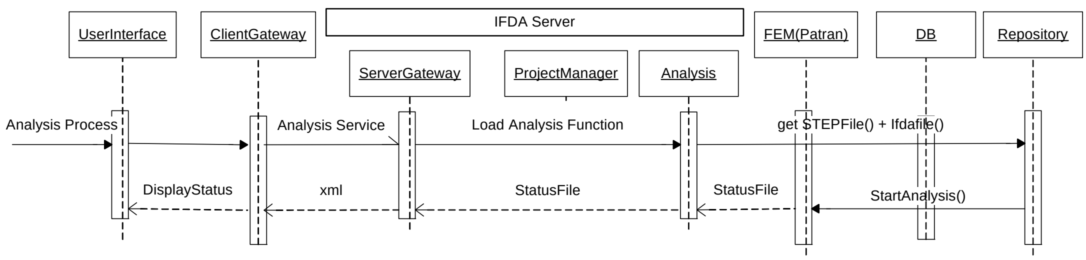



Figure 3.4 Fixture analysis process

Figure 3.5 illustrates the detailed methodology of pro-processing in fixture analysis process. In the pre-processing, the first step is to represent fixture design model with idealized and simplified model from fixture design geometric model and fixture design configuration file. Simplification is to remove some unnecessary details and features, such as fillets, on the workpiece, while idealization is to represent fixture-workpiece contacts with spring elements (Figure 3.6). One end of the spring is fixed at ground;

the other end is attached on a block element to contact with a workpiece surface. The spring elements can only be compressed along the surface normal direction at the contact point. The block element and workpiece can be modeled as a pair of 3D contact with/without friction. Then, the behavior of the spring elements are used to emulate the linear/non-linear behavior of fixture-workpiece contacts in the real world. One of the advantages of this approach is to reduce the amount of computational effort required for the simulation of fixture elements and workpiece. The contact point positions and surface normal directions can be extracted from the fixture design configuration file.

The idealized geometry model, including simplified workpiece and block elements, then can be meshed with automatic meshing algorithm or manually controlled approach.

The material properties of workpiece and fixture elements are either manually input by users or parsed the material names from FDC file and then obtained from material library.

The cutting forces can be calculated based on the method presented by Kline et al [48]. In the tool axial direction, the end mill is divided into several segments, and the length of each segment is equal to that of each element in this direction. In order to calculate cutting forces, each segment is divided into many equal axial slices. For each slice, the instantaneous tangential cutting force $F_t(\theta)$ and the instantaneous radial cutting force $F_r(\theta)$ in term of rotation angle $\theta$ can be expressed as:

$$F_t(\theta) = K_t t_c(\theta)\Delta h \tag{3.1}$$

$$F_r(\theta) = K_r F_t(\theta) \tag{3.2}$$

where $K_t$ and $K_r$ are the cutting pressure constants, $t_c(\theta)$ is the instantaneous undeformed chip thickness. To simplify the analysis process, the peak static cutting forces are deployed as the cutting tool machines the part along its cutting path.

The clamping forces can be obtained by multiplying a safety factor with the minimum clamping forces calculated using the method from Tan et al [108].

Material properties, contact relationships and dynamic forces are used as input to generate the fixture analysis control (FAC) file. The FAC file, together with meshing model and idealized model, provides necessary information for generating input data for analysis solving.

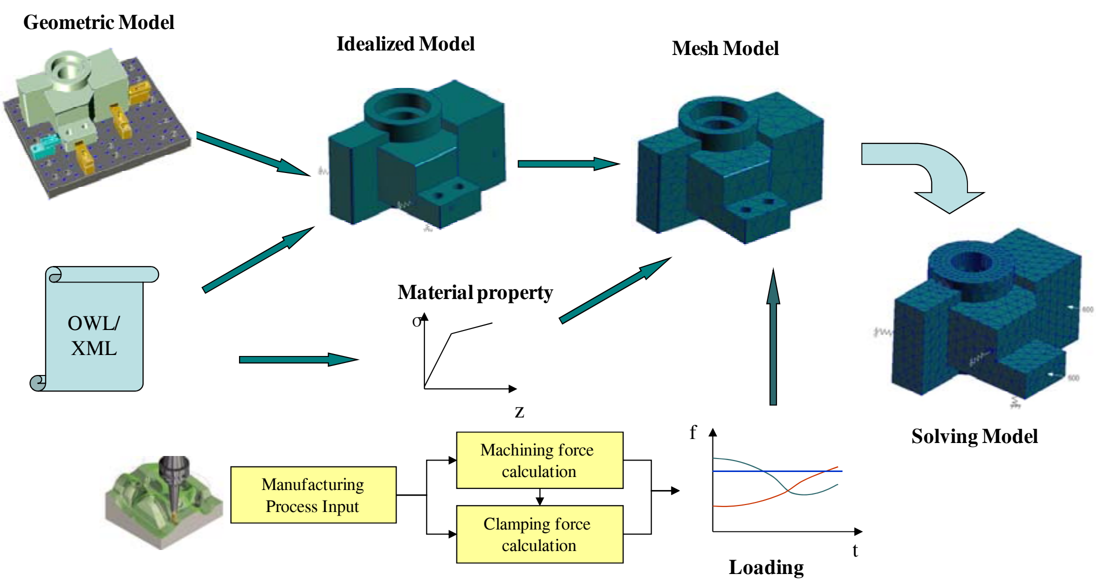



Figure 3.5 The detailed methodology of pre-processing in fixture analysis

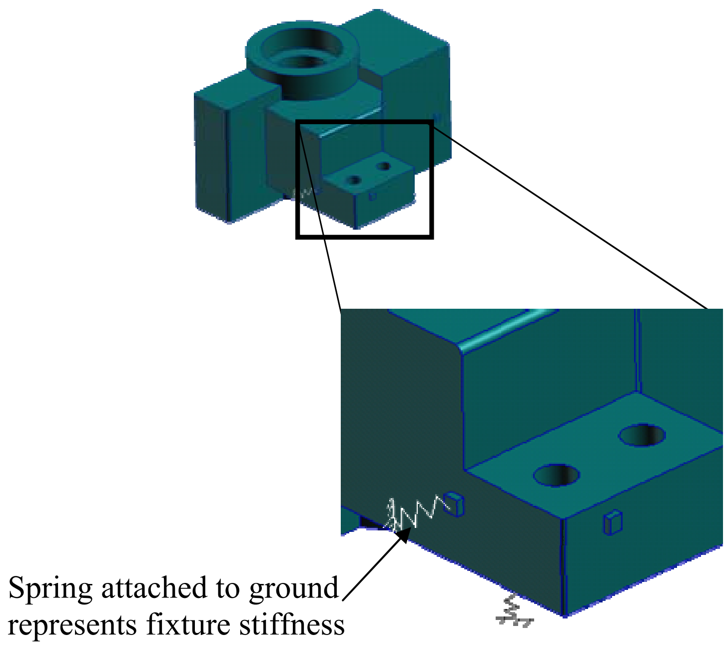



Figure 3.6 The representation of workpiece-fixture contact points as spring elements in FEA environment

## 3.4 Summary

This chapter presents the design and implementation of the fixture design and analysis system based on the service-oriented architecture. This enables designers across the globe to collaborate seamlessly in arriving at a design. The benefits of using WSSOA for collaborative fixture design and analysis system are interoperability, platform-independence and language neutrality of web services and SOA. The developed CFDA system not only can make full use of expertise in the interactive fixture design system guiding novice fixture designers to arrive at a fixture design, but also provide flexibility for expert designers to design more complicated fixtures.

Moreover, SOA enables small to medium sized enterprises to collaboratively design fixtures, which reduces the product lead time and makes the design and manufacturing process more cost-effective. The next chapter discusses how the fixture design knowledge is represented in the development CFDA system.

# Chapter 4 Knowledge Representation for Fixture Design

## 4.1 Application Domain Identification

In order to represent knowledge with ontology, the domains should be first identified. The ontology created in this chapter cover the following domains: product ontology with 3D parametric feature-based geometric modeling, setup ontology, fixture ontology, FEM-based fixture analysis ontology, etc. As for fixture model, the majority of current work concentrates on the machining based fixture.

In manufacturing, machining processes are used to remove materials from a workpiece to obtain higher dimensional accuracy, better surface finishing, or a more complex surface form which cannot be difficult to obtain from other manufacturing processes. To obtain the final product, the workpiece is machined through different setups, referred to as multistage machining processes.

To identify the content of a design, it is important to find out how design and design requirements are represented in practice. Requirements for a fixture are the workpiece to be fixtured, manufacturing resources and fixture elements available. For modular fixture design, design outcomes are fixture planning that deals with overall design concepts and fixture layout that produces a spatial layout of the fixture. Therefore, the representation of a fixture design is divided into three parts: part representation, setup representation and fixture representation (including fixture synthesis and fixture analysis). A workpiece is described using 3D parametric feature-based geometry and material properties. The machining features are grouped according to their orientations and machining constrains into setups. In one setup, only one fixture is associated with it. By this way, the three parts are linked (Figure 4.1). The setup information including manufacturing resources and fixture plan is usually provided by process planners who can access the system and co-operate with fixture designers, while fixture design which includes fixture layout and fixture configuration is final solution for the requirement.

From one setup to another setup, the machining process is considered as a multistage machining process, even the workpiece is manufactured on a single machining station. However, the research in this thesis only focuses on the fixture design process within one setup.

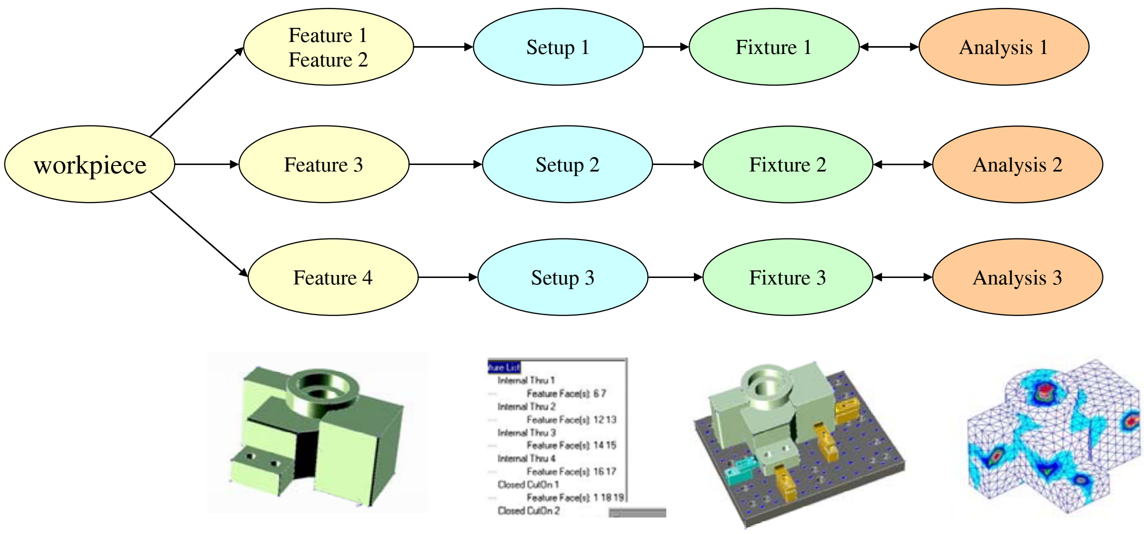



Figure 4.1 Knowledge structure

## 4.2 Ontologies Development

A structured methodology for ontoligies construction will facilitate ontology development in sharing, consistence, and traceability. A three-layer structure is designed to build the fixture ontologies, i.e. abstract ontology (AO), domain specific ontology (DSO) and application specific ontology (ASO). DSO is built upon AO and

ASO is built upon AO and DSO. In this research, all the developed ontologies are coded with OWL using Protégé-OWL.

ABO describes the basic classes that commonly appear in the four domain ontologies. It defines following concepts: “Geometry”, “Material”, and “Feature”. “Geometry” defines primitive geometrical element classes, such as “Solid”, “Shell”, “Surface”, “Curve” and “Point”. “Feature” is the super class of machining features, such as “Hole”, “Slot”, *etc*. “Material” is used to contain material properties of workpiece and fixture elements.

In high-level of ontology, there are mainly three basic properties defined: *is-a*, *has_part* and *has_attribute*. *Is-a* reflects the inheritance relations between two classes. *Has_part* describes composition relation between two classes. *Has_attribute* defines the relations between and object and its attributes.

### 4.2.1 Part Representation

A workpiece/part is the input to the fixture design system. In knowledge representation, its role is similar to the problem description. Part representation not only contains geometrical shape information, but also provides material property.

The geometric information is composed of a set of features, surfaces, points for clamping, locating and supporting, as well as engineering information (tolerance, dimensions, etc.) pertaining to the features. Feature class represents the complete machining area in a workpiece by showing the size and type of features present. The features include the following classes, i.e. “Boss”, “Pocket”, “Hole”, “Slot”, “Step”, *etc*., and each class can be classified further.

Inheritance is exploited in representing the knowledge of the features. In Figure 4.1, “Feature” class is an abstract class only acting as interface for basic shape feature classes, i.e. “Hole”, “Slot”, *etc*. These subclasses inherit the common attributes from “Feature” class and other features are created from basic shape features. For simplicity, subclasses of Tolerance class and basic feature shape classes are not displayed in Figure 4.2. However, in order to clarify the inheritance, the “Hole” class and its subclasses are taken as an example to be shown in Figure 4.3. In Figure 4.3, the classes in the third level refer to the implementation class; the classes in the first two levels are Meta-class. In the class “Hole”, the class “CouterboreThroughHole” is inherited from its super class “ThroughHole” which is inherited from metaclass Hole. The class “CouterboreThroughHole” not only includes its own attributes “OuterDiameter” and “CounterDepth”, but also inherited the attribute “InnerDiameter” which represents the diameter of an inner hole from its super class “ThroughHole” (Figure 4.4).

### 4.2.2 Setup Representations

Setup planning is one of the important steps in process planning and this requires experience on grouping features on the parts to be machined in a setup. Setup planning information enables the consideration of the fixture design configuration, positioning the locators, clamps and supports. Setup links the workpiece and its fixture designs together, and contains information that includes active features in workpiece, workpiece orientation, process for machining, and machine used for manufacturing (Figure 4.5). “Setup” is the main class that contains the details of setup information for fixturing. Process is the super class of machining processes, including Shaping, Turning, Milling, Planing, Drilling, etc. Each process associates the class “CuttingTool”, which describes the cutting tools for a machining operation.

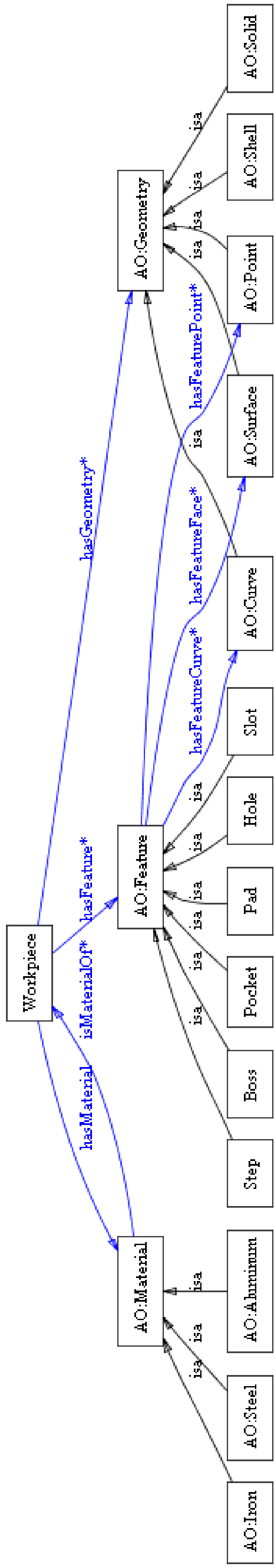



Figure 4.2 Workpiece representation

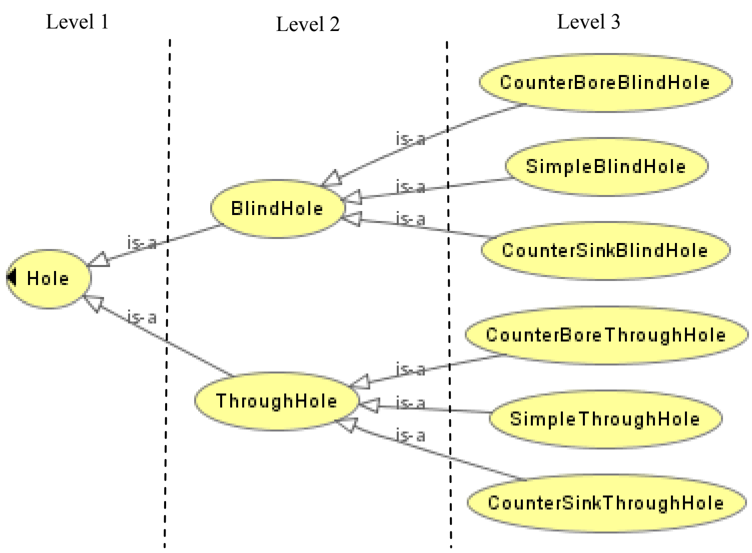



Figure 4.3 Inheritance in the *Hole* class

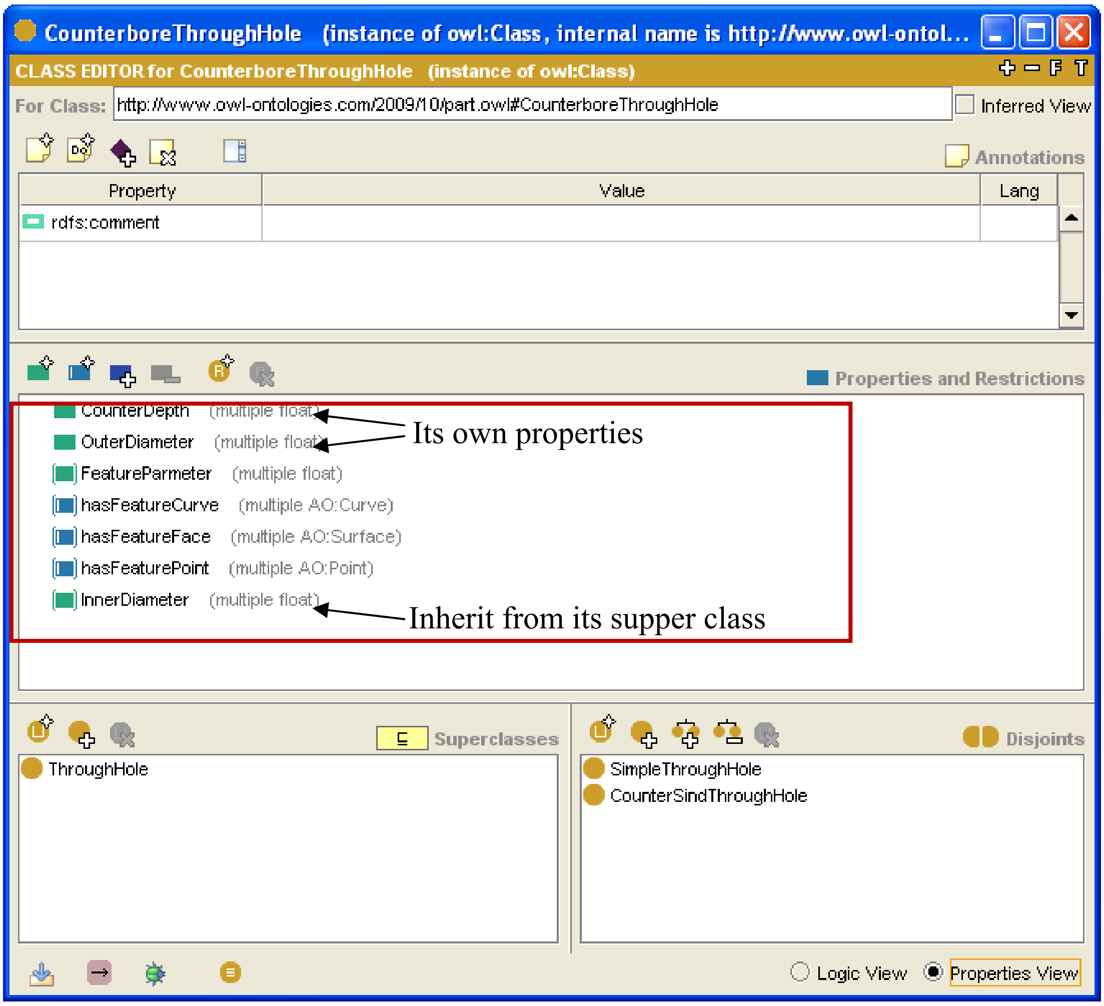



Figure 4.4 Properties inheritance in the *Hole* class

In this phase, a feature is classified as active feature, which will be machined in the current setup, and inactive feature, which has been machined in previous setups. Similarly, the surfaces on the workpiece are categorized as inactive surfaces and active surfaces. Only inactive surfaces, which are machined in previous setups, can be used as fixturing surface candidates, while active surfaces, to be machined in current setup, cannot.

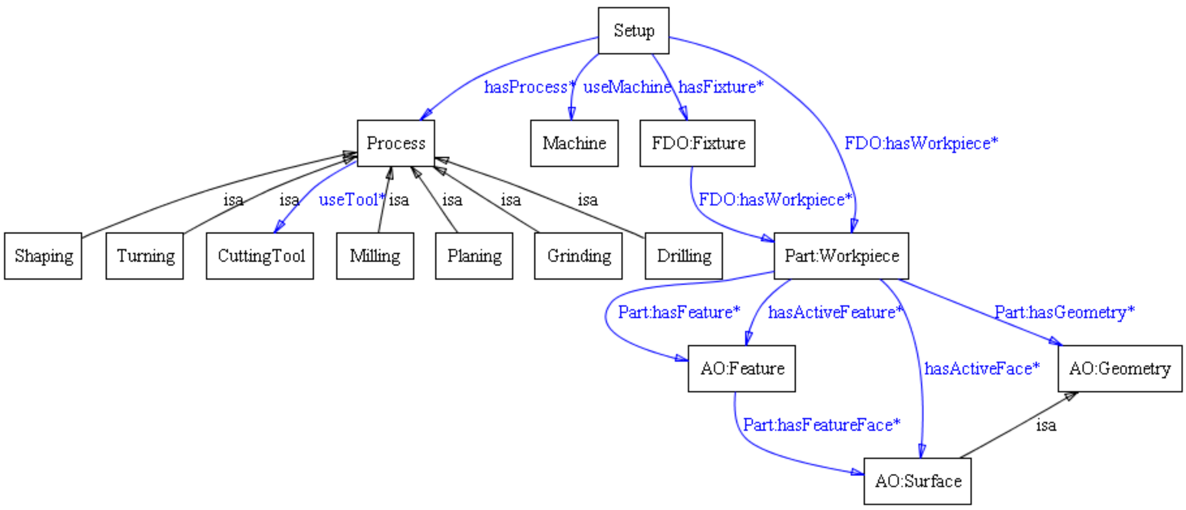



Figure 4.5 Setup representation

### 4.2.3 Fixture Design Representation

“Fixture” is the main class for fixture design ontology, part of which is shown in Figure 4.6. Based on its function, the type of a fixture may be divided into machining fixture, assembly fixture and inspection fixture. Here the machining fixture is mainly focused and discussed. A fixture usually contains functional fixture units: “BaseUnit”, “LocatingUnit”, “SupportingUnit”, and “ClampingUnit”. Each fixture unit is composed of one or more fixture elements, including “baseplate”, “locator”, “support”, and “clamp”. The clamping force is imposed on the clamping element. In the fixture

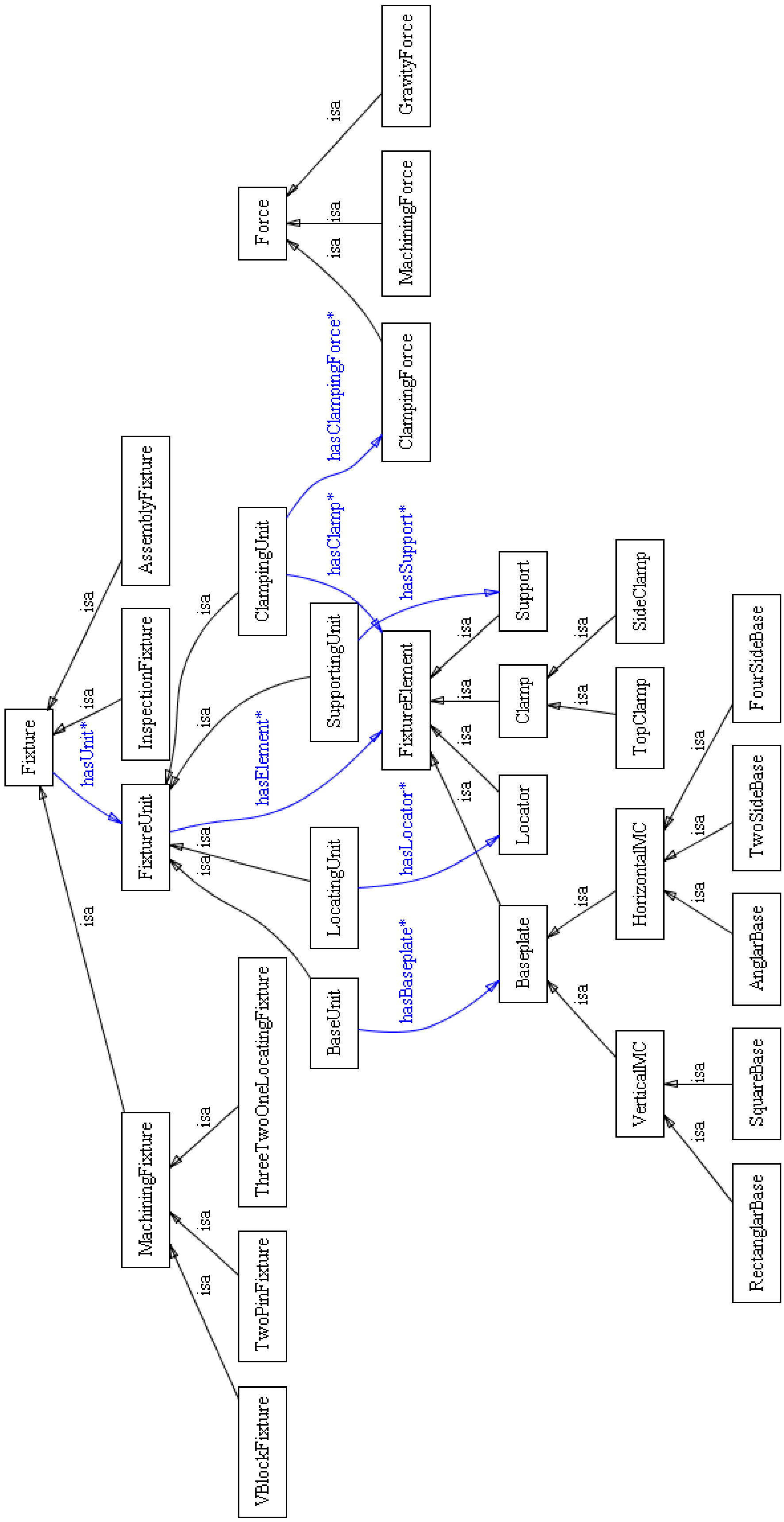



Figure 4.6 Fixture design representation model

design, the workpiece is held, supported and clamped by the fixture elements. These elements contact with workpiece through its supporting surfaces, locating surfaces, and clamping surfaces.

### 4.2.4 Fixture Analysis Representation

Fixture analysis allows an engineer to verify and validate fixture solutions in the design cycle and enables the user to be immersed in the simulation environment. The finite-element based fixture analysis model representation is divided into two parts: control model (Figure 4.7) and result model (Figure 4.8). The control model represents the information to generate input deck for solving in finite-element software package. The information used to determine the relevance of fixture analysis models describes the physical context in which the phenomenon of interest occurs. The scope of information needed to describe physical contexts includes: geometrical elements, relationships between these elements, material, and applied loads.

Figure 4.7 illustrates the developed information model for FEA-based fixture analysis representation. The classes are explained as follows.

- “Geometry Entity” describes the idealized and simplified components in the fixture design, including workpiece and fixture elements.
- “Mesh” includes mesh elements generated from the individuals of “Geometry Entity”. Each individual in “Geometry Entity” has property *hasMesh* with class “Mesh”.
- “Physical Relationship” describes the structural relationships between two components, such as frictional contact, non-frictional contact, glue, etc.
- “Load Case” describes how the force (including machining force, clamping force, etc.) is applied. Each load case is regarded as a step in analysis

solving. The property *hasSubject* indicates the component on which the force is loaded.

- "Boundary Condition" describes the constrains applied on the components, especially on fixture elements.

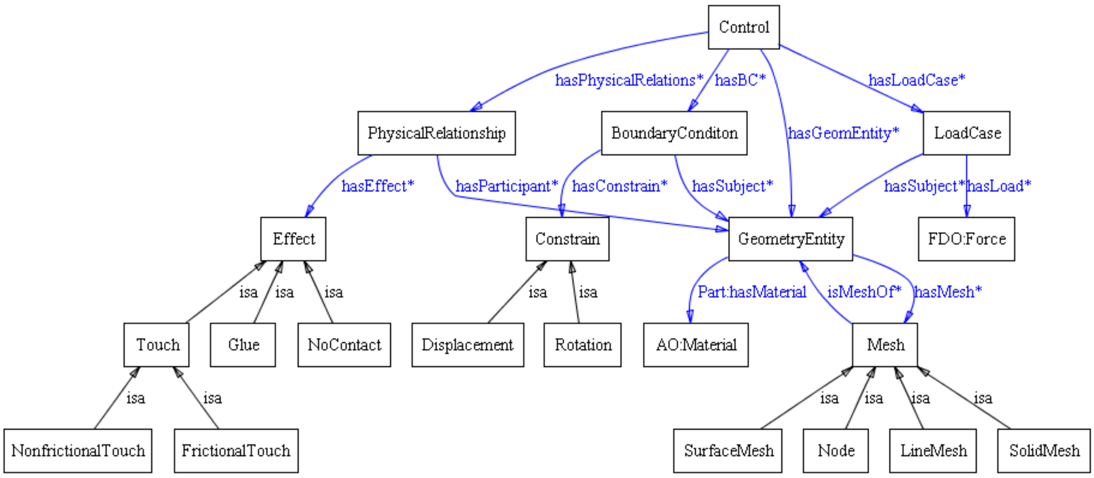



Figure 4.7 The representation for FEA-based fixture analysis control model

The result model mainly represents structural results from finite-element analysis. In Figure 4.8, "Result" class is the main class containing analysis results feedback to fixture designers. It includes not only machining and clamping deformation, stress, and strain at workpiece and fixture elements, but also reaction forces at contact points between fixture elements and the workpiece. The property *hasGeomEntity* indicates entities on which the deformation, stress, and strain are applied. In multi steps, "LoadCase" is used to specify the current result belong to which step.

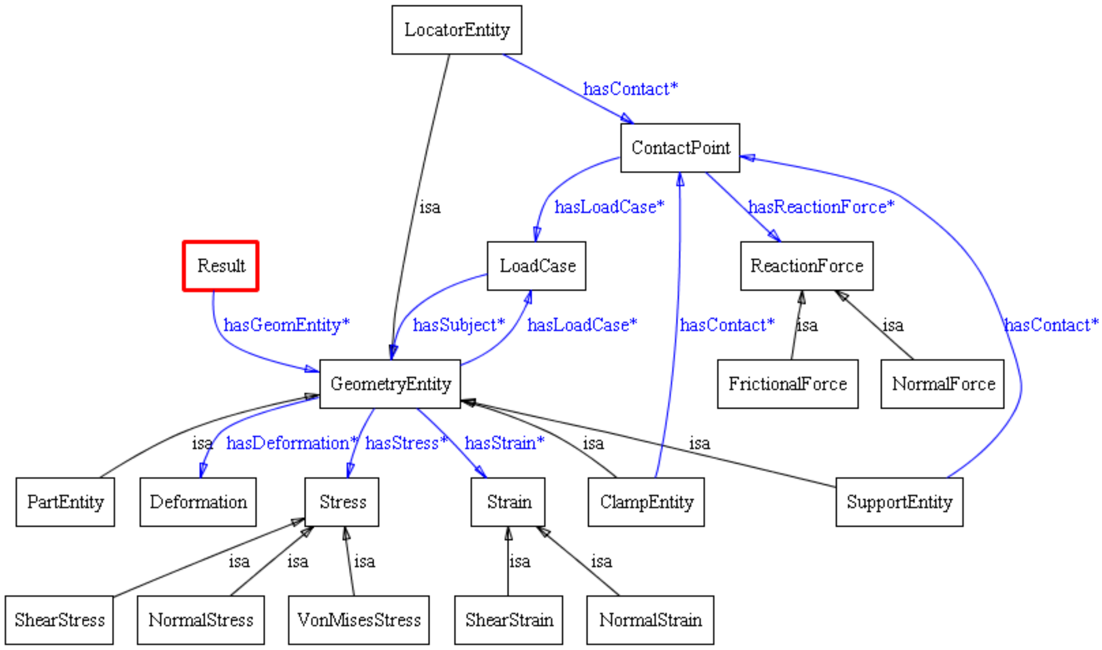



Figure 4.8 The representation for FEA-based fixture analysis solution model

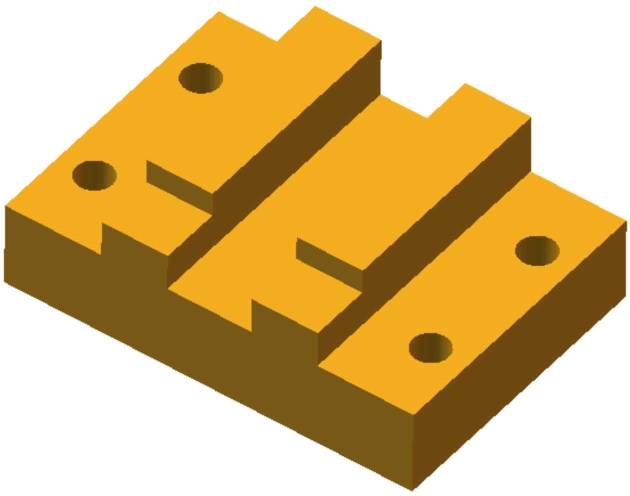
## 4.3 Examples

A mechanical part is selected as a case study for the knowledge representation with ontology. The workpiece name "trial" is shown in Figure 4.9. Part of the OWL source code of the workpiece formulated in ontology is shown in Figure 4.9(a). This example provides basic information of the workpiece, including geometrical information and material information. From the figure, the material of the workpiece is steel AISI 5120 and one of features on the workpiece is a through slot, whose ID is "Slot_2". Its feature parameter "SlotWidth" is 30mm and it has feature surfaces: "Surface_41", "Surface_38" and "Surface_42".

Figure 4.10 shows the setup information for the workpiece in a setup. In the current setup, machining operations will be conducted at an active feature, whose id is "Slot-

```
<Part:Workpiece rdf:ID="Workpiece_1">
   <Part:WorkpieceID rdf:datatype="http://www.w3.org/2001/XMLSchema#string">08-07-
   001</Part:WorkpieceID>
   <Part:WorkpieceName xml:lang="en">Trial</Part:WorkpieceName>
   <Part:hasMaterial rdf:resource="#AISI_5120" />
   <Part:hasSurface>
        <j.0:Surface rdf:ID="Surface_42" />
   </Part:hasSurface>
   <Part:hasSurface>
        <j.0:Surface rdf:ID="Surface_40" />
   </Part:hasSurface>
```

(a) OWL source code for the workpiece



(b) geometrical shape of the workpiece

```
<Part:hasFeature>
 <ThroughSlot rdf:ID="Slot_2">
   <FeaturePositionX
   rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0</FeaturePositionX>
   <FeatureDirectionY
   rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0</FeatureDirectionY>
   <FeaturePositionZ
   rdf:datatype="http://www.w3.org/2001/XMLSchema#float">50.0</FeaturePositionZ>
   <FeatureDirectionX
   rdf:datatype="http://www.w3.org/2001/XMLSchema#float">1.0</FeatureDirectionX>
   <FeaturePositioY
   rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0</FeaturePositioY>
   <FeatureDirectionZ
   rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0</FeatureDirectionZ>
   <SlotDepth
   rdf:datatype="http://www.w3.org/2001/XMLSchema#float">10.0</SlotDepth>
   <SlotWidth
   rdf:datatype="http://www.w3.org/2001/XMLSchema#float">30.0</SlotWidth>
   <SlotLength
   rdf:datatype="http://www.w3.org/2001/XMLSchema#float">120.0</SlotLength>
   <Part:hasFeatureFace rdf:resource="#Surface_41" />
   <Part:hasFeatureFace rdf:resource="#Surface_38" />
   <Part:hasFeatureFace rdf:resource="#Surface_42" />
  </ThroughSlot>
```

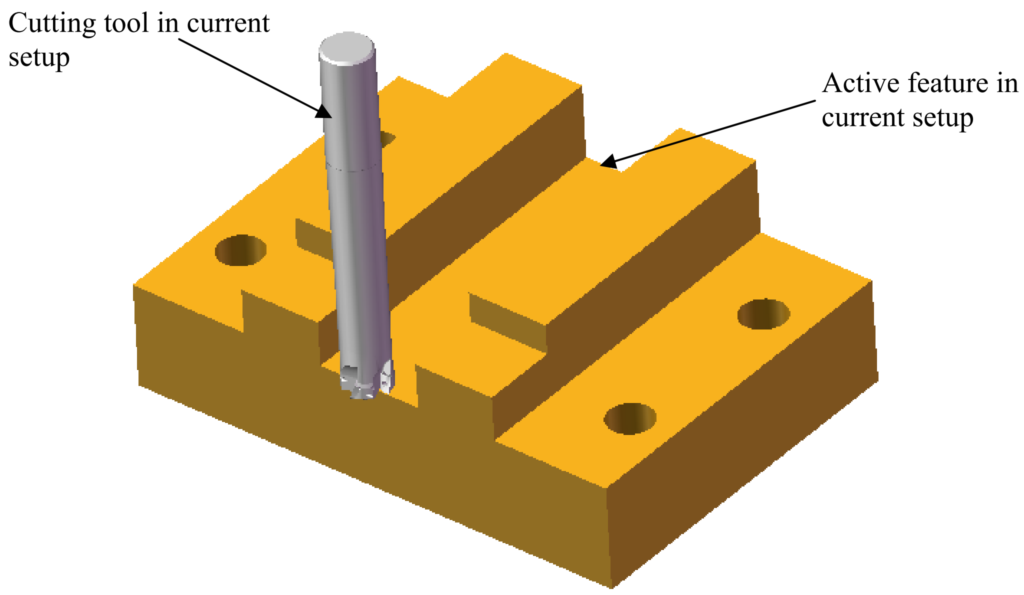
(c) OWL source code the feature of the workpiece

Figure 4.9 An example for workpiece representation

This active feature contains several active surfaces, i.e. “Surface_38”, “Surface_41” and “Surface_42” (refer to Figure 4.10(c)). From Figure 4.10(b), the setup has a milling process, which uses a cutting tool, “CuttingTool_6”. “Makino_V55” is the machine used in the current setup.

The proposed fixture design for current setup is shown in Figure 4.11(a). From the OWL source code shown in Figure 4.11(b), it can be known that a locating unit contains a locator, whose name is BJ400-12075. This locator is translated (0.125, -0.125, 0.05) from its default position. From Figure 4.11(c), the OWL source code indicates that a clamping unit consists of two clamping elements, i.e. BJ101-022 and BJ500-12050. This clamping unit is positioned on the baseplate with “BaseplateID_53”.

Figure 4.12(a) shows finite-element mesh model for the fixture design. Each fixture element is simplified as a cube connected with a spring. The cube contacts with the workpiece with frictions, while the other end of the spring is fixed on the ground. This cube has boundary conditions at its displacement with free at contact surface normal direction and constrained in all other directions. <ADO:hasBC> tag in Figure 4.12(b) shows that the “Locator_1” is constrained at x and z directions. The tag <hasPhysicalRelations> shows that physical relationship, frictional touch, between the workpiece and one locator, “Locator_2”. The contact friction coefficient between these two objects is 0.34. The cutting forces are applied to fixture analysis with a series of peak static forces as the milling cutter cuts through different sections of the workpiece. It is realized by using a series of “LoadCase”. Each load case is regarded as a step in analysis solving. In Figure 4.12(c), each “LoadCase” contains forces with their three directional values and positions applied.




(a) the workpiece and a cutting tool in a setup

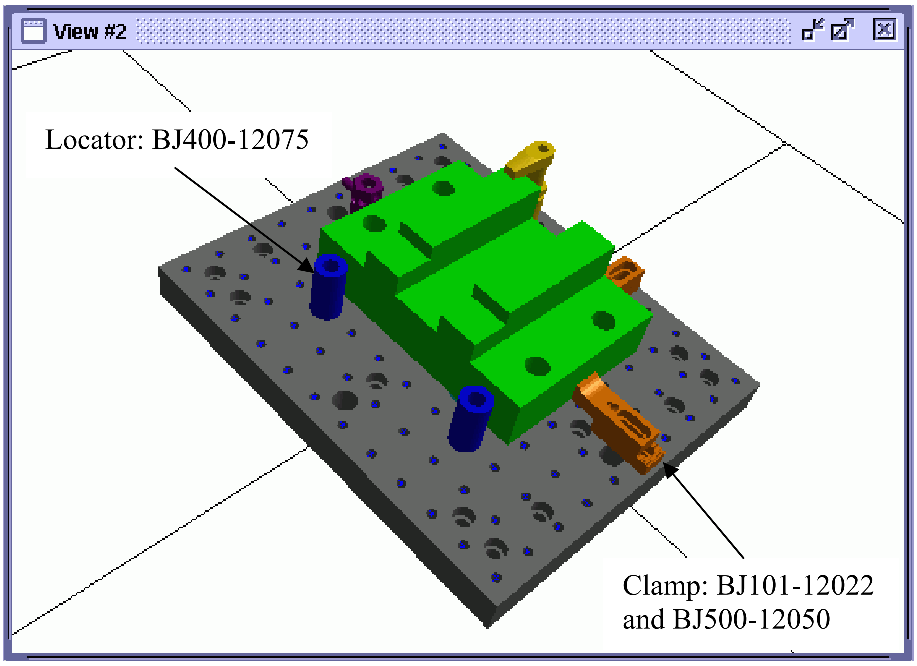
```
- <SDO:Setup rdf:ID="Setup_1">
    <SDO:hasProcess>
      - <SDO:Milling rdf:ID="EndMilling">
          <SDO:hasActiveFeature rdf:resource="http://www.owl-
          ontologies.com/2009/10/part_inst.owl#Slot_2" />
      -   <SDO:useTool>
            <SDO:CuttingTool rdf:ID="CuttingTool_6" />
          </SDO:useTool>
        </SDO:Milling>
    </SDO:hasProcess>
    <SDO:useMachine>
        <SDO:Machine rdf:ID="Makino_V55" />
    </SDO:useMachine>
```

(b) OWL source code for process associated with a setup

```
- <j.0:hasWorkpiece>
  - <rdf:Description rdf:about="http://www.owl-
      ontologies.com/2009/10/part_inst.owl#Workpiece_1">
        <SDO:hasActiveFeature rdf:resource="http://www.owl-
        ontologies.com/2009/10/part_inst.owl#Slot_2" />
        <SDO:hasActiveFace rdf:resource="http://www.owl-
        ontologies.com/2009/10/part_inst.owl#Surface_38" />
        <SDO:hasActiveFace rdf:resource="http://www.owl-
        ontologies.com/2009/10/part_inst.owl#Surface_42" />
        <SDO:hasActiveFace rdf:resource="http://www.owl-
        ontologies.com/2009/10/part_inst.owl#Surface_41" />
    </rdf:Description>
  </j.0:hasWorkpiece>
</SDO:Setup>
```

(c) OWL source code for the workpiece in a setup

Figure 4.10 An example for setup domain ontology representation




(a) the proposed fixture design

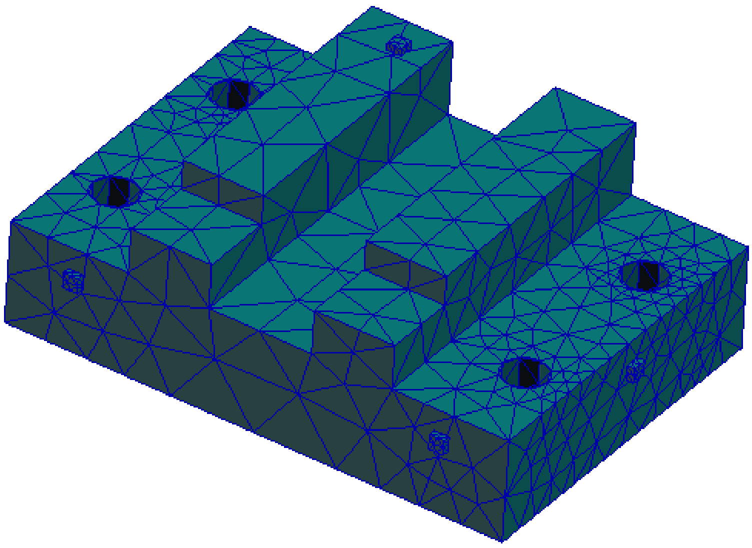
```
- <FDO:MachiningFixture rdf:ID="MachiningFixture_1">
  - <FDO:hasLocatingUnit>
    - <FDO:LocatingUnit rdf:ID="LocatingUnit_1">
      - <FDO:hasLocator>
        - <FDO:BJ400-12075 rdf:ID="BJ400-12075_8">
    - <hasTranslation>
    - <Translation rdf:ID="Translation_10">
        <y rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.125</y>
        <x rdf:datatype="http://www.w3.org/2001/XMLSchema#float">-0.125</x>
        <z rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.05</z>
      </Translation>
    </hasTranslation>
    +
    </FDO:BJ400-12075>
    </FDO:hasLocator>
```

(b) OWL source code for a locator in the fixture design

Figure 4.11 An example for fixture ontology representation

After solving the finite-element analysis, the stress and deformation profile of the workpiece are shown in Figure 4.13(a). Corresponding to the two “LoadCase” in ). Figure 4.12(c), the deformation at “locator_2” is shown in Figure 4.13(b), which is part of OWL source code for fixture analysis result. In Figure 4.13(b), it is shown that “Locator_2” has an attribute “hasDeformation” associated with “LoadCase_1”. The

<Deformation> tag contains <dataValue> at 0.00126 and its direction at (0, -1, 0). Under “LoadCase_2”, deformation value is 0.00132.



(a) Simplified geometries and generated mesh

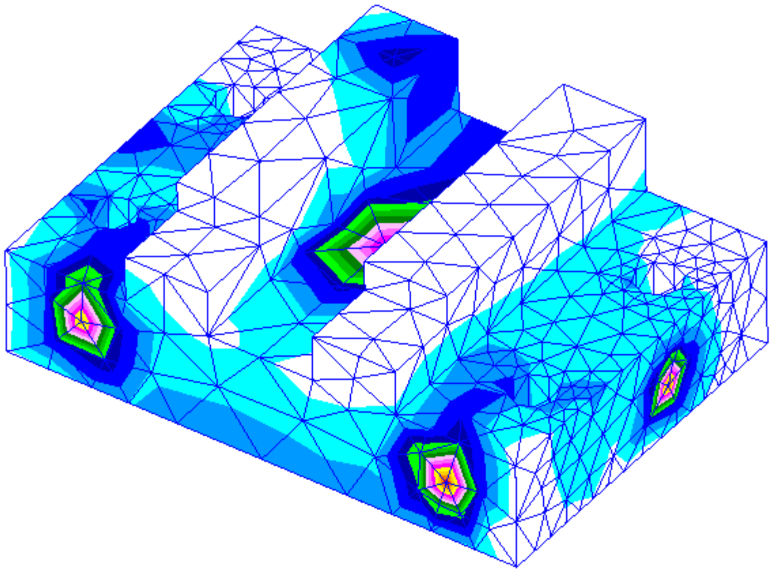
```
- <ADO:hasBC>
   - <ADO:BoundaryConditon rdf:ID="BoundaryConditon_1">
        <ADO:hasSubject rdf:resource="#Locator_1" />
      - <ADO:hasConstrain>
         - <ADO:Displacement rdf:ID="Displacement_3">
              <FIO:x rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0</FIO:x>
              <FIO:z rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0</FIO:z>
              <ADO:constrainOn rdf:resource="#Locator_1" />
           </ADO:Displacement>
        </ADO:hasConstrain>
     </ADO:BoundaryConditon>
  </ADO:hasBC>
- <ADO:hasPhysicalRelations>
   - <ADO:PhysicalRelationship rdf:ID="PhysicalRelationship_12">
        <ADO:hasParticipant rdf:resource="#Locator_2" />
        <ADO:hasParticipant rdf:resource="#Workpiece" />
      - <ADO:hasEffect>
         - <ADO:FrictionalTouch rdf:ID="FrictionalTouch_13">
              <mu rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.34</mu>
           </ADO:FrictionalTouch>
        </ADO:hasEffect>
     </ADO:PhysicalRelationship>
  </ADO:hasPhysicalRelations>
```

(b) OWL source code for control model in fixture analysis ontology

```
- <ADO:hasLoadCase>
 - <ADO:LoadCase rdf:ID="LoadCase_1">
  - <ADO:hasLoad>
   + <FDO:GravityForce rdf:ID="GravityForce_16">
     </FDO:GravityForce>
   + <FDO:GravityForce rdf:ID="ClampingForce_1">
     </FDO:GravityForce>
   + <FDO:GravityForce rdf:ID=" ClampingForce_2">
     </FDO:GravityForce>
   + <FDO:GravityForce rdf:ID=" ClampingForce_3">
     </FDO:GravityForce>
   - <FDO:MachiningForce rdf:ID="MachiningForce_13">
    - <hasPosition>
     - <Position rdf:ID="Position_15">
         <FIO:z rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.25</FIO:z>
         <FIO:x rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0050</FIO:x>
         <FIO:y rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0</FIO:y>
       </Position>
     </hasPosition>
   - <hasForceValue>
   - <ForceValue rdf:ID="forceValue">
         <FIO:z rdf:datatype="http://www.w3.org/2001/XMLSchema#float">-100.0</FIO:z>
         <FIO:x rdf:datatype="http://www.w3.org/2001/XMLSchema#float">550.0</FIO:x>
         <FIO:y rdf:datatype="http://www.w3.org/2001/XMLSchema#float">480.0</FIO:y>
     </ForceValue>
     </hasForceValue>
     </FDO:MachiningForce>
   </ADO:hasLoad>
   </ADO:LoadCase>
 </ADO:hasLoadCase>
- <ADO:hasLoadCase>
 - <ADO:LoadCase rdf:ID="LoadCase_2">
  - <ADO:hasLoad>
    ...
   - <FDO:MachiningForce rdf:ID="MachiningForce_14">
    - <hasPosition>
     - <Position rdf:ID="Position_15">
         <FIO:z rdf:datatype="http://www.w3.org/2001/XMLSchema#float">-0.25</FIO:z>
         <FIO:x rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0050</FIO:x>
         <FIO:y rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0</FIO:y>
       </Position>
     </hasPosition>
   - <hasForceValue>
   - <ForceValue rdf:ID="forceValue">
         <FIO:z rdf:datatype="http://www.w3.org/2001/XMLSchema#float">-100.0</FIO:z>
         <FIO:x rdf:datatype="http://www.w3.org/2001/XMLSchema#float">550.0</FIO:x>
         <FIO:y rdf:datatype="http://www.w3.org/2001/XMLSchema#float">480.0</FIO:y>
     </ForceValue>
     </hasForceValue>
     </FDO:MachiningForce>
   </ADO:hasLoad>
   </ADO:LoadCase>
 </ADO:hasLoadCase>
```

(c) OWL source code for multiple “LoadCase” in control model in fixture analysis ontology

Figure 4.12 An example for fixture analysis ontology representation



(a) Stress and deformation profile of fixture analysis result

```
- <ADO:LocatorEntity rdf:ID="Locator_2">
  + <ADO:hasContact>
  - <ADO:hasDeformation>
    - <ADO:hasLoadCase>
        <ADO:LoadCase rdf:ID="LoadCase_1" />
      </ADO:hasLoadCase>
    - <ADO:Deformation rdf:ID="Deformation_39">
      - <hasDir>
      - <Direction rdf:ID="Dir_1">
          <z rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0</z>
          <y rdf:datatype="http://www.w3.org/2001/XMLSchema#float">-1.0</y>
          <x rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0</x>
        </Direction>
        </hasDir>
        <dataValue
          rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.00126</dataValue>
      </ADO:Deformation>
    </ADO:hasDeformation>
  - <ADO:hasDeformation>
    - <ADO:hasLoadCase>
        <ADO:LoadCase rdf:ID="LoadCase_2" />
      </ADO:hasLoadCase>
    - <ADO:Deformation rdf:ID="Deformation_53">
      - <hasDir>
      - <Direction rdf:ID="Dir_7">
          <z rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0</z>
          <y rdf:datatype="http://www.w3.org/2001/XMLSchema#float">-1.0</y>
          <x rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0</x>
        </Direction>
        </hasDir>
        <dataValue
          rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.00132</dataValue>
      </ADO:Deformation>
    </ADO:hasDeformation>
```

(b) Part of OWL source code in fixture analysis result

Figure 4.13 An example for fixture analysis result representation

## 4.4 Summary

This chapter introduces fixture design knowledge representation using an ontology, which can provide common vocabulary for communication among the fixture design phases. Through providing platform-independent and neutral language for representing fixture design knowledge, OWL DL, which is used as the ontology language, supports integration of disparate CAFD systems in distributed environments. Based on the nature of fixture design process, the ontology is developed for following application domains: 3D parametric feature-based geometric modeling product, manufacturing related setup planning, fixture synthesis, and FEM-based fixture analysis. Moreover, an example is provided to show how the ontology-based fixture design knowledge representation is applied.

However, current ontology for fixture design knowledge is only developed at lab scale and has to be customized when it is used in an industry. Furthermore, current development is only focused on machining fixture. Assembly and inspection fixture is out of the scope of this study.

The relevant information from the developed knowledge representation scheme is transferred to the robust design system for identify the suitable points for fixturing. The developed robust design technique is explained in the next three chapters.

# Chapter 5 Robust Fixture Localization with Taguchi Method

In this chapter, a study on fixture layout synthesis using 3-2-1 locating scheme is carried out using robust design approach by combining Taguchi method [107] and Monte-Carlo statistical method [88] in order to increase the quality of the machined workpieces. Taguchi method is employed to study the locating effect of the locator's position at different levels and Monte-Carlo method is applied to simulate the variation of coordinates of the locating contact points.

## 5.1 Fixture Model

In this study, following assumptions have been made: (1) the workpiece is prismatic and rigid; the elastic deformations of the workpiece are negligible; (2) the fixture-workpiece contacts are modelled as points without friction; (3) the fixture layout uses 3-2-1 locating scheme; (4) machining tool error is not considered. Here, the following two types of error sources are only considered:

- locator profile error: a variation in the geometric shape of the locator;
- datum plane error: geometric variations on the physical datum features of the workpiece.

Figure 5.1 establishes the relationship between the various coordinate systems. The Global Coordinate System (GCS) is a fixed coordinate system in a three-dimensional space, while the Workpiece Coordinate System (WCS) is that attached to the center of mass of the workpiece. In this simulation model, a hole is to be drilled on the workpiece locating on a fixture. Whenever the locating points experience deviations, the exact position of the WCS with respect to the GCS will change. These changes detected in the fixed axes of GCS can then be used to calculate the deviation of the actual hole from its nominal position when an imperfect workpiece is fixtured for machining.

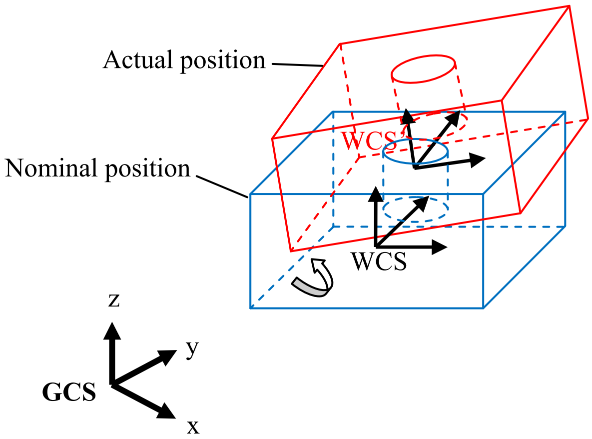



Figure 5.1 Coordinate systems of a 3D model.

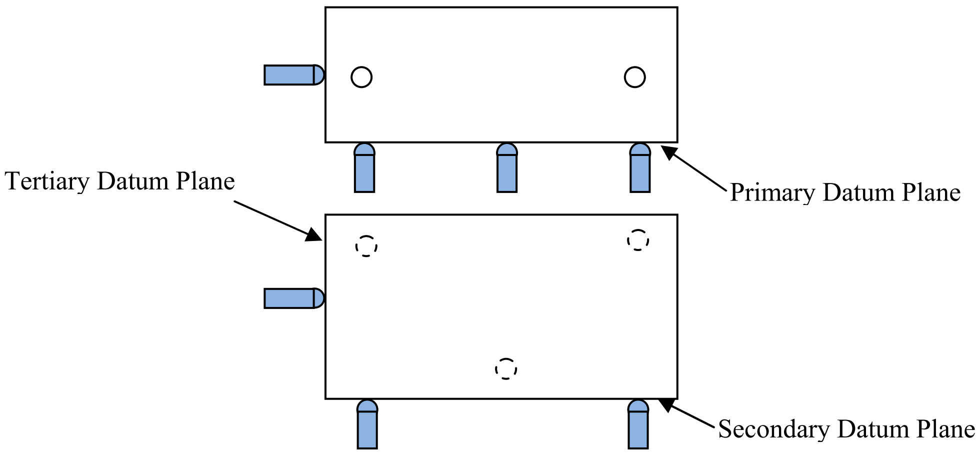



Figure 5.2 The workpiece is located on fixtures with 3-2-1 approach.

When a workpiece is loaded into a fixture, it contacts with all six locators at contact points (Figure 5.2), in which the part loading follows a sequence of steps: firstly contact points on the primary datum plane, and then on the secondary datum plane, finally on the tertiary datum plane. When the part is located on the fixture, the actual coordinated system, WCS', attached on the part may deviate from its nominal coordinated system WCS. This deviation is represented as $\delta\boldsymbol{q}=[\delta x, \delta y, \delta z, \alpha, \beta, \gamma]^T$. The homogeneous transformation matrix from WCS to WCS' is expressed as:

$$\mathbf{H}=\begin{bmatrix}\mathbf{R} & \delta\boldsymbol{t} \\ 0 & 1\end{bmatrix} \tag{5.1}$$

where $\delta\boldsymbol{t}=[\delta x, \delta y, \delta z]^T$ is the translation vector and **R** is the rotational matrix. The rotational angle deviations α, β, γ are small, hence the rotation matrix **R** can be simplified as:

$$\mathbf{R}=\begin{bmatrix}1 & -\sin\gamma & \sin\beta \\ \sin\gamma & 1 & -\sin\alpha \\ -\sin\beta & \sin\alpha & 1\end{bmatrix} \tag{5.2}$$

In the fixture-workpiece system, the nominal contact points are represented as $\mathbf{p}_i=[x_i, y_i, z_i]^T$ and the actual contact points as $\mathbf{p}_i^{'}=[x_i^{'} \quad y_i^{'} \quad z_i^{'}]^T$. The nominal and actual surface normal for primary, secondary and tertiary datum plane are represented as $\mathbf{n}_p$, $\mathbf{n}_s$, $\mathbf{n}_t$ and $\mathbf{n}_p^{'}$, $\mathbf{n}_s^{'}$, $\mathbf{n}_t^{'}$, respectively, where $\mathbf{n}_i=[n_{xi} \quad n_{yi} \quad n_{zi}]^T$ and $\mathbf{n}_i^{'}=[n_{xi}^{'} \quad n_{yi}^{'} \quad n_{zi}^{'}]^T$.

The normal vector of primary datum plane can be obtained from

$$\mathbf{n}_p=(\mathbf{p}_1-\mathbf{p}_2)\times(\mathbf{p}_1-\mathbf{p}_3) \tag{5.3}$$

$$\mathbf{n}_p^{'}=(\mathbf{p}_1^{'}-\mathbf{p}_2^{'})\times(\mathbf{p}_1^{'}-\mathbf{p}_3^{'}) \tag{5.4}$$

Based on 3-2-1 locating approach, where the three datum planes are perpendicular to each other, the normals for the secondary and tertiary datum plane are calculated as:

$$\mathbf{n}_s=\mathbf{n}_p\times(\mathbf{p}_4-\mathbf{p}_5) \tag{5.5}$$

$$\mathbf{n}_s^{'}=\mathbf{n}_p^{'}\times(\mathbf{p}_4^{'}-\mathbf{p}_5^{'}) \tag{5.6}$$

$$\mathbf{n}_t = \mathbf{n}_p \times \mathbf{n}_s \tag{5.7}$$

$$\mathbf{n}_t^{'} = \mathbf{n}_p^{'} \times \mathbf{n}_s^{'} \tag{5.8}$$

The rotational angle deviations α, β, and γ are obtained using a sequential quadratic programming (SQP) method [8] by solving the problem:

$$\min . \begin{cases} \mathbf{n}_p^{'} - \mathbf{R}\mathbf{n}_p \\ \mathbf{n}_s^{'} - \mathbf{R}\mathbf{n}_s \end{cases} \tag{5.9}$$

*subject to* Equation (5.2)-(5.8).

The translation vector is derived by considering the difference in the actual distance from the origin of the nominal and actual datum features along corresponding normal vectors $\mathbf{n}_p^{'}$, $\mathbf{n}_s^{'}$ and $\mathbf{n}_t^{'}$, *i.e.*

$$\delta\mathbf{t} = (d_p^{'} - d_p)\mathbf{n}_p^{'} + (d_s^{'} - d_s)\mathbf{n}_s^{'} + (d_t^{'} - d_t)\mathbf{n}_t^{'} \tag{5.10}$$

where $d_j^{'}$ and $d_j$ are the distance from the origin of GCS to the actual and nominal datum plane

$$d_j = \mathbf{p}_j \mathbf{n}_j^T \tag{5.11}$$

$$d_j^{'} = \mathbf{p}_j^{'} (\mathbf{n}_j^{'})^T \tag{5.12}$$

where $j=p, s, t$.

For a given point $\mathbf{X}_n$ on a manufactured feature, after the transformation, the true position $\mathbf{X}_t$ is given by $\mathbf{X}_t = \mathbf{X}_n + \xi$, where ξ is the positional deviation caused by localization error:

$$\begin{aligned} \xi &= \delta\mathbf{t} + \delta\boldsymbol{\theta} \times \mathbf{X}_n \\ &= \begin{bmatrix} \mathbf{I} & -\hat{\mathbf{X}}_n \end{bmatrix} \delta\mathbf{q} \end{aligned} \tag{5.13}$$

where $\mathbf{I} \in \Re^{3\times3}$ is the identity matrix, and the notation ^ for a vector $\mathbf{d}=[x, y, z]^T \in \Re^3$ which means

$$\hat{\mathbf{d}} = \begin{pmatrix} 0 & -z & y \\ z & 0 & -x \\ -y & x & 0 \end{pmatrix}$$

is a 3×3 skew-symmetric matrix uniquely identified with the linear cross product operator $\times\mathbf{d}$, i.e. for $\forall \omega \in \Re^3$, $\boldsymbol{\omega} \times \boldsymbol{d} = -\hat{\boldsymbol{d}}\boldsymbol{\omega}$.

## 5.2 Robust Design Methodology

In this research, the aim is to study the real location of the workpiece or fixture on the machine table considering the workpiece surface tolerances and fixturing errors. This process can be represented in the parameter-diagram (P-diagram), using associated variables such as noise, control, signal (input), and response (output) factors [79] . The P-diagram in Figure 5.3 illustrates the design process where the input signal (M) is transformed into output response (Y) by adjusting control factors (C) in the presence of noise factors (N). The geometry of the workpiece is the signal factor for the fixture design process. The response factors include the true location of the workpiece and the true position and orientation of key product characteristics (KPCs) on the workpiece. The geometrical features or the points on the workpiece surfaces are often used as KPCs. The KPCs also define the product functional characteristics and influence the quality of the final product.

The control factors are product parameters specification, such as design parameters, material and processes, whose values are the responsibility of the designer. The control variables in this research are the positioning and tolerance of the locating points. Each control factor can take more than one value, referred as levels. By adjusting the values of the control variables, the fixture is designed with minimum effects from the noise factors.

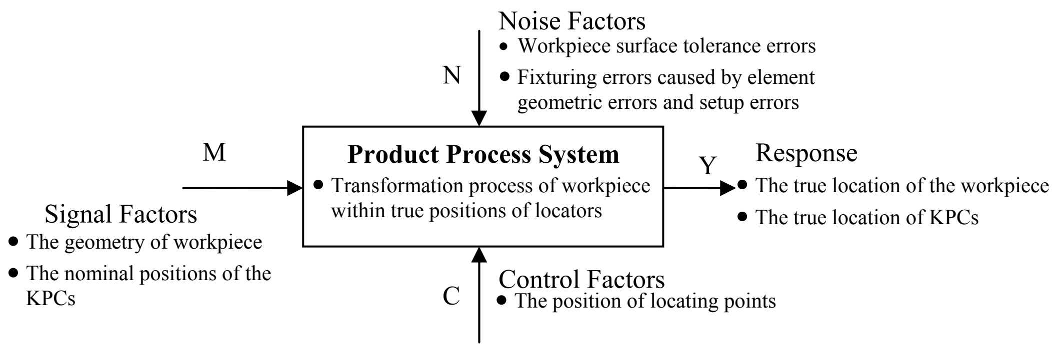



Figure 5.3 P-diagram for fixture design.

The noise factors, such as environmental factors, degradation over time, piece to piece variation, etc., can influence the design but are not under the control of the designer. If these noise factors not protected, they can downgrade the quality of product and make it useless. In this study, it is assumed that machining tool does not contribute any This is not wholly true in real case, but this allows us to focus on errors due to fixturing and datum planes on the workpiece. In this study, only two noise factors are considered, viz. (1) the dimensional and geometrical errors of the workpiece and (2) contact point errors due to locators' geometric errors and fixturing setup errors. Figure 5.4 illustrates some examples of the various forms of tolerance errors that can occur on the locating face of a workpiece.

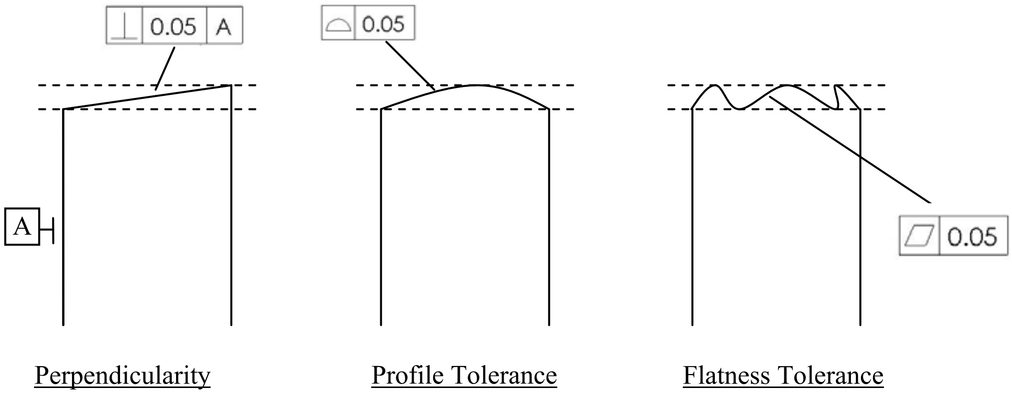



Figure 5.4 Various surface tolerance errors.

In this study, computer simulation is applied to simulate fixturing behavior to obtain locating variation using Robust Design approach combining Taguchi method and Monte-Carlo statistical method. In this simulation, Taguchi method is employed to study the locating effect of the locator's position at different levels and Monte-Carlo method is applied to generate variation of coordinates of the locating contact points and the associated uncertainty.

Taguchi design method is executed in a two-step procedure where quality during product design and development is measured, and experiments to detect dependable information about the design parameters are gathered. Orthogonal array (OA) is employed in order to reduce the number of test sets during running of simulations and the signal-to-noise (S/N) ratio is applied to represent the stochastic variability of simulation outputs and to evaluate the design performance.

### 5.2.1 Orthogonal Array

Orthogonal Array (OA) is useful in this study as it can significantly reduce the number of test sets during the running of simulations. The three-dimensional model used in this research involves six locators consisting of five different levels each as shown in Figure 5.5, such that a total of $5^6$ = 15,625 possible combinations exist. For each locating face, a set of 5 locating points will be assigned at random initially. Following the analysis of S/N ratios at each individual locating point, the set of locating points at each face can be further distributed around the locating faces in simulations, and eventually determine the locating point that returns the highest S/N ratio. When OA is applied to the simulation, it will be able to significantly reduce the number of combinations to 25, while providing uniformly distributed coverage of the test domain, ensuring relatively accurate test results for easy analysis.

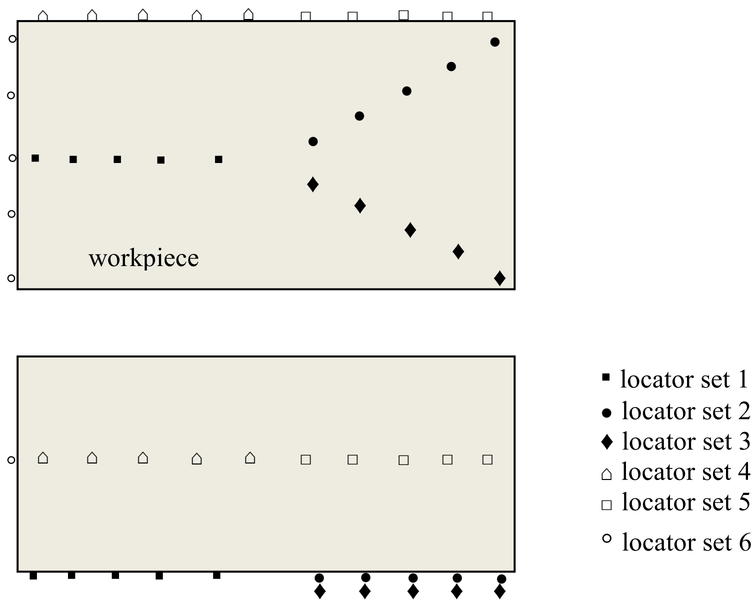



Figure 5.5 Each of the six locators possesses 5 different levels.

### 5.2.2 Signal-to-Noise Ratio

In robust design, S/N ratio tries to capture the magnitude of signals after making some adjustment for noises. It is utilized as a metric in deciding the best level for the control factors and measures robustness. In this study, the aim is to make sure that the true positions $\boldsymbol{X}_t$ of a KPC are as close to the nominal positions $\boldsymbol{X}_n$ as possible. That is, the distances between the true positions $\boldsymbol{X}_t$ and the nominal positions $\boldsymbol{X}_n$, $\xi = \|\boldsymbol{X}_t - \boldsymbol{X}_n\|$ ($\|\bullet\|$ represents Euclidean norm), need to be minimized. In real scenario, geometrical variations are also needed to be considered. Take the perpendicularity of a hole as an example, the perpendicular form error can be evaluated based on the deviation of two centre points of the hole:

$$\xi = \left| (\boldsymbol{X}_2 - \boldsymbol{O}_2)^T \boldsymbol{X}_2 - (\boldsymbol{X}_1 - \boldsymbol{O}_1)^T \boldsymbol{X}_1 \right| \tag{5.14}$$

where $\boldsymbol{X}_1$ and $\boldsymbol{X}_2$ are actual position and $\boldsymbol{O}_1$ and $\boldsymbol{O}_2$ are the nominal position of centre points of the hole.

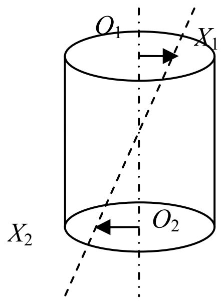



Figure 5.6 Perpendicular form error for a hole.

After Monte-Carlo simulation, S/N ratios can be calculated as a "smaller-the-better" problem:

$$snr = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\xi_i^2\right] \tag{5.15}$$

where $\xi_i = \left\| \mathbf{X}_t^i - \mathbf{X}_n \right\|$ and $n$ is the number of simulations. If multiple KPCs are selected in a single fixture setup, it is reasonable to use weight sum of S/N ratios for representation of the overall S/N ratio:

$$SNR = \sum_{j=1}^{m} w_j (snr)_j \tag{5.16}$$

where $m$ is the number of KPCs and $w_j$ is the weight of KPCs $(\sum w_j = 1)$.

Let us examine how the experimental data can be used to evaluate the S/N ratio of a locator, at a particular level. For illustration, the S/N ratio of locator 2 at level 2 can be obtained by the following steps. If locator 2 positions at level 2 are in experiments 2, 7, 12, 17 and 22 in the orthogonal array, in order to obtain the S/N ratio for the locator at this particular level, the average from the above experiments is worked out using following equation.

$$M_{L2-2} = \frac{(SNR)_2 + (SNR)_7 + (SNR)_{12} + (SNR)_{17} + (SNR)_{22}}{5} \tag{5.17}$$

The quantity $M_{L2-2}$ represents the average S/N ratio for locator 2 at level 2. This method of calculation applies to all other control variables in this study, and since the matrix experiment is derived from the orthogonal array, average value obtained will be statistically balanced.

## 5.3 Proposed Method

Based on the P-diagram illustrated in Figure 5.3, including noise factor, input signal factor, control factor and response, the procedure of the methodology developed in this paper is described as follows:

(1) the workpiece at current setup is loaded into the system; the geometric information of the workpiece, including dimensions and tolerances, is also input into the system;

(2) to determine the locating contact points at different levels $\mathcal{L}$ and to calculate their associated uncertainties due to surface tolerances $\tau_s$, fixturing setup and locator profile tolerances $\tau_f$;

(3) an orthogonal array $\mathcal{OA}$ is generated based on control factors $\mathcal{C}$ and their levels $\mathcal{L}$;

(4) the KPCs for the workpiece are specified;

(5) for each experiment representing by a row in the $\mathcal{OA}$

  (i) the number of simulation $N_s$ are set;

(ii) the variations are generated using Monte-Carlo simulation method based on locating positions, workpiece surfaces, and their associated tolerance, and then added to nominal contact points to obtain the true contact points;

(iii) the translation $\delta\mathbf{t}$ and rotation $\delta\boldsymbol{\theta}$ are computed based on Equation (5.9) and (5.10);

(iv) the deviations of KPCs$\{\xi\}$ are calculated based on Equation (5.13).

(v) the S/N ratio for current levels of control factors is calculated with Equation (5.15) and (5.16);

(6) the S/N ratios for each control factor at a particular level $\{M_{C\text{-}L}\}$ are calculated based on Equation (5.17).

(7) the best levels $\{\mathcal{L}_b\}$ of each locator are selected and combined as the robust locating layout;

## 5.4 Case Study

### 5.4.1 Example Description

This case study shall examine the effects of workpiece and locators tolerances in each individual locating datums, and how the tolerances in various datums result in variations on the machined feature. In this example, a cylindrical blind hole of $\phi$10mm × 20mm is drilled using a vertical machine centre (VMC) within a prismatic workpiece of steel AISI 5120 (Figure 5.7). In Figure 5.7, the primary, secondary and tertiary datum planes are bottom surface A and side surface B and C respectively. The surface flatness tolerances for the three datum planes is set to be 0.1mm, and the fixturing tolerance due to fixture setup error and locator profile error is assumed within ±0.05mm. In this study, the control factors $\mathcal{C}$ are the locators using 3-2-1 locating scheme, and their levels $\mathcal{L}$ are the candidate positions of the locators. The fixture locating layout follows the position levels illustrated in Figure 5.5 and the coordinates of candidate locating points are shown in Table 5.1. Considering the position tolerance and perpendicularity of the drilling hole (0.05 relative to plane A), the point $O_1$ and perpendicular form error are deemed as KPCs. RD is applied to a control model to generate the locating scheme that undergo the least variations from the errors of the workpiece and locators, and returns the highest average S/N ratio.

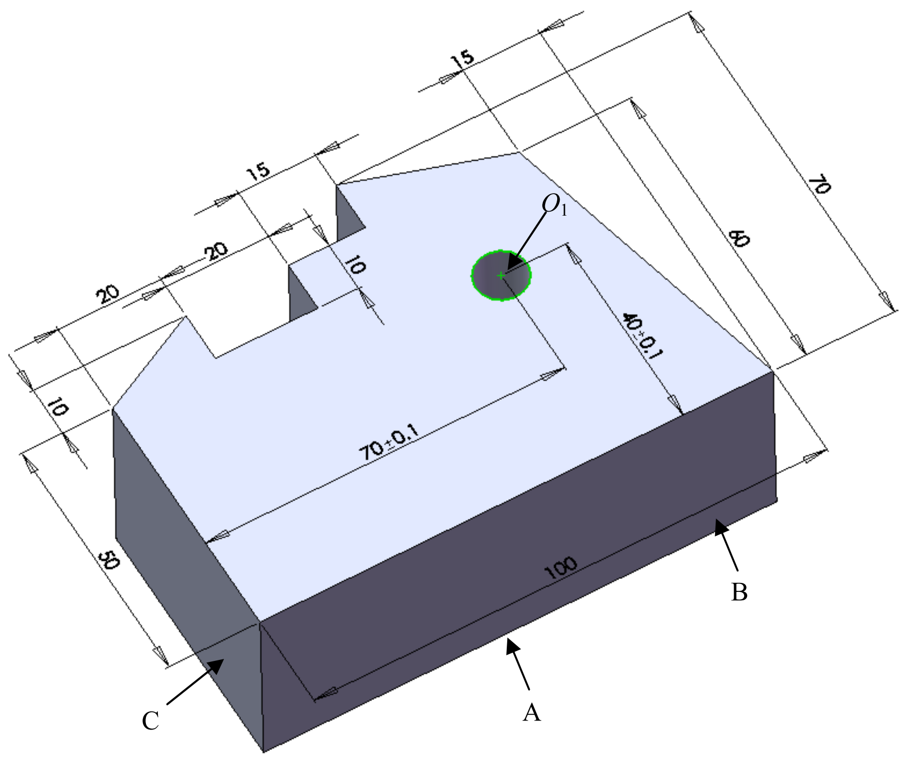



Figure 5.7 The workpiece for hole drilling (all dimension in *mm*).

Table 5.1 The coordinates of locating points at five levels.

| Control Factor ($\mathcal{C}$) | Levels (Coordinates of locators) | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| A: Locator 1 | (3, 25, 0) | (11, 25, 0) | (20, 25, 0) | (30, 25, 0) | (40, 25, 0) |
| B: Locator 2 | (98, 3, 0) | (90, 7, 0) | (80, 13, 0) | (70, 19, 0) | (60, 24, 0) |
| C: Locator 3 | (98, 49, 0) | (90, 44, 0) | (80, 38, 0) | (70, 32, 0) | (60, 26, 0) |
| D: Locator 4 | (3, 0, 20) | (10, 0, 20) | (20, 0, 20) | (30, 0, 20) | (40, 0, 20) |
| E: Locator 5 | (98 0, 20) | (90, 0, 20) | (80, 0, 20) | (70, 0, 20) | (60, 0, 20) |
| F: Locator 6 | (0, 5, 20) | (0, 15, 20) | (0, 25, 20) | (0, 35, 20) | (0, 45, 20) |

### 5.4.2 Simulation Results

In order to initialize the Monte-Carlo simulation, the locating contact points with uncertainties are introduced as initial values for the random number generation function. The true positions of contact points are generated with Gaussian random distribution $f_g(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp(\frac{-(x-\mu)^2}{2\sigma^2})$, where μ is the nominal coordinate value, and σ is the standard deviation that can be calculated using *σ=t/3*, where *t* is the tolerance at the contact point. Figure 5.8(a) shows the histogram of *z* data generated by Matlab for one locating point and Figure 5.8(b) shows probability plot of normal distribution for the generated data. If the plot is linear as shown in Figure 5.8(b), the generated data follow Gaussian distribution. Otherwise, the data follow another probability distribution, e.g. Binormal, Chi-Square, etc.

An orthogonal array can be constructed from the control factors and their levels. In this study, a L25 orthogonal array (Table 5.2) with 6 columns and 25 rows is chosen. Each control factor (locator) has five levels assigned to each column of the array. The 25 rows represent the 25 experiments to be conducted. The calculated S/N ratios for each experiment are listed in Table 5.2. Based on the simulation results with 1000 runs, a response table (Table 5.2) is derived for the control factors of each experiment and the average S/N ratio for each locator and each level is calculated and shown in Table 5.3. From Table 5.3 and Figure 5.9, the best level for each control factor can be identified, i.e. the best condition for locators become A1, B1, C1, D1, E1, F4.

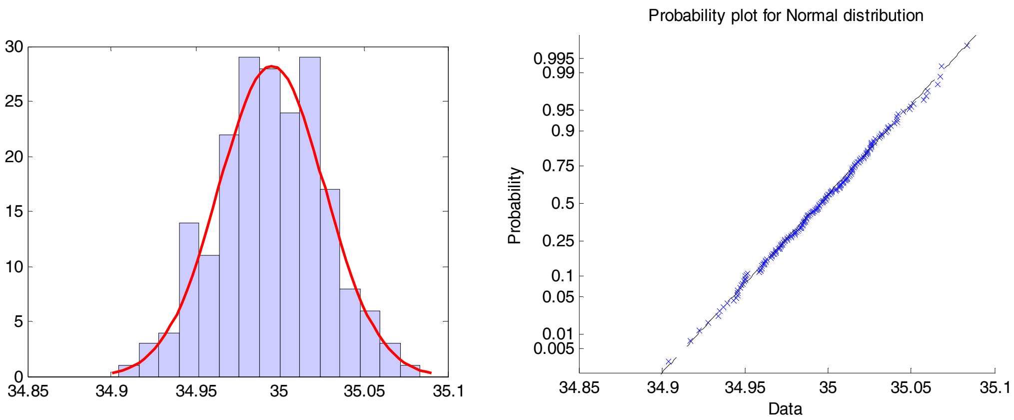



Figure 5.8 Normal distribution histogram (μ=35.002) and normal probability plot of sample data.

Table 5.2 Orthogonal array and S/N ratio for computational experiments.

| Experiment No. | Locator 1 | Locator 2 | Locator 3 | Locator 4 | Locator 5 | Locator 6 | S/N Ratio |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 73.0821 |
| 2 | 1 | 2 | 2 | 2 | 2 | 2 | 69.7547 |
| 3 | 1 | 3 | 3 | 3 | 3 | 3 | 64.6382 |
| 4 | 1 | 4 | 4 | 4 | 4 | 4 | 54.8679 |
| 5 | 1 | 5 | 5 | 5 | 5 | 5 | 30.9447 |
| 6 | 2 | 1 | 2 | 3 | 4 | 5 | 62.9378 |
| 7 | 2 | 2 | 3 | 4 | 5 | 1 | 49.5653 |
| 8 | 2 | 3 | 4 | 5 | 1 | 2 | 58.6271 |
| 9 | 2 | 4 | 5 | 1 | 2 | 3 | 57.6735 |
| 10 | 2 | 5 | 1 | 2 | 3 | 4 | 65.1877 |
| 11 | 3 | 1 | 3 | 5 | 2 | 4 | 63.9936 |
| 12 | 3 | 2 | 4 | 1 | 3 | 5 | 62.0992 |
| 13 | 3 | 3 | 5 | 2 | 4 | 1 | 50.1090 |
| 14 | 3 | 4 | 1 | 3 | 5 | 2 | 54.0577 |
| 15 | 3 | 5 | 2 | 4 | 1 | 3 | 65.1694 |
| 16 | 4 | 1 | 4 | 2 | 5 | 3 | 48.9875 |
| 17 | 4 | 2 | 5 | 3 | 1 | 4 | 56.5920 |
| 18 | 4 | 3 | 1 | 4 | 2 | 5 | 65.7836 |
| 19 | 4 | 4 | 2 | 5 | 3 | 1 | 60.7157 |
| 20 | 4 | 5 | 3 | 1 | 4 | 2 | 55.1545 |
| 21 | 5 | 1 | 5 | 4 | 3 | 2 | 50.4609 |
| 22 | 5 | 2 | 1 | 5 | 4 | 3 | 57.4806 |
| 23 | 5 | 3 | 2 | 1 | 5 | 4 | 54.2679 |
| 24 | 5 | 4 | 3 | 2 | 1 | 5 | 59.6057 |
| 25 | 5 | 5 | 4 | 3 | 2 | 1 | 51.9176 |

Table 5.3 Signal-to-noise ratio for locators at different levels.

| Control factor | | S/N Ratio at Different Levels | | | | | Deviation |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | |
| A | Locator 1 | 60.6994 | 58.9930 | 58.0895 | 57.2347 | 54.1284 | 6.5710 |
| B | Locator 2 | 62.7645 | 62.1555 | 60.4165 | 56.1238 | 47.6847 | 15.0798 |
| C | Locator 3 | 63.0199 | 62.7046 | 58.8076 | 55.5619 | 49.0511 | 13.9688 |
| D | Locator 4 | 59.1491 | 58.8798 | 58.8473 | 57.5460 | 54.7379 | 4.4112 |
| E | Locator 5 | 60.1488 | 58.8768 | 58.6672 | 57.5130 | 53.9392 | 6.2096 |
| F | Locator 6 | 57.2672 | 57.9863 | 58.8151 | 58.9372 | 56.1393 | 2.7979 |

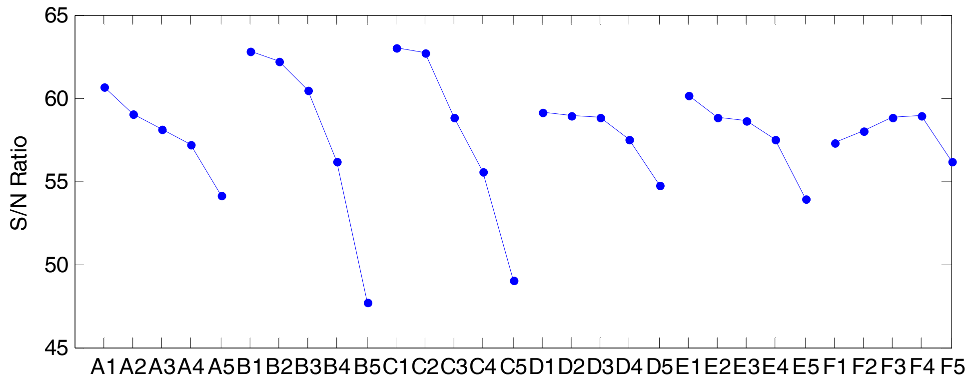



Figure 5.9 Signal-to-noise plot for control factors at different levels.

### 5.4.3 Simulation Comparison

#### *5.4.3.1 Layout comparison*

The importance of robustness will be more apparent when the robust locating layout is compared with the non-robust one. In Table 5.4, the layout no. 1 is a locating layout with best level at each locator and the second one is a random combination of locators. When the two layouts are simulated using Monte-Carlo method with 2000 runs, the positions of the centre of drilling-hole $O_1$ is shown in Figure 5.10, where the dash lines represent the boundaries of the tolerance of the centre position of the hole $O_1$. Comparing the two plots in Figure 5.10, it is obvious that the simulation positions of $O_1$ in Figure 5.10(a) are denser at the centre than those in Figure 5.10(b). Table 5.4 shows that the first locating layout obtains higher S/N ratio (76.56) and higher success rate (percentage of the simulated drilling-hole centers within the tolerance) at 98.25%

than the second one. Moreover, the mean and standard deviation (STD) of {ξ} in the first locating layout have lower value at 0.0026 and 0.003, while those in the second one have higher values at 0.0074 and 0.009. From above, it is obvious that the first locating layout (A1, B1, C1, D1, E1, F4) is more robust than the second layout (A3, B3, C3, D3, E3, F2).

Table 5.4 Comparison between robust and non-robust locating.

| No. | Layout | Mean | STD | SN_Ratio | Success Rate |
|---|---|---|---|---|---|
| 1 | A1, B1, C1, D1, E1, F3 | 0.0026 | 0.003 | 76.56 | 98.25% |
| 2 | A3, B3, C3, D3, E3, F2 | 0.0074 | 0.009 | 65.99 | 82.55% |

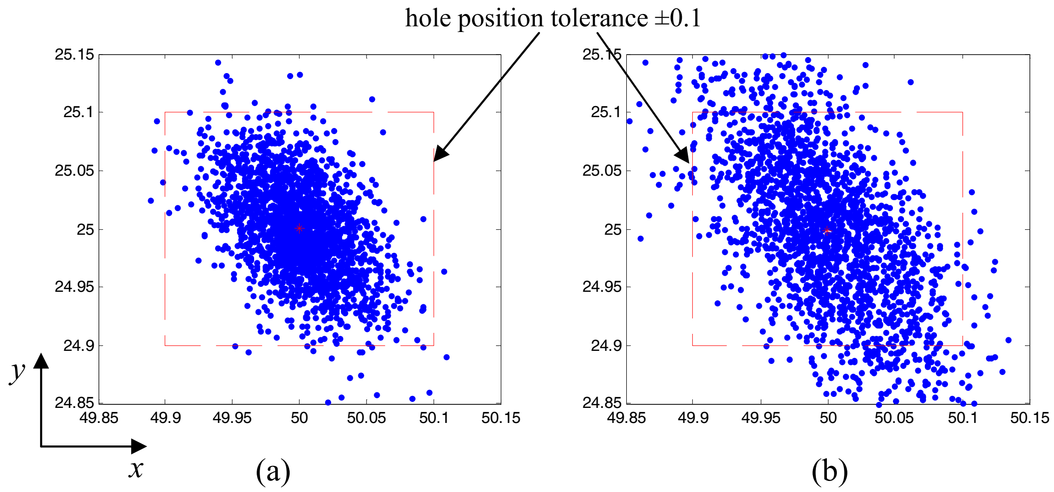



Figure 5.10 Positions of the centre of the drilling-hole (a) using the best locating layout (layout 1); (b) using a random selected locating layout (layout 2).

*5.4.3.2 Comparison for different drilling-hole centers*

In this section, a simulation is being conducted to get the robust locations with different positions of the drilling-hole centers. Figure 5.11 shows all centers of the drilling-holes, the coordinates of which are listed in Table 5.5. After a serial of simulations once with one hole, the simulation results are shown in Table 5.5. Although the positions of the hole centers are different, the best levels of locator 4 to 6 are almost consistent and only the level of locator 6 varies a little bit. Moreover, the S/N ratios vary with different positions of drilling-holes. The maximum S/N ratio is at hole #1 and the minimum S/N ratio is at hole #8. Meanwhile, hole #1 has the highest success rate at 99.68% and hole #8 has the lowest success rate at 92.44%.

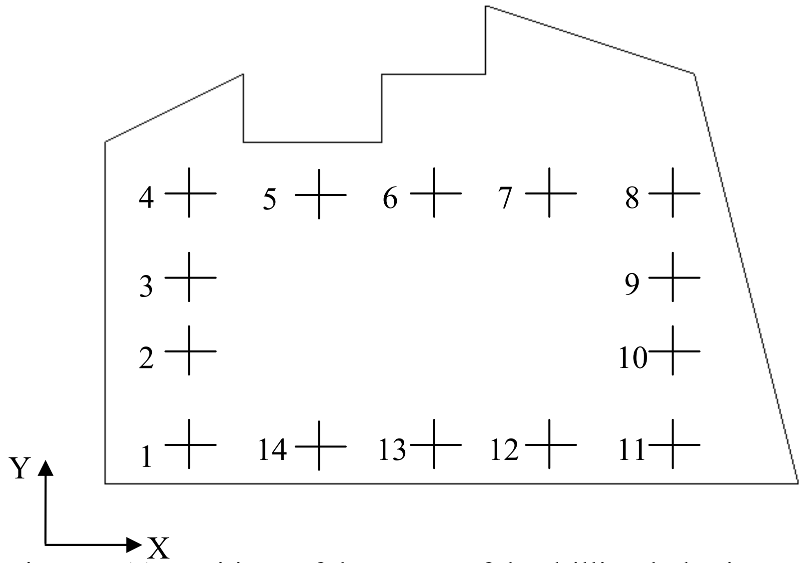



Figure 5.11. Positions of the centre of the drilling-holes in X-Y plane

Table 5.5 Results for different position of holes

| Hole no | Position | Locator 4 | Locator 5 | Locator 6 | SN Ratio | Success Rate (%) |
|---|---|---|---|---|---|---|
| 1 | (10, 10, 40) | 1 | 1 | 4 | 63.8395 | 99.68 |
| 2 | (10, 20, 40) | 1 | 1 | 5 | 63.7485 | 99.52 |
| 3 | (10, 30, 40) | 1 | 1 | 5 | 63.4816 | 99.4 |
| 4 | (10, 40, 40) | 1 | 1 | 5 | 63.3532 | 99.46 |
| 5 | (30, 40, 40) | 1 | 1 | 4 | 61.7166 | 98.76 |
| 6 | (50, 40, 40) | 1 | 1 | 4 | 60.0309 | 97.62 |
| 7 | (70, 40, 40) | 1 | 1 | 4 | 57.8838 | 96.16 |
| 8 | (80, 40, 40) | 1 | 1 | 4 | 55.8466 | 92.44 |
| 9 | (80, 30, 40) | 1 | 1 | 4 | 56.2689 | 93.02 |
| 10 | (80, 20, 40) | 1 | 1 | 4 | 56.1928 | 93.1 |
| 11 | (80, 10, 40) | 1 | 1 | 4 | 56.2287 | 93.34 |
| 12 | (70, 10, 40) | 1 | 1 | 4 | 58.7414 | 97.06 |
| 13 | (50, 10, 40) | 1 | 1 | 4 | 61.0421 | 98.78 |
| 14 | (30, 10, 40) | 1 | 1 | 4 | 62.8455 | 99.4 |

*5.4.3.3 Comparison with different locating surface tolerances*

In addition, the tolerance on each locating datum is assumed to encompass all workpiece surface variations (such as surface roughness, waviness, form errors etc.), locating setup errors and locator geometry errors. Robustness at the various settings is measured in terms of S/N ratios and examination of the results obtained from varying the tolerance setting at different datums revealed that each locating surface contribute differently to the errors in the KPCs. As shown in Table 5.6, four experiments are conducted using the procedure described in Section 5.3, in which the tolerances at contact points on the different surfaces are varied. After simulation, the S/N ratios of the best level for each control factor are selected and the averages of them are calculated.

Table 5.6 Comparison of overall S/N ratios due to surface tolerance effect.

| No. | Contact Points Tolerance on the Surfaces | S/N Ratio at Various Locators | | | | | | Average S/N Ratio |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | |
| 1 | All surfaces = ±0.1 mm | 43.92 | 44.70 | 46.32 | 44.96 | 44.19 | 42.84 | 44.49 |
| 2 | Primary Surface = ±0.15 mm<br>Secondary Surface = ±0.1 mm<br>Tertiary Surface = ±0.1 mm | 40.88 | 41.36 | 42.81 | 40.24 | 39.35 | 38.97 | 40.60 |
| 3 | Secondary Surface = ±0.15 mm<br>Primary Surface = ±0.1 mm<br>Tertiary Surface = ±0.1 mm | 41.04 | 42.92 | 43.33 | 43.19 | 42.73 | 40.65 | 42.31 |
| 4 | Tertiary Surface = ±0.15 mm<br>Primary Surface = ±0.1 mm<br>Secondary Surface = ±0.1 mm | 43.60 | 44.17 | 46.04 | 44.68 | 43.87 | 42.77 | 44.19 |

The tabulation of results in the three different scenarios is consolidated in Table 5.6. Based on the control model, with tolerances on the surfaces fixed at 0.1mm, an average S/N ratio of 44.49 is attained. The increased tolerances of contact points in the primary surface have the most drastic effect on the overall S/N ratio, and the average S/N ratio dropped from 44.49 to 40.60. Similar phenomenon has occurred for tolerance changes of contact points in the secondary and tertiary surfaces, though not as severe. Tolerances increase in the secondary locating surface led to a 2.18 drop in overall S/N ratio, and that for the tertiary locating surface lead to a mild 0.3 decrease in S/N ratio. This trend can be attributed to the fact that the primary locating datum consists of three contacting points, thus contributing more errors to the machined hole as compared to surfaces with less locators, and consequently giving rise to less locating errors. The same deduction can be applied to the secondary datum. When the secondary datum experiences greater deviation as a result of errors, the two locators in contact with the secondary datum will result in more errors as compared to the single locator in the tertiary datum.

The discovery of such fixture behavior is especially useful for fixture designers, as it prompts for further attention to be paid during the placement of locators in the primary datum. Robust design can be applied to determine the suitability of each point for location, which will result in the best S/N ratio. For the datums that are deemed more sensitive to tolerance variations, fixture designers may consider arresting these deviations by tightening the tolerances of workpiece surfaces. However, these measures are taken usually at the expense of higher production cost.

### 5.4.4 Discussions & Recommendations

Although drilling a hole is only studied to analyze the robustness of fixture design in this case study, the approach can be extended to other machining operation, e.g. cutting a slot, milling a surface, etc. Take cutting a slot as an example, multiple points along the cutting path can be selected as KPCs. After conducting simulations, the average S/N ratio can be used as the measurement of robustness.

An area for exploration to further enhance the use of RD in fixtures is to factor clamping forces and external forces into simulations to provide a more realistic study. In an actual working environment, varying cutting processes and fixturing methods will contribute differently to the accuracy of machining. The inclusion of the force components in the proposed method will thus provide users with a more reasonable feedback.

As orthogonal array is limited at only a few levels, a locator can only be contacted with workpiece at specified positions, such that it is difficult to reach the optimal locating positions on the workpiece. In order to make up for the downfalls of orthogonal array in Taguchi method, the proposed method can be improved by incorporating a search algorithm (e.g. genetic algorithm) to explore the whole points on the workpiece surfaces. In addition, accuracy of locating can also be improved with the search algorithm and positions of contact points can be optimized. This is discussed in the next chapter.

## 5.5 Summary

In this chapter, a 3D fixture design simulation model has been developed to explore the effects of surface tolerances, which arises due to dimensional and geometrical variations, on optimal location of a workpiece. This study has shown that the errors on the locators and workpiece have significant effects on the features to be machined and thus these variations should not be ignored. The noise factors which are usually indicated by tolerance values of the workpiece surface have significant effect on the machining features. Using robust design approach, the noise effect across a large batch size can be significantly reduced such that the errors on the machining feature due to the fixture can be minimized. From the case study illustrated in this chapter, it is evident that the errors on the drilling holes using VMC can be significantly reduced if the tolerance on the primary datum plane can be tightly controlled.

# Chapter 6 Fixture Robust Design for Localization using Genetic Algorithm

Due to surface errors and fixture set-up errors, the fixtured workpieces have positional and orientation errors that consequently affect product quality. This chapter introduces a robust design method with genetic algorithm to minimize point-wise manufacturing errors on the machining features and thus to improve product quality by simulating locating process with Monte-Carlo statistical method. The evaluation criteria focus on both the workpiece localization accuracy and insensitivity to contact point errors between fixture elements and workpiece. A case study is carried out to illustrate the proposed method and a comparison is conducted with non-robust fixture design.

## 6.1 Fixture Problem Formation

### 6.1.1 Workpiece localization

In the process of loading a part on a fixture for a machining operation, geometrical errors of machining features on the part are generated due to the three types of source errors. In Figure 6.1, the solid-line objects represent the nominal position of the workpiece and fixture elements and the dash-line objects indicate the actual positions. The coordinate systems (CS) are described as follows:

- CS1 ($O_1X_1Y_1Z_1$) is the global coordinate system (GCS) that is often attached with the machine table and selected as the machine coordinate system.

- CS2 ($O_2X_2Y_2Z_2$) is the nominal design coordinate system indicating the machining part location and $\mathbf{q}_p=[\mathbf{d}_p^T,\boldsymbol{\theta}_p^T]^T = [x_p, y_p, z_p, \alpha_p, \beta_p, \gamma_p]^T$ represents the position and orientation of the workpiece under GCS.
- CS3 is the actual part coordinate system. The deviation between CS3 and CS2 is the part positional and rotational error represented by $\delta\mathbf{q}_p=[\delta\mathbf{d}_p^T,\delta\boldsymbol{\theta}_p^T]^T = [\delta x_p, \delta y_p, \delta z_p, \delta\alpha_p, \delta\beta_p, \delta\gamma_p]^T$.
- CS4 ($O_4X_4Y_4Z_4$) is the nominal coordinate system of the $i$th fixture element and $\mathbf{q}_e=[\mathbf{d}_e^T,\boldsymbol{\theta}_e^T]^T = [x_e, y_e, z_e, \alpha_e, \beta_e, \gamma_e]^T$ represents the position and orientation of the origin $O_4$ of CS4 under GCS.
- CS5 is the actual coordinate system of the $i$th fixture element. The deviation between CS5 and CS4 is the fixture element positional and rotational error represented by $\delta\mathbf{q}_e=[\delta\mathbf{d}_e^T,\delta\boldsymbol{\theta}_e^T]^T$.
- CS6 is the nominal coordinate system of the $j$th feature on the workpiece with respect to CS2.
- CS7 is the actual coordinate system of the $j$th feature. The deviation between CS7 and CS6 is the feature's error represented by $\delta\mathbf{q}_f=[\delta\mathbf{d}_f^T,\delta\boldsymbol{\theta}_f^T]^T$.

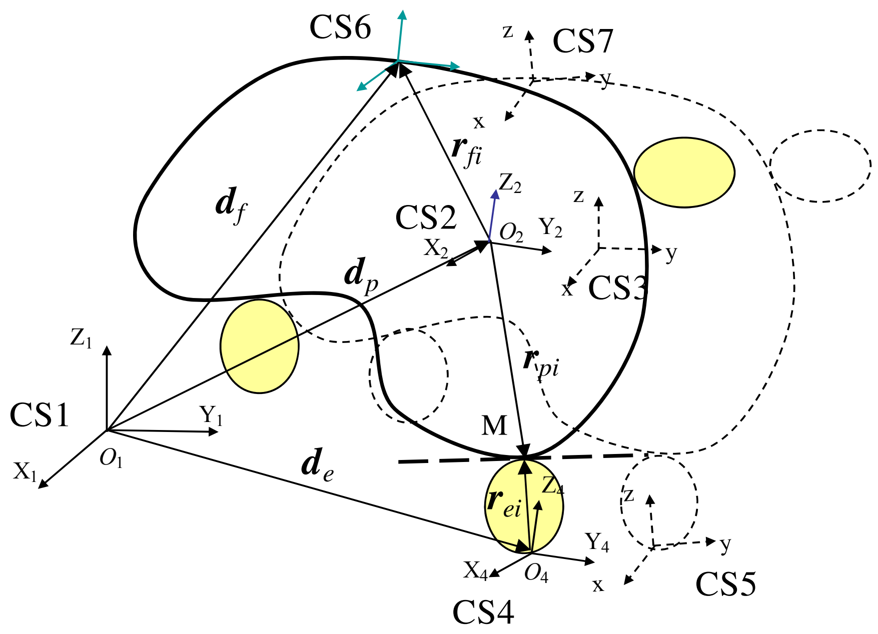



Figure 6.1 Fixture coordinate frames

In fixture-workpiece system, the workpiece must be contacted with fixture elements, then at the *i*th contact point of the workpiece surface, the equation of tangent plane related to GCS is represented as:

$$\phi_i(\mathbf{r},\mathbf{q}_p,\mathbf{r}_{pi}) = \mathbf{n}_i^{'T}\, {}_G^P R(\mathbf{r}-\mathbf{d}_p) - \mathbf{n}_i^{'T}\mathbf{r}_{pi} \tag{6.1}$$

where ${}_G^P R \in \Re^{3\times3}$ is rotational matrix from CS1 to CS2, $\mathbf{d}_\mathrm{p}$ is the positional vector of the origin of CS2 ($O_2$) in CS1, $\mathbf{r}_{pi}$ denotes the positional vector of the *i*th contact point in CS2, and $\mathbf{n}_i^{'}$ represents the outward normal direction of the workpiece surface at the *i*th contact point.

Similarly, at the *i*th contact point of the locator surface, the equation of tangent plane related to GCS is represented as:

$$\varphi_i(\mathbf{r},\mathbf{q}_e,\mathbf{r}_{ei}) = {}_P^E R\mathbf{n}_i^{'T}\, {}_G^E R(\mathbf{r}-\mathbf{d}_e) - {}_P^E R\mathbf{n}_i^{'T}\mathbf{r}_{ei} \tag{6.2}$$

where ${}_{P}^{E}R \in \Re^{3\times3}$ is rotational matrix from CS2 to CS4, ${}_{G}^{E}R \in \Re^{3\times3}$ is rotational matrix from CS1 to CS4, $\mathbf{r}_e$ is the positional vector of the origin of CS4 ($O_4$) in CS1, and $\mathbf{r}_{ei}$ denotes the positional vector of the *i*th contact point in CS4.

Since the two equations represent the same plane at the global coordinate system CS1, these two equations are equal, i.e. $\phi_i(\mathbf{r},\mathbf{q}_p,\mathbf{r}_{pi}) = \varphi_i(\mathbf{r},\mathbf{q}_e,\mathbf{r}_{ei})$. When the locators move to new position due to fixture setup error, the part has to transform from CS2 to CS3 in order to keep contact with the locators. The new position of contact point between the *i*th locator and workpiece is represented using first order Taylor's explanation series:

$$\phi_i(\mathbf{r},\mathbf{q}_p+\delta\mathbf{q}_p,\mathbf{r}_{pi}+\delta\mathbf{r}_{pi}) = \phi_i(\mathbf{r},\mathbf{q}_p,\mathbf{r}_{pi}) + \frac{\partial\phi_i}{\partial\mathbf{q}_p}\delta\mathbf{q}_p + \frac{\partial\phi_i}{\partial\mathbf{r}_{pi}}\delta\mathbf{r}_{pi} \tag{6.3}$$

$$\varphi_i(\mathbf{r},\mathbf{q}_e+\delta\mathbf{q}_e,\mathbf{r}_{ei}+\delta\mathbf{r}_{ei}) = \varphi_i(\mathbf{r},\mathbf{q}_e,\mathbf{r}_{ei}) + \frac{\partial\varphi_i}{\partial\mathbf{q}_e}\delta\mathbf{q}_e + \frac{\partial\varphi_i}{\partial\mathbf{r}_{ei}}\delta\mathbf{r}_{ei} \tag{6.4}$$

As mentioned above, the two equations indicate the identical plane at the GCS, then

$$\phi_i(\mathbf{r},\mathbf{q}_p+\delta\mathbf{q}_p,\mathbf{r}_{pi}+\delta\mathbf{r}_{pi}) = \varphi_i(\mathbf{r},\mathbf{q}_e+\delta\mathbf{q}_e,\mathbf{r}_{ei}+\delta\mathbf{r}_{ei}) \tag{6.5}$$

$$\frac{\partial\phi_i}{\partial\mathbf{q}_p}\delta\mathbf{q}_p + \frac{\partial\phi_i}{\partial\mathbf{r}_{pi}}\delta\mathbf{r}_{pi} = \frac{\partial\varphi_i}{\partial\mathbf{q}_e}\delta\mathbf{q}_e + \frac{\partial\varphi_i}{\partial\mathbf{r}_{ei}}\delta\mathbf{r}_{ei} \tag{6.6}$$

or in a compact form:

$$J_i\delta\mathbf{q}_p = G_i\delta\mathbf{q}_e - \mathbf{n}_i^{'T}\delta\mathbf{r}_{pi} + {}_{P}^{E}R\mathbf{n}_i^{'T}\delta\mathbf{r}_{ei} \tag{6.7}$$

Equation (6.7) represents the general locating error model in the workpiece-fixture system. It describes the relationship between the workpiece deviation $\delta\mathbf{q}_p$, the orientation and position error $\delta\mathbf{q}_e$ of the *i*th locator and the position errors $\delta\mathbf{r}_{ei}$ & $\delta\mathbf{r}_{pi}$ of the *i*th contact point on the workpiece.

For simplification and generality, the orientations of the part and fixture nominal coordinate systems (CS2 and CS4) are taken same as that of the global coordinate system (CS1). In that case, ${}_P^E R$, ${}_G^E R$ and ${}_G^P R$ are identity matrix and the matrix form of Equation (6.7) can be rearranged as:

$$J_i \delta \mathbf{q}_p = G_i \delta \mathbf{q}_{ei} - \mathbf{n}_i^{'T} (\delta \mathbf{r}_{pi} - \delta \mathbf{r}_{ei}) \tag{6.8}$$

Meanwhile, a small deviation of the workpiece and the locator can be represented by homogenous transformation matrixes $T_p = \begin{bmatrix} R_p & \mathbf{d}_p + \delta \mathbf{d}_p \\ \mathbf{0} & 1 \end{bmatrix}$ and $T_e = \begin{bmatrix} R_e & \mathbf{d}_e + \delta \mathbf{d}_e \\ \mathbf{0} & 1 \end{bmatrix}$,

where $R_p = \begin{bmatrix} 1 & -\delta\gamma_p & \delta\beta_p \\ \delta\gamma_p & 1 & -\delta\alpha_p \\ -\delta\beta_p & \delta\alpha_p & 1 \end{bmatrix}$ and $R_e = \begin{bmatrix} 1 & -\delta\gamma_e & \delta\beta_e \\ \delta\gamma_e & 1 & -\delta\alpha_e \\ -\delta\beta_e & \delta\alpha_e & 1 \end{bmatrix}$, then the matrix $J_i$ and $G_i$ can be calculated as:

$$J_i = \left[ -n_{ix}^{'}, -n_{iy}^{'}, -n_{iz}^{'}, (n_{iz}^{'} r_{pi}^{y} - n_{iy}^{'} r_{pi}^{z}), (n_{ix}^{'} r_{pi}^{z} - n_{iz}^{'} r_{pi}^{x}), (n_{iy}^{'} r_{pi}^{x} - n_{ix}^{'} r_{pi}^{y}) \right] \tag{6.9}$$

$$G_i = \left[ -n_{ix}^{'}, -n_{iy}^{'}, -n_{iz}^{'}, (n_{iz}^{'} r_{ei}^{y} - n_{iy}^{'} r_{ei}^{z}), (n_{ix}^{'} r_{ei}^{z} - n_{iz}^{'} r_{ei}^{x}), (n_{iy}^{'} r_{ei}^{x} - n_{ix}^{'} r_{ei}^{y}) \right] \tag{6.10}$$

When the workpiece is constrained by $m$ locators, the matrix equation is formalized as:

$$J \delta \mathbf{q}_p = G^T \Delta \mathbf{q}_e - N^T (\Delta \mathbf{r}_p - \Delta \mathbf{r}_e) \tag{6.11}$$

where

$$J = \left[ J_1^T, J_2^T, \ldots, J_m^T \right]^T \in \Re^{m \times 6}$$

$$G = diag\left[ G_1^T, G_2^T, \ldots, G_m^T \right] \in \Re^{6m \times m}$$

$$N = diag\left[ \mathbf{n}_1^{'}, \mathbf{n}_2^{'}, \ldots, \mathbf{n}_m^{'} \right] \in \Re^{3m \times m}$$

$$\Delta \mathbf{q}_e = [\delta \mathbf{q}_{e1}^T, \cdots, \delta \mathbf{q}_{em}^T]^T \in \Re^{6m \times 1}$$

$$\Delta \mathbf{r}_e = [\delta \mathbf{r}_{e1}^T, \cdots, \delta \mathbf{r}_{em}^T]^T \in \Re^{3m \times 1}$$

$$\Delta \mathbf{r}_p = [\delta \mathbf{r}_{p1}^T, \cdots, \delta \mathbf{r}_{pm}^T]^T \in \Re^{3m \times 1}$$

To calculate $\delta\mathbf{q}_p$, Equation (6.11) can be expressed as

$$\delta\mathbf{q}_p = J^{-1}G^T\Delta\mathbf{q}_e - J^{-1}N^T\Delta\mathbf{r}_p + J^{-1}N^T\Delta\mathbf{r}_e \tag{6.12}$$

In this equation, the first term on the right-hand-side (RHS) represents the position and orientation error of locating elements. In practice, all the locators are fixed and immovable in the workpiece-fixture systems and the desired position and orientation can be obtained, so that this term is normally neglected. The second term on the RHS represents the workpiece surface errors at contact points and the third term denotes the locating errors.

The Equation (6.12) is only valid when the Jacobian $J$ is nonsingular, i.e. the workpiece is deterministically located. In that case, the workpiece is fully constrained in its six degree-of-freedoms (DOFs). In order to calculate $\delta\mathbf{q}_p$ at the under location situation as well, the Equation (6.12) can be written as:

$$\delta\mathbf{q}_p = J^{+}(G^T\Delta\mathbf{q}_e - N^T(\Delta\mathbf{r}_p - \Delta\mathbf{r}_e)) + (I - J^{+}J)\lambda \tag{6.13}$$

where $J^+$ is a Moore-Penrose inverse matrix of $J$, and $\lambda \in \Re^{6\times1}$ is an arbitrary constant vector. In this equation, the second term $(I - J^{+}J)\lambda$ of RHS introduces the freedom of the workpiece unconstrained by locators. If the workpiece is complete location, i.e. fully constrained at six DOFs by locators, the second term will be zero. If it is under location, the second term generates large value element at the unconstrained DOF.

### 6.1.2 The Machining Features Accuracy

Each machining feature is represented as parametric set $F=\{\boldsymbol{d}_f, \boldsymbol{\theta}_f, \boldsymbol{f}_d, \boldsymbol{f}_F\}$, where location vector $\mathbf{d}_f = [x_f, y_f, z_f]^T$, orientation vector $\boldsymbol{\theta}_f = [\alpha_f, \beta_f, \gamma_f]^T$, geometric parametric set $\mathbf{f}_d = [p_1, p_2, \ldots, p_m]^T$, and form equation $\mathbf{f}_F$: $F(x, y, z)=0$.

In Figure 6.1, the positional deviation from CS6 to CS7 caused by workpiece locating error is given as:

$$\delta\mathbf{d}_f = \delta\mathbf{d}_p + \delta\boldsymbol{\theta}_p \times \mathbf{d}_f = \begin{bmatrix} I & -\hat{\mathbf{d}}_f \end{bmatrix} \delta\mathbf{q}_p \tag{6.14}$$

where $I \in \Re^{3\times3}$ is the identity matrix, and the notation ^ for a vector $\mathbf{d}=[x, y, z]^T \in \Re^3$ which means

$$\hat{\mathbf{d}} = \begin{pmatrix} 0 & -z & y \\ z & 0 & -x \\ -y & x & 0 \end{pmatrix}$$

is a 3×3 skew-symmetric matrix uniquely identified with the linear cross product operator $\mathbf{d}\times$, i.e. for $\forall\boldsymbol{\omega} \in \Re^3$, $\mathbf{d}\times\boldsymbol{\omega} = \hat{\mathbf{d}}\boldsymbol{\omega}$ [71].

Since the workpiece is rigid object, the rotational deviation from CS6 to CS7 can be obtained from $\delta\boldsymbol{\theta}_f = {}^{F_j}_{G}R\delta\boldsymbol{\theta}_p$, where ${}^{F_j}_{G}R$ is the rotation matrix for the $j$th feature coordinate system CS6 in GCS. Thus the deviation of the $j$th feature on the workpiece can be expressed as:

$$\delta\mathbf{q}_f = \begin{bmatrix} I & -\hat{\mathbf{d}}_f \\ O & {}^{F_j}_{G}R \end{bmatrix} \delta\mathbf{q}_p \tag{6.15}$$

For a given key point $\mathbf{t} \in \Re^3$ on the feature to be machined in the current setup, its positional deviation $\delta\mathbf{t}$ caused by the workpiece error $\delta\mathbf{q}_p$ can be calculated same as Equation (6.14), i.e.

$$\delta\mathbf{t} = \delta\mathbf{d}_p + \delta\boldsymbol{\theta}_p \times \mathbf{t} = \begin{bmatrix} I & -\hat{\mathbf{t}} \end{bmatrix} \delta\mathbf{q}_p \tag{6.16}$$

In some manufacturing applications, considered is the directional deviation, which means the deviation of the point $\mathbf{t} \in \Re^3$ in a given direction $\mathbf{s} \in \Re^3$. Thus, the directional point-wise manufacturing error can be obtained from:

$$d = \mathbf{s}^T \delta \mathbf{t} = \mathbf{s}^T \begin{bmatrix} I & -\hat{\mathbf{t}} \end{bmatrix} \delta \mathbf{q}_p \tag{6.17}$$

For a set of key points $P=\{\mathbf{t}_i, i=1,\ldots,m\}$ on the machining features of the workpiece, a set of deviation vector $S=\{\mathbf{s}_i, i=1,\ldots,m\}$ are accompanied with the points. The locator configuration in current setup can be evaluated in two forms:

$$\begin{aligned} e_1 &= \sum_{i=1}^{m} \|\delta \mathbf{t}_i\|^2 = \sum_{i=1}^{m} \delta \mathbf{q}_p^T \begin{bmatrix} I \\ \hat{\mathbf{t}}_i \end{bmatrix} \begin{bmatrix} I & -\hat{\mathbf{t}}_i \end{bmatrix} \delta \mathbf{q}_p \\ &= \delta \mathbf{q}_p^T \left( \sum_{i=1}^{m} \begin{bmatrix} I \\ \hat{\mathbf{t}}_i \end{bmatrix} \begin{bmatrix} I & -\hat{\mathbf{t}}_i \end{bmatrix} \right) \delta \mathbf{q}_p \\ &= \delta \mathbf{q}_p^T M_1 \delta \mathbf{q}_p \end{aligned} \tag{6.18}$$

$$\begin{aligned} e_2 &= \sum_{i=1}^{m} d_i^2 = \sum_{i=1}^{m} \delta \mathbf{q}_p^T \begin{bmatrix} I \\ \hat{\mathbf{t}}_i \end{bmatrix} \mathbf{s}_i^T \mathbf{s}_i \begin{bmatrix} I & -\hat{\mathbf{t}}_i \end{bmatrix} \delta \mathbf{q}_p \\ &= \delta \mathbf{q}_p^T \left( \sum_{i=1}^{m} \begin{bmatrix} I \\ \hat{\mathbf{t}}_i \end{bmatrix} \mathbf{s}_i^T \mathbf{s}_i \begin{bmatrix} I & -\hat{\mathbf{t}}_i \end{bmatrix} \right) \delta \mathbf{q}_p \\ &= \delta \mathbf{q}_p^T M_2 \delta \mathbf{q}_p \end{aligned} \tag{6.19}$$

where

$$M_1 = \sum_{i=1}^{m} \begin{bmatrix} I \\ \hat{\mathbf{t}}_i \end{bmatrix} \begin{bmatrix} I & -\hat{\mathbf{t}}_i \end{bmatrix}$$

$$M_2 = \sum_{i=1}^{m} \begin{bmatrix} I \\ \hat{\mathbf{t}}_i \end{bmatrix} \mathbf{s}_i^T \mathbf{s}_i \begin{bmatrix} I & -\hat{\mathbf{t}}_i \end{bmatrix}$$

These two equations are frame-invariant [133], which means the value is constant and not changed with the change of coordinate system. In order to minimize the machining feature errors on the workpiece, the evaluation criteria must be minimized, i.e.

$$\min.\ \xi = \delta \mathbf{q}_p^T M \delta \mathbf{q}_p \tag{6.20}$$

where $M=M_1$ or $M_2$.

### 6.1.3 Problem for Robust Locating Contacts

In this research, the fixture design for machining parts was conducted in consideration of both performance and robustness. Using Monte-Carlo statistics method, a batch of workpieces is simulated to be located on the designed fixture for a manufacturing process. $\Delta\mathbf{q}_e$, $\Delta\mathbf{r}_e$, and $\Delta\mathbf{r}_p$ are the noise factors that affect the fixture design performance. They are independently generated with Gaussian random distribution $N(0, \sigma^2)$, where σ is the standard deviation that can be calculated using $\sigma=t/3$, where $t$ is the tolerance for each of them. The performance is to minimize the mean of feature error $E(\xi_k) = \frac{1}{S_n}\sum_{k=1}^{S_n}\xi_k$ and the robustness is to minimize the variation of feature errors $Var(\xi_k) = \frac{1}{S_n}\sum_{k=1}^{S_n}\left[\xi_k - E(\xi_k)\right]^2$ under Monte-Carlo simulation, where $S_n$ is the number of simulation run. Weighted mean square error (WMSE) is an effective criterion to combine the mean and the variance in the dual response robust design [24]. For the "smaller-the-better" case, the mean square error (MSE) function can be written as:

$$MSE = wE(\xi_k)^2 + (1-w)Var(\xi_k) \tag{6.21}$$

where $w$ is the weight of the mean error. Then the problem for optimal robustness is defined as to find the combination of contact points such that

$$\rho = \min\left(MSE_j\right) \qquad j = 1, 2, ... \tag{6.22}$$

Here, $j$ represents the index of current locator configuration in the setup. This problem investigates the combination of contact points to minimize the WMSE in current setup given the resource errors.

## 6.2 Robust Fixture Design Approach Based on Genetic Algorithm

In this section, an approach with GA is presented to solve the problem in Equation (6.22) defined in the previous section. The candidate contact points are given by a finite number of points on the workpiece surfaces, and the points are assumed to be close enough.

### 6.2.1 Representation of Fixture Localization

A fixture is a mechanical device that fixture elements secure workpiece by contacting the workpiece's surfaces. The contact areas between fixture elements and surfaces of the workpiece are usually simplified as points. Thus, a fixture solution can be represented as three levels: root level, face level and point level (shown in Figure 6.2). The face level contains bottom supporting surfaces, side locating surfaces and clamping surfaces. The point level includes supporting points, locating points and clamping points on corresponding surfaces.

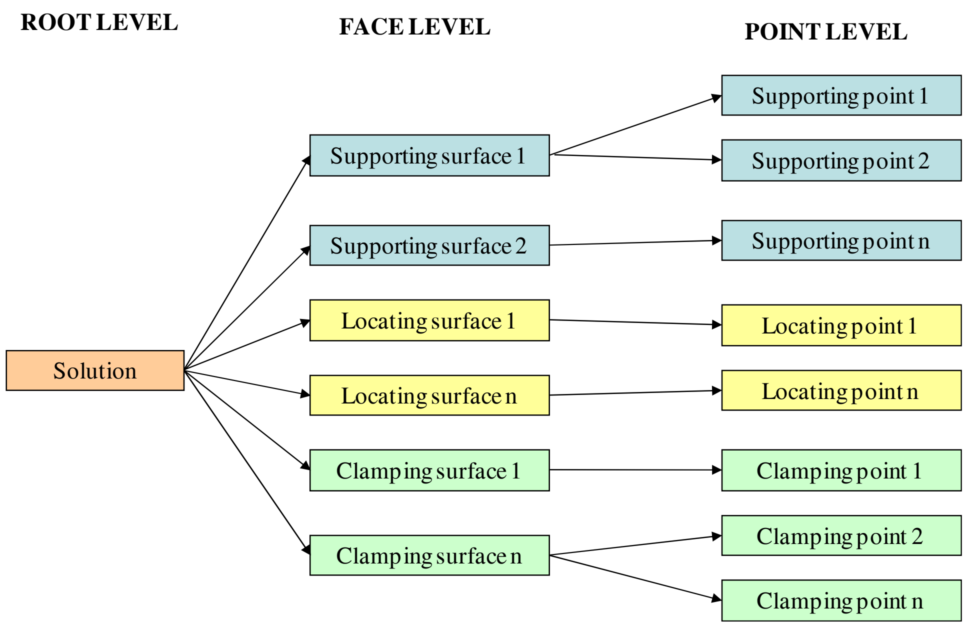



Figure 6.2 Solution representation for fixture localization

Based on the representation described above, a chromosome encoded for a design solution (Figure 6.3) is formalized with digital numbers and it is divided into two levels: face level and point level. As 3-2-1 locating approach is applied in this research, face level includes three bottom supporting faces, three side locating faces and clamping faces. Corresponding to face level, point level includes three supporting points, three side locating points and clamping points. Note that clamping faces and clamping points of the chromosome are not used here. The digital number in face level represents face ID of the workpiece and the number in point level is point ID of the corresponding surface, e.g. supporting point ID "6" is on the supporting surface whose face ID is "5".

When a chromosome is encoded, each gene includes geometrical information of the workpiece and fixture elements. For surface level, the information contains surface id, surface tolerance, fixture tolerance, point id list on current surface; for point level, the information includes point id, point coordinates and surface normal at current contact point. The details are listed in Table 6.1.

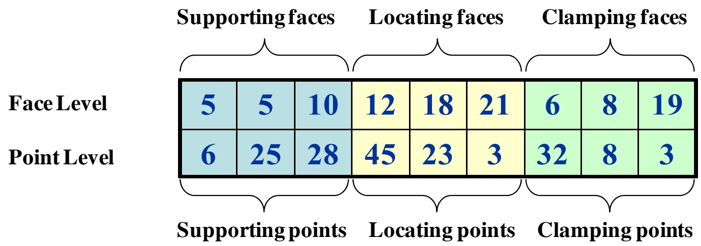



Figure 6.3 Encoding of fixture locating method with 3-2-1 approach

Table 6.1 Information for encoding and decoding

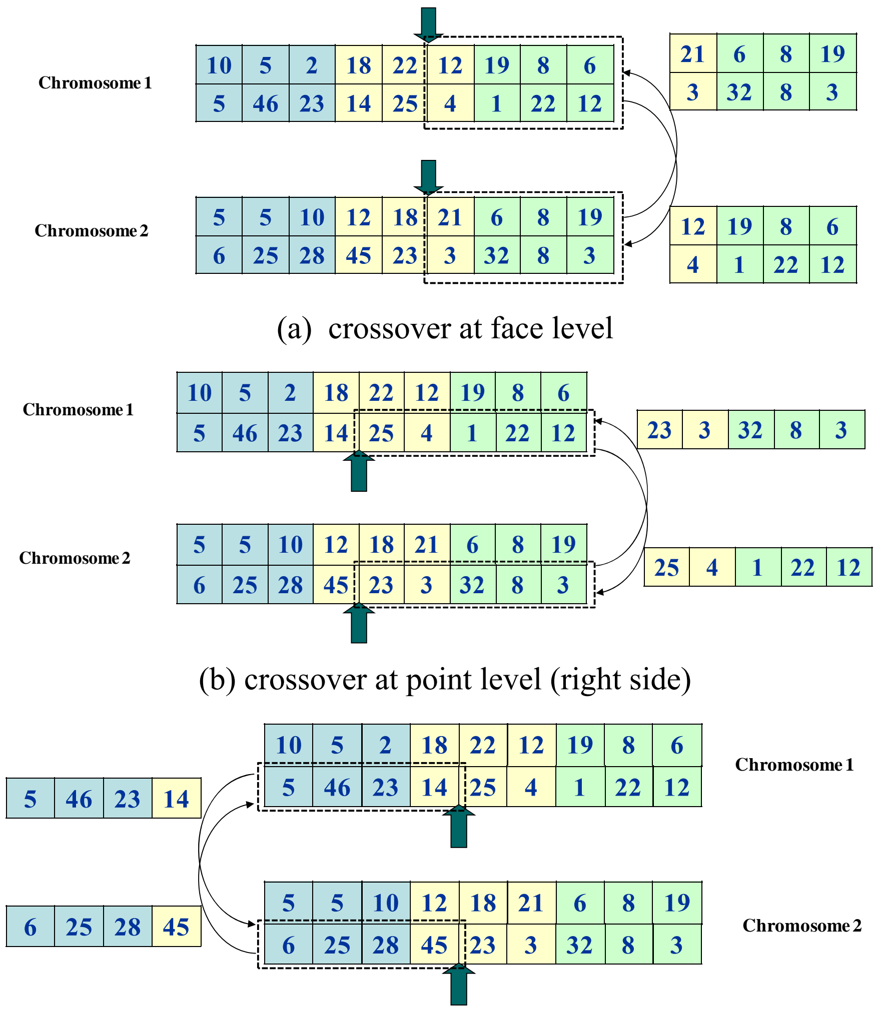
| Level | Variable | Description |
|---|---|---|
| Root | support_surface_list[] | the candidate supporting surface IDs list |
| | locating_surface_list[] | the candidate locating surface IDs list |
| | clamp_surface_list[] | the candidate clamping surface IDs list |
| | target_feature[] | the feature list to be machined in current setup |
| | center_of_mass | the coordinate of center of mass of the workpiece |
| Face | surface_id | the id of the surface |
| | surface_tol | the total geometrical tolerance of surface |
| | point_id_list | the list of candidate contact points |
| | fixture_tol | the tolerace caused by fixture setup and locator profile |
| Point | point_id | the id of the node |
| | point_coord | the coordinates of the node in x, y and z axis direction |
| | surface_normal | the surface normal at the contact |

### 6.2.2 Genetic Operation – Crossover

In crossover operation, two chromosomes are selected from population as parent chromosomes. Two types of crossover strategies are applied. A cutting point (the block arrow in Figure 6.4) is random determined at either face level or point level, and each parent chromosome is separated as left and right parts at the cutting point at each level. For the first type of crossover operation, the face IDs and points IDs of left part of parent 1 and the right part of parent 2 are reorganized to form child 1. Child 2 can be obtained from similar procedure. An example of the above procedure is illustrated in Figure 6.4(a). For the second type of crossover operation, only genes at point level are separated at cutting point. The points IDs of left or right part of parent 1 and the right or left part of parent 2 are reorganized to form child 1. The moving part is either left part or right part of genes at point level. Child 2 can be obtained in a similar way. The procedure described above is shown in Figure 6.4(b) and (c).

### 6.2.3 Genetic Operation -- Mutation

In mutation operation, a gene is randomly selected at either face level or point level from a chromosome. When the gene selected is at face level, a random face ID from supporting or locating surface candidates is chosen to replace this gene. This replacement is based on original selected face belong to supporting or locating surface. If the gene selected is at point level, a random point ID is chosen to replace this gene from node candidates of the surface on which the original point is in order to guarantee the replaced point ID is not out of range. The procedure described above is illustrated in Figure 6.5.




(a) crossover at face level

(b) crossover at point level (right side)

(c) crossover at point level (left side)

Figure 6.4 Genetic operation for crossover

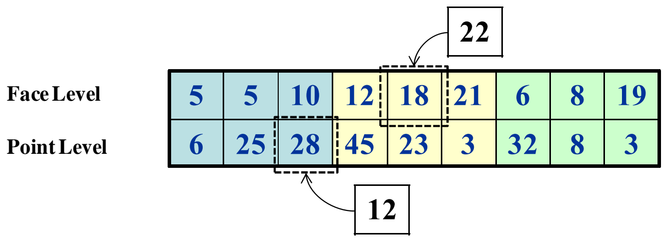



Figure 6.5 Genetic operation for mutation

### 6.2.4 Design Algorithm

In this section, the procedure of the algorithm to obtain the robust design solution is described. Figure 6.6 shows the flowchart of the algorithm.

(1) The part model is first input into the system. The candidate fixturing features {**S**} (Figure 6.7(a)) are specified for supporting and locating from all surfaces of the workpiece based on machining conditions, e.g. machine table, machining tool, etc. The candidate nodes {**N**} are generated for each candidate fixturing feature (Figure 6.7(b)). Moreover, the key points {P} on the machining features and their main feature directions {D} are input.

(2) Initialize all the chromosomes using the method described in section 6.2.1 to form the population {Pop}.

(3) Decode every chromosome (design solution) to get the contact point coordinates and contacting surface normals at the contact points. Then the design performance is evaluated to calculate the fitness using Monte-Carlo statistical method:

a. For each contact point in the design solution, noises are generated and added to the coordinates in x, y and z direction. The noises are produced with Gaussian random distribution $N(0,\sigma^2)$, $\sigma(=tol./3)$ is the standard deviation and *tol.* is the tolerance at the contact point due to surface error, fixture setup error and locating profile error.

b. The point-wise manufacturing errors on the machining features are calculated based on Equation (6.18) and (6.19).

c. The MSE of the machining features on the workpiece are calculated as described in Equation (6.21) as the fitness of current chromosome.

(4) Based on fitness calculated above, the chromosomes are sorted.

(5) Populations are reproduced for the next generation using some selection strategies. In this algorithm, the tournament selection and an "elite" strategy are employed to expedite the search.

(6) Crossover: two chromosomes are selected from parent population as parent chromosome for a crossover operation. The detailed two-level crossover operation is described in section 6.2.2. The probability of applying the crossover is defined as $P_c$.

(7) Mutation: one chromosome is selected from parent population for a two-level mutation operation as described in section 6.2.2. The probability of applying the mutation is defined as $P_m$.

(8) After genetic operations (crossover and mutation), the offspring chromosomes are combined together and sent to Step (3) to evaluate fitness.

(9) Steps (3-8) are repeated for *m* generations.

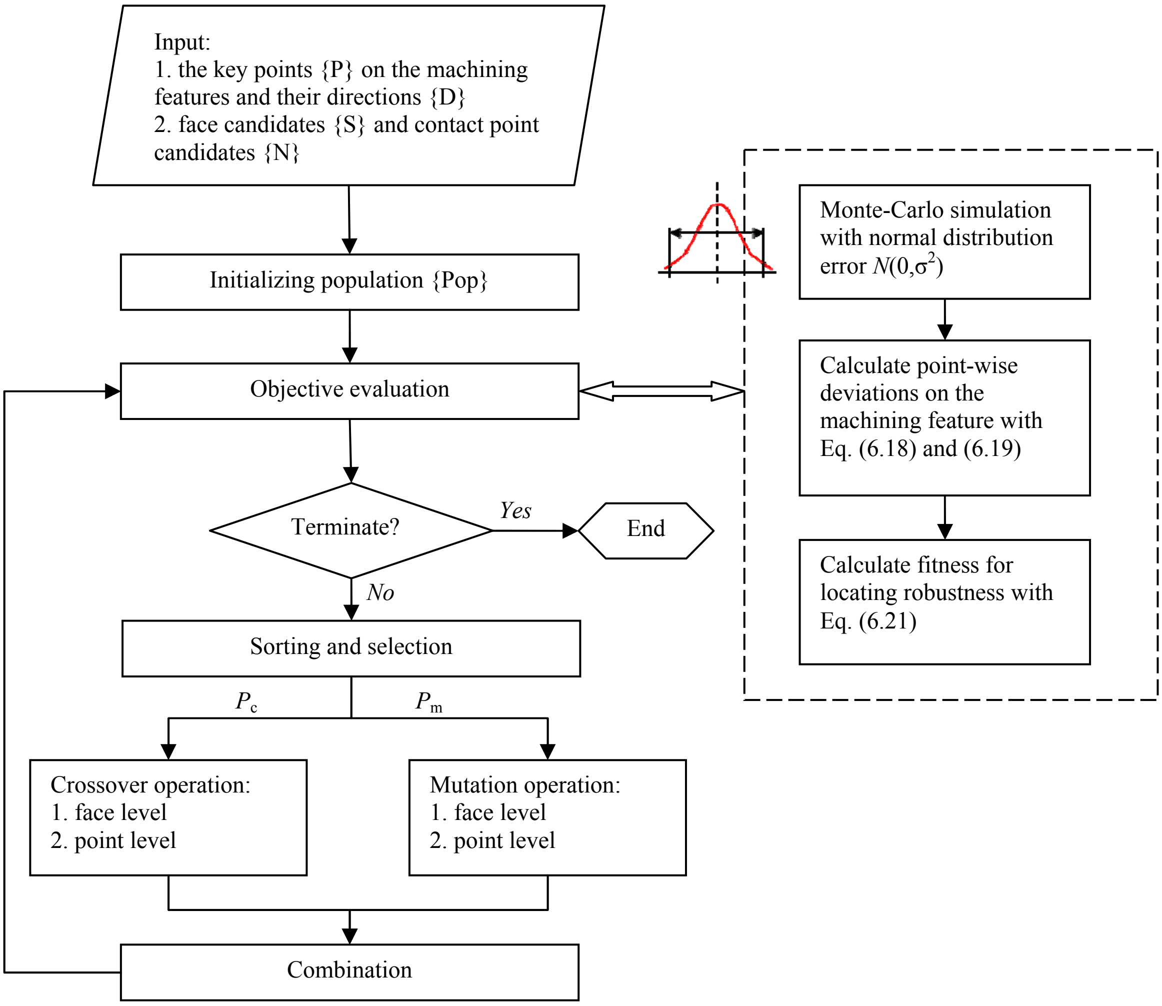



Figure 6.6 Fixture design process with genetic algorithm

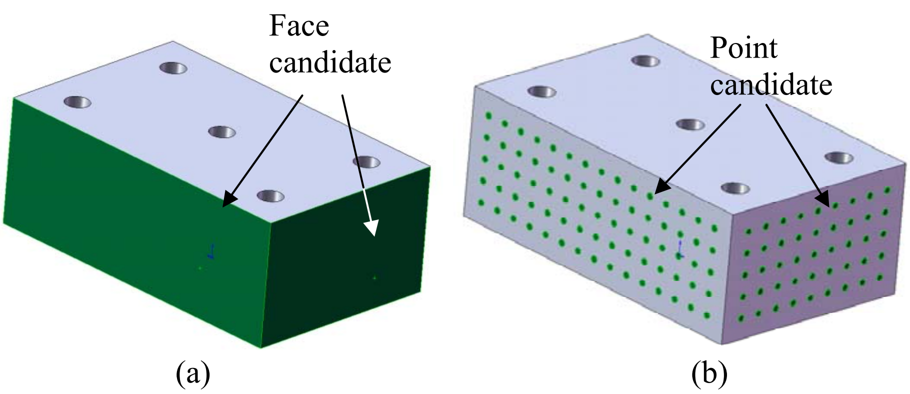



Figure 6.7 Design exploration at face level (a) and point level (b)

## 6.3 Case Study

### 6.3.1 Case Description

An experiment has been conducted to illustrate the computational results of the developed GA algorithm. The sample workpiece (Figure 6.8) of steel AISI 5120 consists of five machining features, which are four holes and one slot. The machine operation in current setup will be drilling and end milling. The datum surface candidates for supporting and locating and contact candidates are illustrated in Figure 6.9. The geometrical tolerance for each surface candidate is assumed to be 0.05mm at its normal direction. The geometrical error of locators and the fixture setup error are set as 0.05 at three directions respectively. The local coordinate systems for the machining features are listed in Table 6.2.

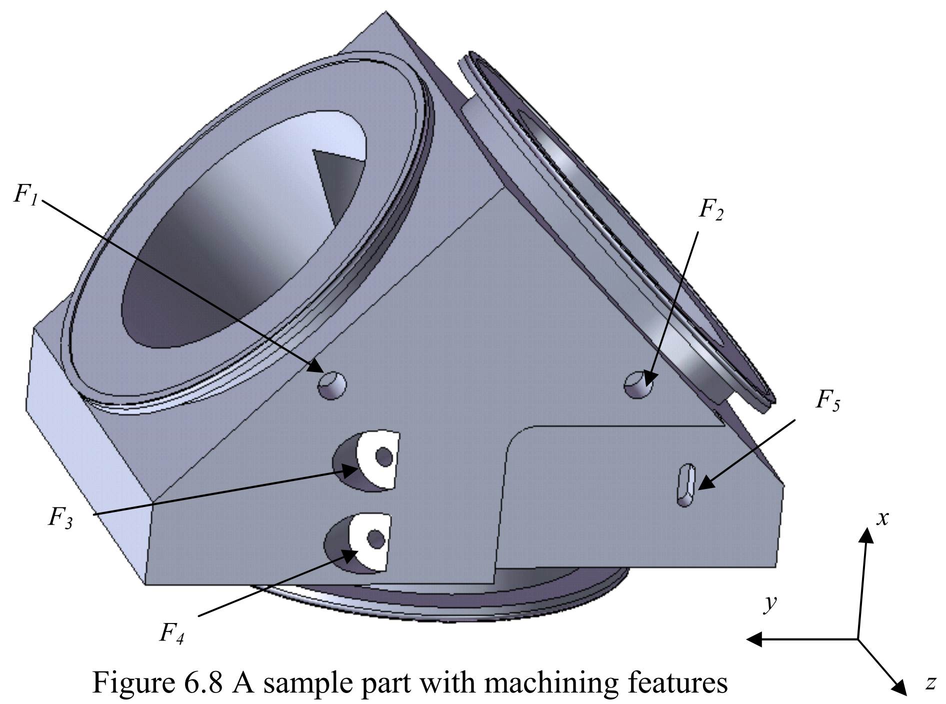



Figure 6.8 A sample part with machining features

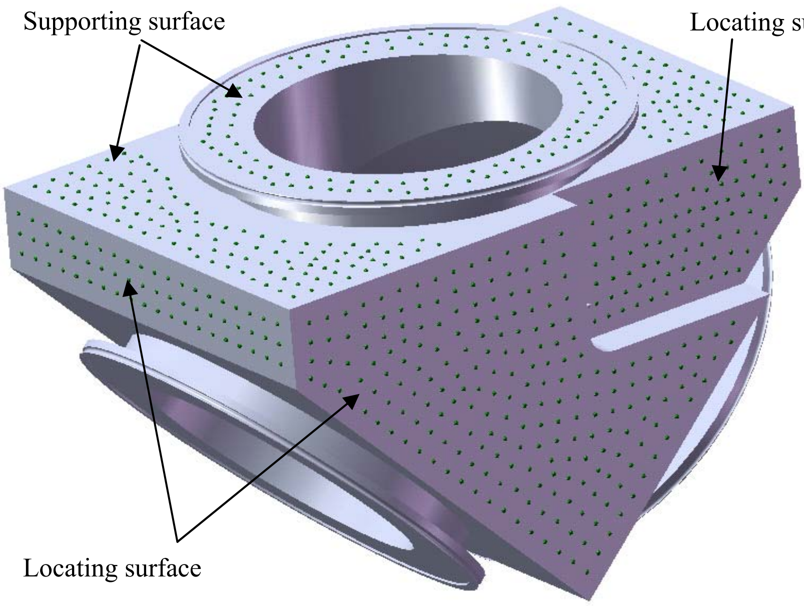


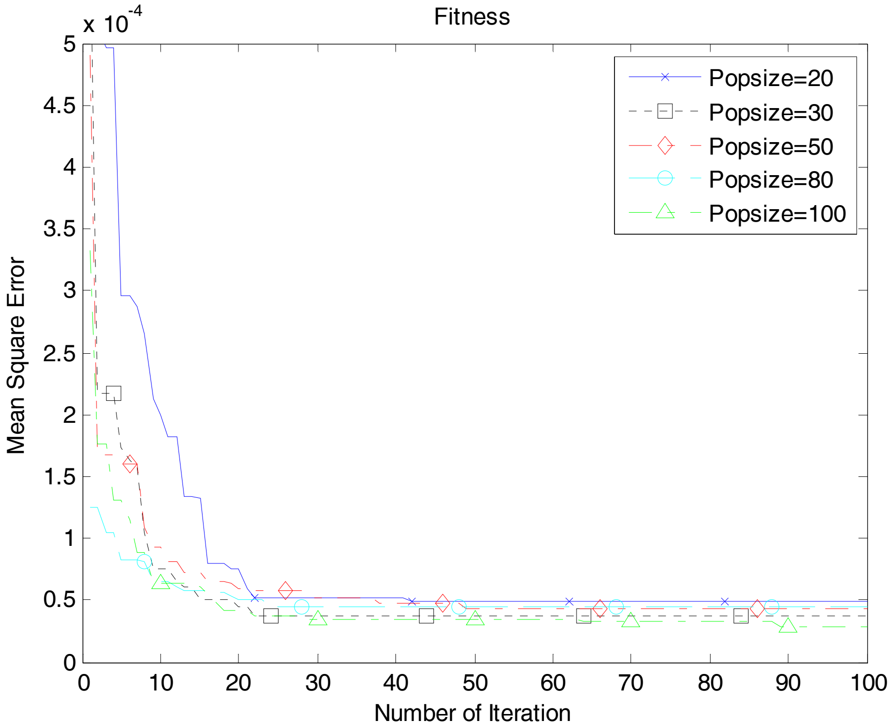

Figure 6.9 The candidate contact points for supporting and locating on the workpiece

Table 6.2 Nominal position and orientation of key machining features and their MSE under simulations

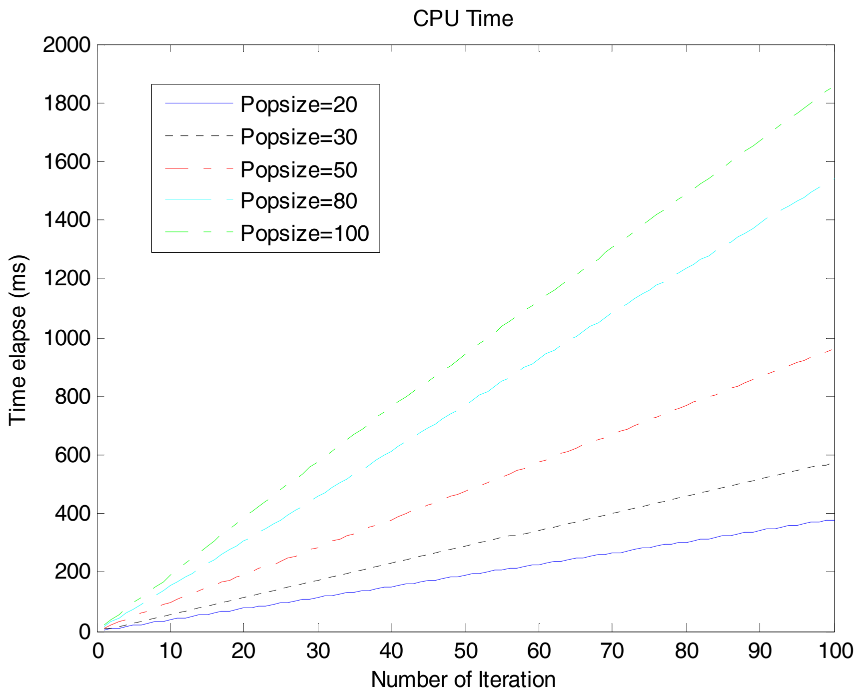
| Feature # | Type | Position | Orientation | *Feaure error* (×$10^{-3}$) | *Direction deviation* (×$10^{-3}$) | *MSE* (×$10^{-5}$) |
|---|---|---|---|---|---|---|
| $F_1$ | Hole | (54, 70, 210) | (0, 0, 0) | $[-0.4896\ \ -0.6178\ \ -0.1297\ \ 0.0010\ \ -0.0017\ \ -0.0009]^T$ | 0.7328 | |
| $F_2$ | Hole | (54, -70, 210) | (0, 0, 0) | $[-0.3625\ \ -0.6178\ \ 0.0122\ \ 0.0010\ \ -0.0017\ \ -0.0009]^T$ | 0.8074 | |
| $F_3$ | Hole | (19, 41.5, 205) | (π/6, 0, 0) | $[-0.0383\ \ -0.6929\ \ -0.0746\ \ 0.0017\ \ -0.0009\ \ -0.0009]^T$ | 0.6263 | 4.63 |
| $F_4$ | Hole | (-19, 41.5, 205) | (π/6, 0, 0) | $[-0.0555\ \ -0.6630\ \ -0.1379\ \ 0.0017\ \ -0.0009\ \ -0.0009]^T$ | 0.6115 | |
| $F_5$ | Slot | (-6, -102, 190) | (0, 0, 0) | $[-0.4853\ \ -0.5539\ \ -0.2422\ \ 0.0010\ \ -0.0017\ \ -0.0009]^T$ | 0.6121 | |

### 6.3.2 Determination of Parameters in GA Approach

In genetic algorithms, the main parameters to be determined are the number of population $N_p$, the probability of crossover $P_c$, and probability of mutation $P_m$. The number of population $N_p$ should be chosen properly. If $N_p$ is too small, not enough number of chromosomes can be generated to explore the whole design space and it takes long time to reach an optimal solution. If $N_p$ is too large, the computation time is too long for each iteration. From Figure 6.10(a), the number of population $N_p$ and the number of generation are selected as 50 and 200 respectively. From Figure 6.10(b), when $P_c$=0.9 and $P_m$=0.05, the algorithm can achieve a better performance.

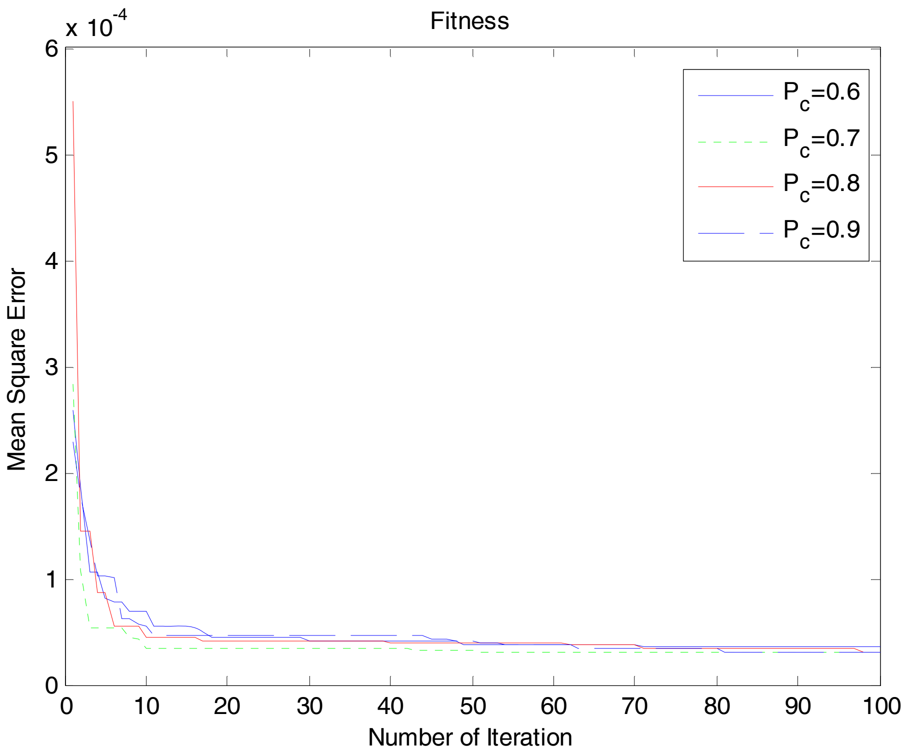



(a) number of iteration vs. mean square error for different population size

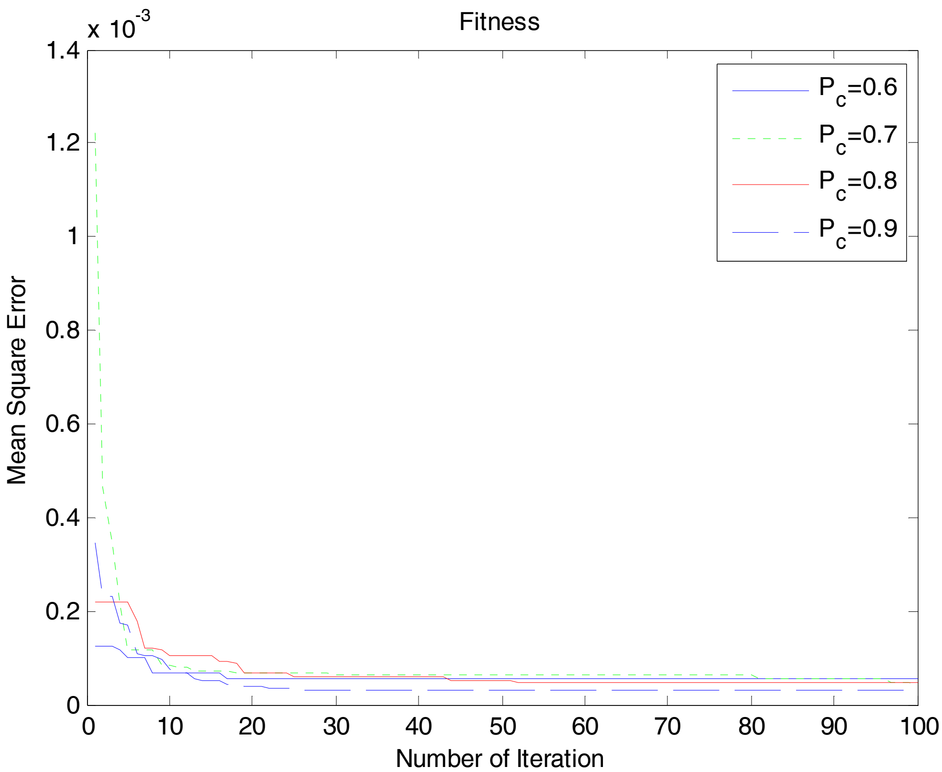



(b) number of iteration vs. elapse time for different population size

Figure 6.10 Test for population size in design process

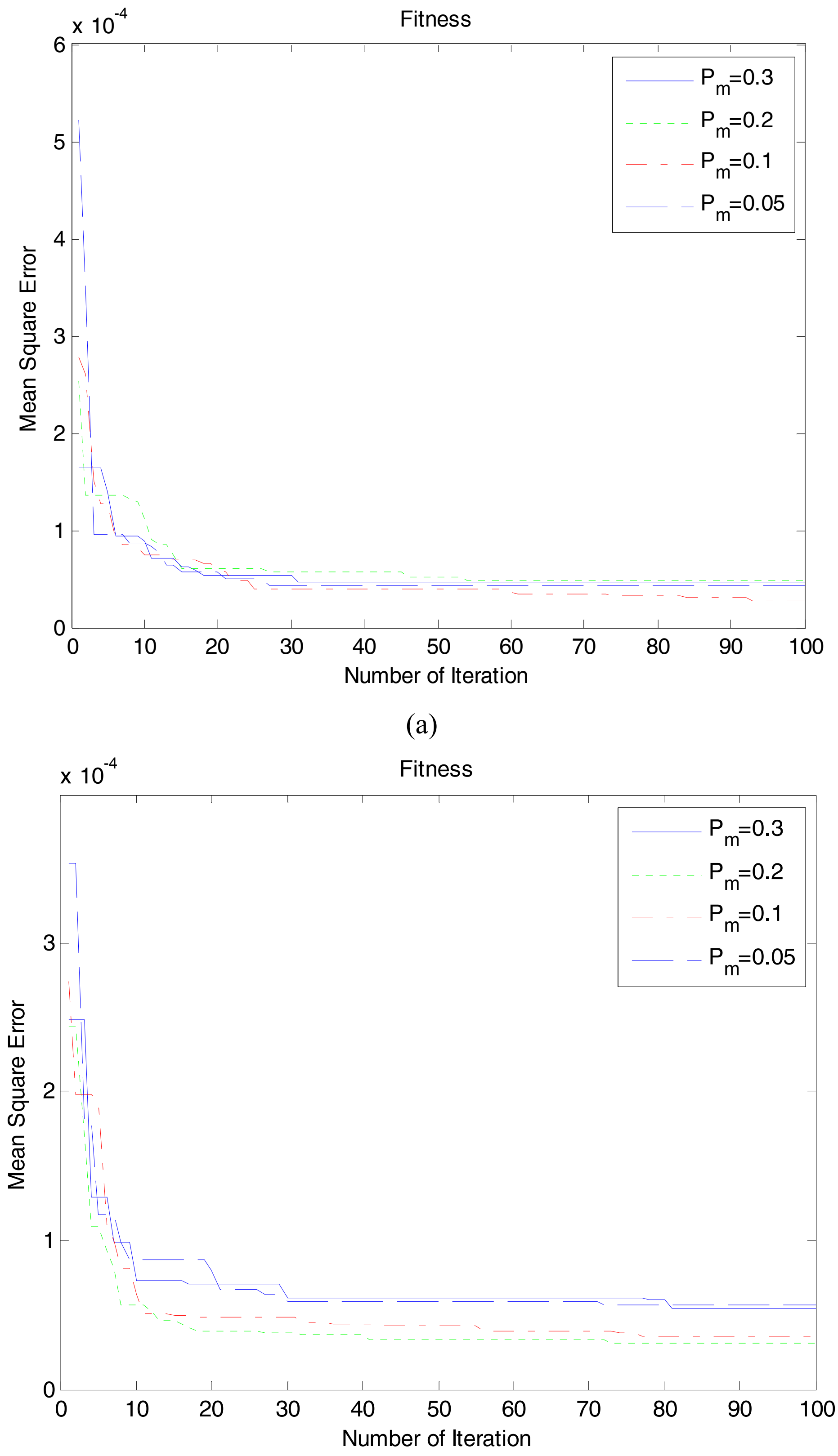



(a)




(b)

Figure 6.11 Test of probability for applying crossover $\boldsymbol{P_c}$. in the design process (a) when $\boldsymbol{P_m}$=0.1 with different $\boldsymbol{P_c}$. (b) when $\boldsymbol{P_m}$=0.05 with different $\boldsymbol{P_c}$.




(b)

Figure 6.12 Test of probability for applying mutation $P_{m.}$ in the design process (a) when $P_c$=0.8 with different $P_m$. (b) when $P_c$=0.9 with different $P_m$.

### 6.3.3 Computation Results

Except the parameters described in section 6.3.2, the weight for each feature MSE $w_j$=0.2, $j$=1,…,5 and the number of simulation run in Monte-Carlo simulation is set as 1000. Given the parameters obtained above, a numerical experiment for the machining part is conducted and the plot of mean square error vs. iteration is shown in Figure 6.13. The contact points for locating and supporting of this approach is shown in Figure 6.14. Based on these contacts, the final fixture design solution can be reached. The contacts are (-38 66 11), (-38 -116 200), (-38 126 180), (1 132 20), (-10 146 200), (49 83.5 0). With this combination of contact points, the feature errors and MSEs for each machining features are listed in Table 6.2.

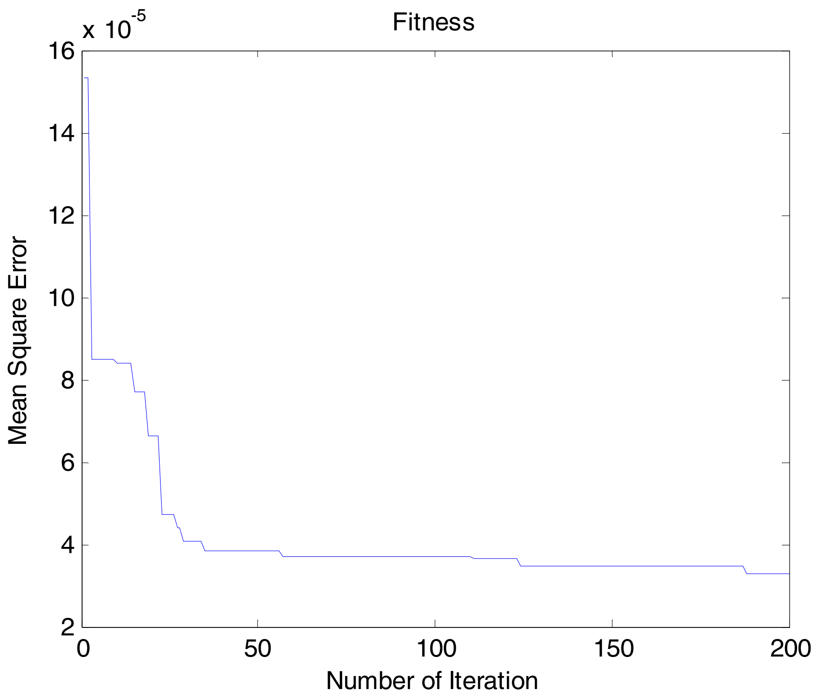
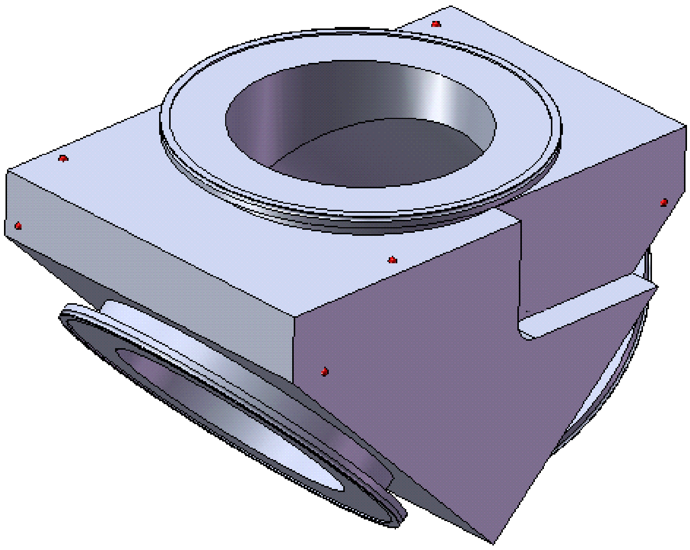
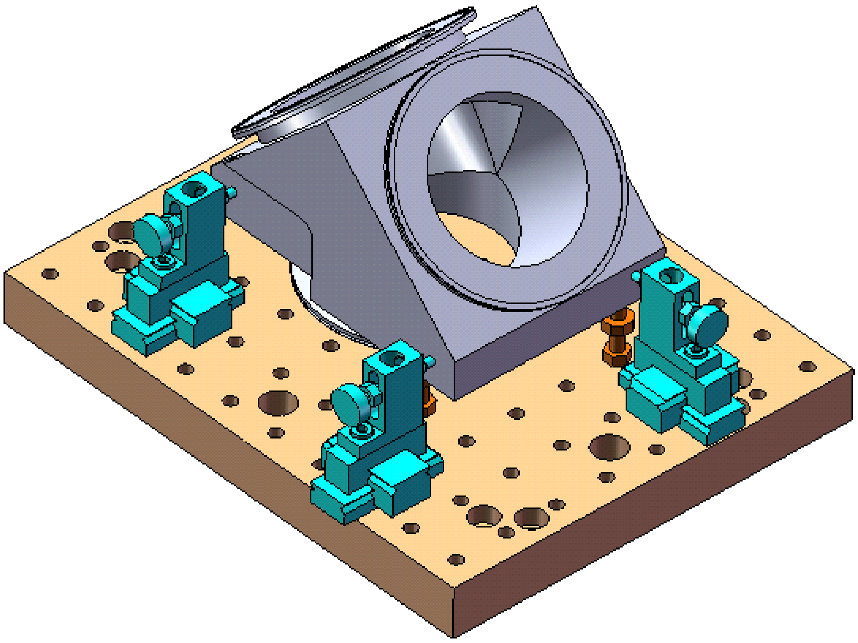



Figure 6.13 The fitness plot with popsize = 50, Pc = 0.9 and Pm = 0.05.



(a)



(b)

Figure 6.14 (a) The contact points for locating and supporting of the result; (b) The final configuration locating design based on contacts

### 6.3.4 Comparison with Non-robust Design

In this section, a comparison between non-robustness and robustness is conducted with the sample part (Figure 6.15) from ref. [61]. In the current setup, the operation is to mill the top surface $f_1$. The contacts for fixture layout are listed in Table 6.3. This table consists of three options: Option 1 is the layout from original configuration; Option 2 is the optimal solution when computing with the approach proposed with feature $f_2$, $f_3$ and $f_4$; Option 3 is the optimal solution when computing with the approach proposed with feature $f_2$, $f_3$, $f_4$ and $f_6$. For each solution, the feature errors at the local coordinate system are computed using Monte-Carlo simulation approach with 5000 simulation runs given the source errors and listed in this table. Comparing Option 1 with Option 2 given the same datum features, $f_2$, $f_3$ and $f_4$, the combination of contacts of Option 2 can provide better configuration in terms of the mean-square-error than that of Option 1. However, when considering feature $f_6$ to one of the locating candidates, the design space is expanded. After computing with the proposed approach, the solution in Option 3 is better than that in Option 2.

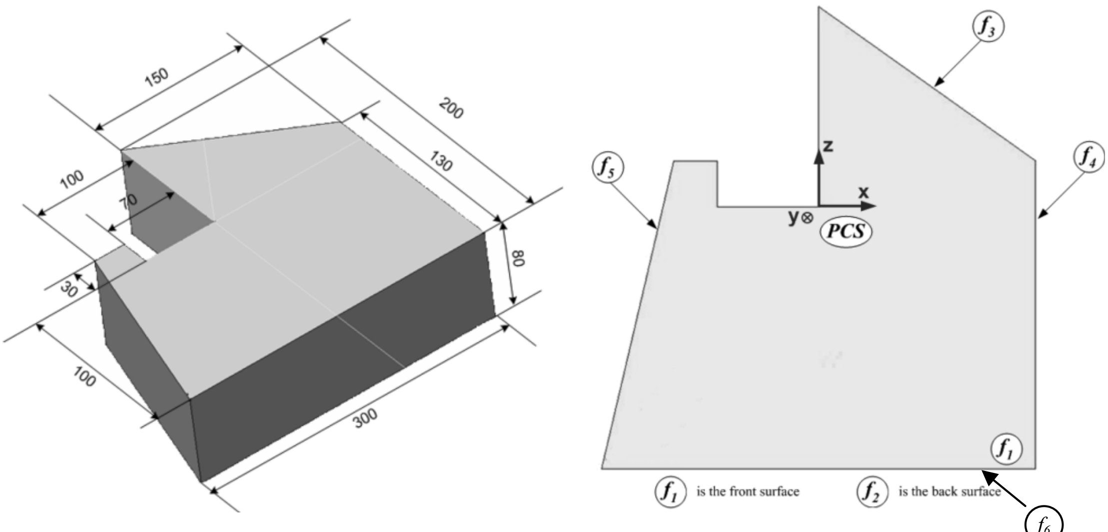



Figure 6.15 The sample part from ref. [61]

Table 6.3 Comparison of robust design and non-robust design

| Option No. | Locator No. | Surface | Position | Orientation | Feature error ($10^{-3}$ *mm*) | *mse* ($10^{-5}$) |
|---|---|---|---|---|---|---|
| | 1 | $f_2$ | (-100, 80, -100) | (0, 1, 0) | -0.1861 | |
| | 2 | $f_2$ | (20, 80, 80) | (0, 1, 0) | 0.7504 | |
| | 3 | $f_2$ | (100, 80, 0) | (0, 1, 0) | 0.5751 | |
| 1 | 4 | $f_3$ | (45, 40, 100) | (0.4229, 0, 0.9062) | -0.0047 | 1.98 |
| | 5 | $f_3$ | (75, 40, 80) | (0.4229, 0, 0.9062) | -0.0011 | |
| | 6 | $f_4$ | (150, 40, -85) | (1, 0, 0) | -0.0040 | |
| | 1 | $f_2$ | (80, 80, 41.1) | (0, 1, 0) | -0.0487 | |
| | 2 | $f_2$ | (99.1, 80, -60.4) | (0, 1, 0) | 0.1643 | |
| 2 | 3 | $f_2$ | (-118.3, 80, -70.9) | (0, 1, 0) | 0.2595 | |
| | 4 | $f_3$ | (61.4, 39.8, 71.4) | (0.4229, 0, 0.9062) | 0.0001 | 0.08 |
| | 5 | $f_4$ | (150, 40, -70) | (1, 0, 0) | -0.0069 | |
| | 6 | $f_4$ | (150, 40, 10) | (1, 0, 0) | 0.0008 | |
| | 1 | $f_2$ | (89.9, 80, -70.1) | (0, 1, 0) | -0.3457 | |
| | 2 | $f_2$ | (36.5, 80, 54) | (0, 1, 0) | -0.0276 | |
| 3 | 3 | $f_2$ | (-50, 80, -90) | (0, 1, 0) | -0.0293 | |
| | 4 | $f_4$ | (150, 40, -30) | (1, 0, 0) | 0.0016 | 0.04 |
| | 5 | $f_6$ | (-80, 10, -100) | (0, 0, -1) | 0.0022 | |
| | 6 | $f_6$ | (120, 60, -100) | (0, 0, -1) | -0.0002 | |

## 6.4 Summary

In this chapter, a robust design approach for fixture locating process is presented. In the modeling of workpiece localization, the product quality is measured based on sum square of point deviation. These evaluation criteria are frame-invariant, which means the value is constant and not changed with the change of coordinate system. In addition, in order to balance the product performance and robustness effectively, mean-square-error is employed to evaluate both performance and robustness during simulation process.

In order to search the contact points for localization, a modified genetic algorithm is developed by combining with Monte-Carlo statistical method, which is used to simulate the locating process. An illustrative example is used to validate the proposed approach. The fixture points obtained from the proposed approach can be used to design the fixture using the developed CFDA system. Moreover, a comparison is conducted between robust and non-robust fixture design. It shows that robust design can commit smaller errors on the machining features.

# Chapter 7 Fixture Design Optimization for Compliant Workpiece using Particle Swarm Method

In previous chapters, it is assumed that workpiece and fixture elements are rigid, and only geometric of the workpiece and locators contribute to the final position and orientation of the part. However, when a workpiece is under clamping and machining loads, variations in workpiece compliance and fixture compliance also lead to inaccurate part location, which can adversely affect part quality. In this chapter, a model that predicts the final position and orientation of a workpiece due to fixture workpiece compliance is firstly presented. A method for robust fixture design is then developed using modified particle swarm optimization and a case is finally studied using the developed method.

## 7.1 Modelling Assumptions

A fixture–workpiece model aims to relate the interaction between the fixture and the workpiece during the machining operation. Different forms of fixture–workpiece model have been derived in order to make its application more convenient for the subjects under study [70]. The model proposed for robust fixture design is based on static equilibrium of the workpiece considering uncertainty of friction, forces, and contact positions.

In this model, the fixture consists of $N_L$ locators and supporters and $N_C$ clamps with either spherical or planar tips. The clamp can operate with constant force with hydraulic or pneumatic clamping. Some assumptions are made as follows:

(1) each fixture element makes a frictional point contact with the workpiece;

(2) the fixture layout uses 3-2-1 approach;

(3) there is no machining tool error considered;

(4) dynamic effects are negligible;

(5) quasi-static motion and linearly elastic contact between fixture elements and workpiece are considered.

### 7.1.1 Frictional Constrain

At each contact point, fixture element contacts with workpiece with friction under the Coulomb's friction law, such that $(\mu_i p_{ni})^2 \geq (p_{ti}^2 + p_{bi}^2)$, where $\mu_i$ is friction coefficient at $i$th contact point $C_i$, $p_n$ is normal direction force and $p_t$ and $p_b$ are orthogonal tangential forces.

An approximation of friction cone is satisfied with

$$\mathbf{Hp} \geq \mathbf{0} \tag{7.1}$$

The overall matrix that describes the linear approximation of the friction cone (shown in Figure 7.1) is $\mathbf{H}$=diag($\mathbf{H}_1$, $\mathbf{H}_2$, …, $\mathbf{H}_m$)$\in\mathcal{R}^{sm\times 3m}$ and

$$\mathbf{H}_i = \begin{bmatrix} \mu_i & -\cos\alpha_1 & -\sin\alpha_1 \\ \cdots & \cdots & \cdots \\ \mu_i & -\cos\alpha_k & -\sin\alpha_k \\ \cdots & \cdots & \cdots \\ \mu_i & -\cos\alpha_s & -\sin\alpha_s \end{bmatrix}$$

$$\alpha_k = \frac{\pi}{s} + \frac{2\pi}{s}(k-1) \quad k = 1,\ldots,s,\ and\ s \geq 4$$

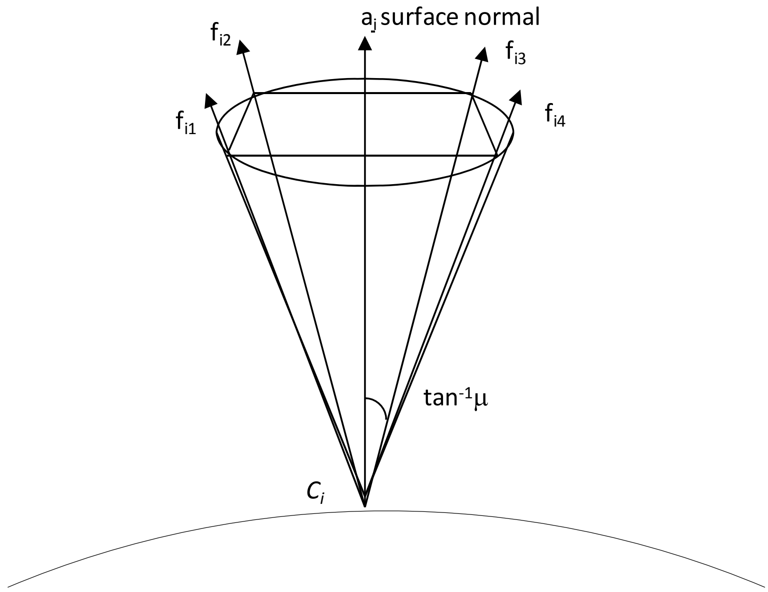



Figure 7.1 Friction cone approximation of contact $C_i$

### 7.1.2 Static Force Equilibrium Equation

When a workpiece is under external wrench vector $\mathbf{W}_E$ (including cutting forces and moments) gravity wrench $\mathbf{W}_G$ and active clamping wrench vectors $\mathbf{W}_C$, the static equilibrium equation of the workpiece is given as:

$$\mathbf{G}\mathbf{p}^C + \mathbf{W}_C + \mathbf{W}_E + \mathbf{W}_G = \mathbf{0} \tag{7.2}$$

where

$$\mathbf{G} = \left[\mathbf{G}_1^L, \mathbf{G}_2^L, \ldots, \mathbf{G}_{N_L}^L, \mathbf{G}_1^C, \mathbf{G}_2^C, \ldots, \mathbf{G}_{N_C}^C\right]$$

$$\begin{aligned}\mathbf{p}^C &= \left[\left(\mathbf{p}_L\right)^T, \left(\mathbf{p}_C\right)^T\right]^T \\ &= \left[\left(\mathbf{p}_1^l\right)^T, \left(\mathbf{p}_2^l\right)^T, \ldots, \left(\mathbf{p}_{N_L}^l\right)^T, \left(\mathbf{p}_1^c\right)^T, \left(\mathbf{p}_2^c\right)^T, \ldots, \left(\mathbf{p}_{N_C}^c\right)^T\right]^T \\ &= \left[f_{1n}^l, f_{1t}^l, f_{1b}^l, \ldots, f_{N_L n}^l, f_{N_L t}^l, f_{N_L b}^l, f_{1t}^c, f_{1b}^c, \ldots, f_{N_C t}^c, f_{N_C b}^c\right]^T\end{aligned}$$

The passive forces vector $\mathbf{p}^C$ are locating forces vector $\mathbf{f}_L$ which consists of one normal and two orthogonal tangential forces at supporting and locating contact points and clamping passive forces vector $\mathbf{f}_L$ which includes two orthogonal tangential passive forces at each clamping contact point.

The gravity wrench due gravity force on the workpiece is

$$\begin{aligned}\mathbf{W}_G &= \begin{bmatrix}\mathbf{f}_g & \mathbf{r}_c \times \mathbf{f}_g\end{bmatrix}^T \\ &= \begin{bmatrix}0 & 0 & -mg & -mgy_c & -mgx_c & 0\end{bmatrix}^T\end{aligned} \tag{7.3}$$

## 7.2 Workpiece-Fixture Contact Compliance Model

### 7.2.1 Local Stiffness

In the workpiece-fixture system subjected to quasi-static loading, external wrenches including clamping forces, gravity, machining forces, and their corresponding moments, may cause three kinds of deformations, *i.e.* the fixture element deformation, the workpiece deformation and contact deformation. For the quasi-rigid workpiece, the contact areas between workpiece and fixture elements are relatively small compare to the workpiece and the local linear elastic contact deformations caused by external wrenches on the workpiece at contact points are highly localized, thus each source of compliance can be modeled as linear spring in three orthogonal directions ***n***, ***t*** and ***b*** in the local coordinate system. Figure 7.2 shows the three orthogonal directions ***n***, ***t*** and ***b***. The contact deformation is independent with others. $K_{i\mathbf{j}}^{c}$, $K_{i\mathbf{j}}^{w}$ and $K_{i\mathbf{j}}^{f}$ (**j**= ***n***, ***t*** and ***b***) represent the contact stiffness, workpiece stiffness and the fixture element stiffness at the *i*th contact point. Then the overall local stiffness of the workpiece-fixture system is calculated as:

$$\frac{1}{K_{i\mathbf{j}}} = \frac{1}{K_{i\mathbf{j}}^{w}} + \frac{1}{K_{i\mathbf{j}}^{c}} + \frac{1}{K_{i\mathbf{j}}^{f}} \tag{7.4}$$

When considering the workpiece structurally rigid, the workpiece stiffness $K_{i\mathbf{j}}^{w}$ is equal to infinity and its effect to overall local stiffness is considered to be negligible. Then the equation can be rewritten as

$$\frac{1}{K_{i\mathbf{j}}} = \frac{1}{K_{i\mathbf{j}}^{c}} + \frac{1}{K_{i\mathbf{j}}^{f}} \tag{7.5}$$

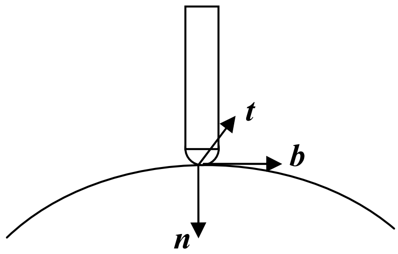



Figure 7.2 The direction at local contact point

For a given fixture layout with $N_L$ locators and supporters and $N_C$ clamps, the local stiffness matrix of the system is yielded as

$$\begin{aligned} \mathbf{K} &= blockdiag(\mathbf{K}_1, \mathbf{K}_1, ..., \mathbf{K}_m) \\ &= diag(K_{1\mathbf{n}}, K_{1\mathbf{t}}, K_{1\mathbf{b}}, ..., K_{m\mathbf{n}}, K_{m\mathbf{t}}, K_{m\mathbf{b}}) \end{aligned} \tag{7.6}$$

where $m = N_L + N_C$ is total number of fixture elements.

### 7.2.2 Contact Stiffness

Contact deformations between the workpiece and the fixture elements can be characterized by a locally elastic model following the classical Hertz contact theory [41]. The nominal contact modulus that represents the elastic properties of both workpiece and the *i*th fixture element effectively as a series combination of springs is expressed as:

$$\frac{1}{E_i^*} = \frac{1-\nu_{wi}^2}{E_{wi}} + \frac{1-\nu_{fi}^2}{E_{fi}}$$

where $E_{wi}$ and $E_{fi}$ are denoted as the Young's moduli of the workpiece and fixture, respectively, at the *i*th contact point. $\nu_{wi}$ and $\nu_{fi}$ are Possion's ratios.

The equivalent contact Poison's ratio and contact shear modulus can be expressed as

$$\frac{1}{\nu_i^*} = \frac{1}{2\nu_{wi}} + \frac{1}{2\nu_{fi}} \qquad \frac{1}{G_i^*} = \frac{2-\nu_{wi}}{G_{wi}} + \frac{2-\nu_{fi}}{G_{fi}}$$

where $G_{wi}$ and $G_{fi}$ are the shear moduli of two contact bodies.

When any two surfaces with arbitral shape contact, the two surfaces can be locally approximated with elliptical surface, each of which described with orthogonal radii of curvature, at contact point. $R_{wi}^{'}$, $R_{wi}^{"}$ and $R_{fi}^{'}$, $R_{fi}^{"}$ are the principal radii of the workpiece and the *i*th fixture element at the *i*th contact point, respectively. The plane of principle radii $R_{wi}^{'}$ and $R_{fi}^{'}$ may form an arbitrary angle $\theta_i$. The radius is positive for a convex surface and negative for a concave surface. Then the relative radius $R_i^*$ representing an equivalent sphere in contact with a plane is expressed as [33, 84]:

$$R_i^* = (R_{ai} R_{bi})^{1/2}$$

where
$$R_{ai} = \frac{1}{A_i - B_i}$$

$$R_{bi} = \frac{1}{A_i + B_i}$$

$$A_i = \frac{1}{2}\left(\frac{1}{R_{wi}^{'}} + \frac{1}{R_{wi}^{"}} + \frac{1}{R_{fi}^{'}} + \frac{1}{R_{fi}^{"}}\right)$$

$$B_i = \frac{1}{2}\left[\left(\frac{1}{R_{wi}^{'}} - \frac{1}{R_{wi}^{"}}\right)^2 + \left(\frac{1}{R_{fi}^{'}} - \frac{1}{R_{fi}^{"}}\right)^2 + 2\left(\frac{1}{R_{wi}^{'}} - \frac{1}{R_{wi}^{"}}\right)\left(\frac{1}{R_{fi}^{'}} - \frac{1}{R_{fi}^{"}}\right)\cos 2\theta_i\right]^{\frac{1}{2}}$$

If $R_{wi} = R_{wi}^{'} = R_{wi}^{"}$ and $R_{fi} = R_{fi}^{'} = R_{fi}^{"}$, then $R_i^* = \frac{1}{R_{wi}} + \frac{1}{R_{fi}}$

The major and minor radii of the elliptical contact area following from the eccentricity $e_i$ and equivalent radius $R_i^*$ can be written as:

$$a_i = c_i \left( \frac{R_{ai}}{R_{bi}} \right)^{\frac{1}{3}}$$

$$b_i = c_i \left( \frac{R_{bi}}{R_{ai}} \right)^{\frac{1}{3}}$$

$$c_i = \left( \frac{3 f_{i\mathbf{n}}^c R_i^*}{4 E_i^*} \right)^{\frac{1}{3}} \alpha_i$$

The contact displacement and contact stiffness at the *i*th contact point can be achieved as:

$$\delta_{i\mathbf{n}}^c = \left( \frac{9 f_{i\mathbf{n}}^{c2}}{16 R_i^* E_i^{*2}} \right)^{\frac{1}{3}} \frac{\alpha_i}{\beta_i^2}$$

$$\delta_{i\mathbf{t}}^c = \frac{f_{i\mathbf{t}}^c}{8 a_i G_i^*} \gamma_i$$

$$\delta_{i\mathbf{b}}^c = \frac{f_{i\mathbf{b}}^c}{8 a_i G_i^*} \lambda_i$$

$$K_{i\mathbf{n}}^c = \frac{\left( 6 R_i^* E_i^{*2} f_{i\mathbf{n}}^c \right)^{1/3}}{\alpha_i \beta_i^2}$$

$$K_{i\mathbf{t}}^c = \frac{8 a_i G_i^*}{\gamma_i}$$

$$K_{i\mathbf{b}}^c = \frac{8 a_i G_i^*}{\lambda_i}$$

Correction factors are expressed as:

$$\alpha_i \cong 1 - \left[ \left( \frac{R_{ai}}{R_{bi}} \right)^{0.0602} - 1 \right]^{1.456}$$

$$\beta_i \cong 1 - \left[ \left( \frac{R_{ai}}{R_{bi}} \right)^{0.0684} - 1 \right]^{1.531}$$

$$\gamma_i \cong 1 + (1.4 - 0.8\nu_i^*) \log\left( \frac{a_i}{b_i} \right)$$

$$\lambda_i \cong 1 + (1.4 + 0.8\nu_i^*) \log\left( \frac{a_i}{b_i} \right)$$

From above, the contact displacement between the workpiece and a fixture element is dependent on the type of contact and pressure distribution. In special case, if the workpiece surface and the tip of the fixture element are sphere at the *i*th contact point, then the correction factors $\alpha_i = \beta_i = \gamma_i = \lambda_i = 1$, the contact displacements at the normal and tangential direction are as follows:

$$\delta_{i\mathbf{n}}^c = \left( \frac{9 f_{i\mathbf{n}}^{c2}}{16 R_i^* E_i^{*2}} \right)^{\frac{1}{3}}$$

$$\delta_{i\mathbf{t}}^c = \frac{f_{i\mathbf{t}}^c}{8 a_i G_i^*}$$

$$\delta_{i\mathbf{b}}^c = \frac{f_{i\mathbf{b}}^c}{8 a_i G_i^{*2}}$$

The contact stiffness can be written as

$$K_{i\mathbf{n}}^c = \left( 6 R_i^* E_i^{*2} f_{i\mathbf{n}}^c \right)^{\frac{1}{3}}$$

$$K_{i\mathbf{t}}^c = K_{i\mathbf{b}}^c = 8 a_i G_i^* = \frac{4}{E_i^*} G_i^* K_{i\mathbf{n}}^c$$

The contact stiffness varies with the change of normal directional contact force $f_{i\mathbf{n}}^c$. A reasonable linear approximation of the contact stiffness can be obtained from a least-square fit to the above equation for $f_{i\mathbf{n}}^c$ ranging from 0 to 1000*N*:

$$K_{i\mathbf{n}}^{c} = 5.85\left(6R_i^{*}E_i^{*2}\right)^{\frac{1}{3}}$$

Specially, if a planar workpiece surface and a flat-tipped cylindrical cross-section fixture element are contacted, the resulting contact stiffnesses at the normal and tangential direction are represented as:

$$K_{i\mathbf{n}}^{c} = \frac{2E_{wi}}{1-\nu_{wi}^{2}} r_{fi}$$

$$K_{i\mathbf{t}}^{c} = K_{i\mathbf{b}}^{c} = \frac{8G_{wi}}{2-\nu_{wi}} r_{fi}$$

where $r_{fi}$ is the radius of the cross section of the *i*th fixture element.

Fixture elements can be modeled as cantilevered beam elements with a cylindrical cross section of radius $r_{fi}$ and length $l_{fi}$, so that the stiffness of fixture element at the *i*th contact is expressed as:

$$K_{i\mathbf{n}}^{f} = \frac{\pi E_{fi} r_{fi}^{2}}{l_{fi}}$$

$$K_{i\mathbf{t}}^{f} = K_{i\mathbf{b}}^{f} = \frac{3\pi G_{fi} r_{fi}^{2}}{4l_{fi}}$$

### 7.2.3 Calculating the Reaction Forces at Contact Points

The unknown reaction forces at contact points can be determined by the principle of the minimum total complementary energy [81]. Since the structural compliance of the workpiece is not considered here, the total complementary energy is composed of contact energy between workpiece and fixture elements and energy from fixture elements [52], i.e.

$$\Pi = \Pi_c + \Pi_f \tag{7.7}$$

As each fixture element is fixed on the baseplate at one end, the displacement of the fixture element is a zero vector, thus the related potential is also zero:

$$\Pi_f = \left(\mathbf{f}^c\right)^T \boldsymbol{\delta}^c = 0 \tag{7.8}$$

The strain energy from workpiece and fixture element contacts can be expressed as:

$$\Pi_c = \frac{1}{2}\left(\mathbf{f}^c\right)^T \left(\mathbf{K}\right)^{-1} \mathbf{f}^c \tag{7.9}$$

Consequently, the reaction forces can be obtained by the optimization problem:

*Find* **f**

Minimize $\Pi_c = \frac{1}{2}\left(\mathbf{f}^c\right)^T \left(\mathbf{K}\right)^{-1} \mathbf{f}^c$

*Subject to:*

(1) Static equilibrium constraints $\mathbf{G}\mathbf{p}^C + \mathbf{W}_C + \mathbf{W}_E + \mathbf{W}_G = \mathbf{0}$

(2) Friction cone constraints $\mathbf{H}\mathbf{f}^c \geq \mathbf{0}$

(3) Minimum normal reaction force $f_{i\mathbf{n}} \geq 0$

(4) Maximum normal reaction force, non-yield constraint on the contact stress $f_{i\mathbf{n}} \leq \sigma_{yield}(\pi a_i^2)$

### 7.2.4 Determination of the Final Location of the Part

It is assumed that the part coordinate system has identical orientation with the global coordinate system, then the workpiece location error $\delta\mathbf{q}_w^{"} = \left[\delta\mathbf{r}_w^T, \delta\boldsymbol{\theta}_w^T\right]^T$ due to local deformation at locators $\boldsymbol{\delta}^c = \left[\left(\boldsymbol{\delta}_1^c\right)^T, ..., \left(\boldsymbol{\delta}_m^c\right)^T\right]^T$ can be determined by:

$$\mathbf{E}\delta\mathbf{q}_w^{"} = \mathbf{T}\boldsymbol{\delta}^c \tag{7.10}$$

where $\mathbf{E} = \left[\mathbf{E}_1^T, ..., \mathbf{E}_m^T\right]^T$ and **T**=diag($\mathbf{T}_1$,…,$\mathbf{T}_m$) are the location matrix of locators and the sytem transformation matrix respectively,

$$\mathbf{E}_i = \begin{bmatrix} 1 & 0 & 0 & 0 & z_{ci} & -y_{ci} \\ 0 & 1 & 0 & -z_{ci} & 0 & x_{ci} \\ 0 & 0 & 1 & y_{ci} & -x_{ci} & 0 \end{bmatrix}$$

and

$$\mathbf{T}_i = [\mathbf{n}_i, \mathbf{t}_i, \mathbf{b}_{ci}]$$

$$\delta\mathbf{q}_w^{"} = \mathbf{E}^{+}\mathbf{T}(\mathbf{K}_l^c)^{-1}\mathbf{f}_l^c$$

## 7.3 Search Method – Particle Swarm Optimization (PSO)

### 7.3.1 Overview

Particle swarm optimization (PSO) is a modern evolutionary computation technique based on a population mechanism. It was motivated by the simulation of the social behavior of bird flocking and fish schooling. Its emergent behavior has found popularity in solving difficult optimization problems.

$$V_{t+1}^i = \omega V_t^i + \varphi_1\beta_1(P_i^t - X_i^t) + \varphi_2\beta_2(P_g^t - X_i^t) \tag{7.11}$$

$$X_{t+1}^i = X_t^i + V_{t+1}^i \tag{7.12}$$

where $\varphi_1$ and $\varphi_2$ are the constants to balance the influence of the individual's knowledge and that of the group, $\beta_1$ and $\beta_2$ are uniformly distributed random numbers, ω is the inertia weight to adjust the tendency to facilitate global exploration (smaller ω) or local exploration (larger ω) in the current search area, $X_t^i$ and $X_{t+1}^i$ represent the positions in the current and next iteration for the *i*th individual, $V_{t+1}^i$ and $V_{t+1}^i$ represent the velocities in the current and next iteration for the *i*th particle. $P_i^t$ is the local best position that the *i*th particle has achieved so far and $P_g^t$ is the global best position that all particles have achieved so far. This problem can be formulated as:

**Given**

- Workpiece geometry information
- Machining process conditions, including cutting tools, tool path, etc.

**Find**

**System Variables**

- Fixture contact positions $\mathbf{x}=\{\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_n\}$ , $\mathbf{x}_i=\{x,y,z\}$, n—number of fixture elements
- Clamping forces $\mathbf{f}=\{\mathbf{f}_1, \mathbf{f}_2, \ldots, \mathbf{f}_m\}$, m—number of clamps

**Satisfy**

**Geometrical Constrains**

- Fixture elements keep contact with workpiece surfaces

**Force Constrains**

- locating forces $\mathbf{0} < \mathbf{f}_i < \mathbf{f}_{max}$

**Minimize**

- Mean of workpiece localization error
- Variation for workpiece translation and rotation

### 7.3.2 Representation of Fixture Design

In Chapter 6, the representation for fixture localization is expressed as three levels, i.e. root level, surface level and point level. However, for designing a fixture, this is insufficient as the force information is not considered. Therefore, the representation for fixture design is developed by extending the location representation in Chapter 6. In this representation, a force level is added (Figure 7.3). For a point in the point level, only one force vector in force level is associated with it. Each contact point in the point level includes three elements, i.e. the coordinates in x, y, and z direction, while each force vector in force level consists of three force elements in one normal and two tangential directions of surface at the contact point. In the force level, only the normal directional elements of the force vectors associated with clamping points are active forces, the others, including tangential forces at clamping points and force vectors at supporting and locating points, are passive forces. The active forces are the input parameters for optimization while the passive forces need to be calculated based on contact positions and the magnitudes of the active forces.

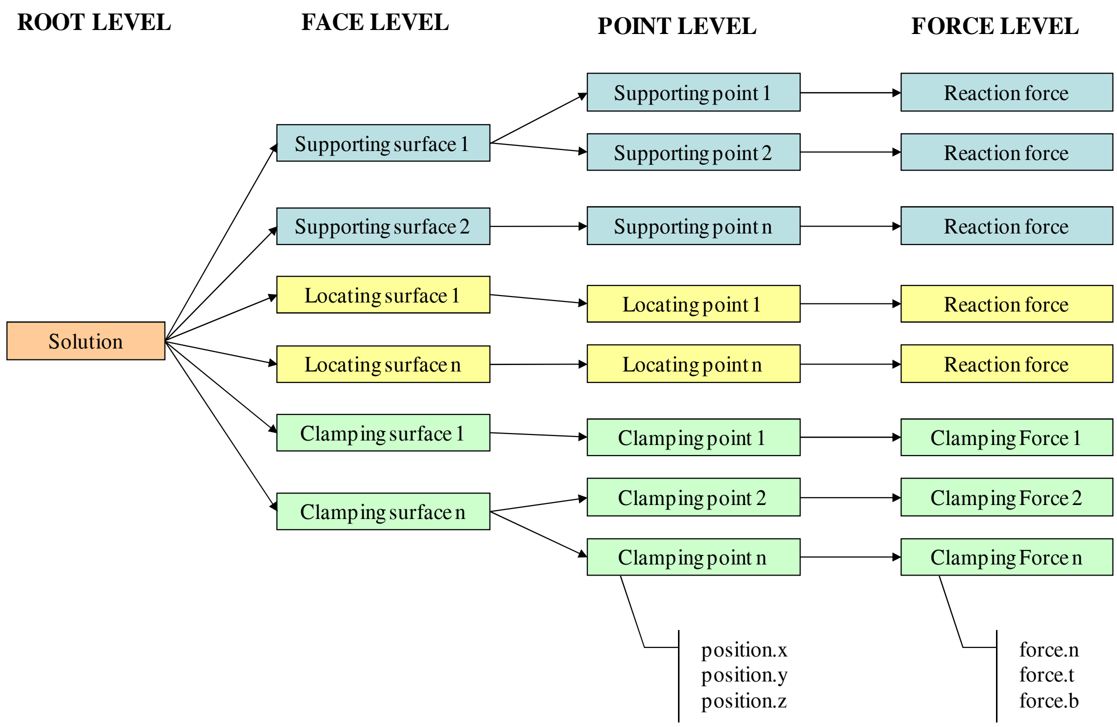



Figure 7.3 The representation for fixture design

Corresponding to the representation of fixture design, the design solution for each individual is encoded to digital number illustrated as Figure 7.4. The encoded solution is divided into three levels, i.e. face level, point level and force level. The digital numbers in face and point level are represented same as those in last chapter. The force elements at the force level are the active clamping forces and act towards the opposite direction of face normal at their corresponding contact points. Figure 7.5 illustrates the details of an individual encoding. Based on the 3-2-1 locating approach, the number of supporting and locating points on the workpiece are fixed at three respectively. However, the number of clamping points varies from at least one to the maximum number clamping elements $N_{clamp\text{-}max}$.

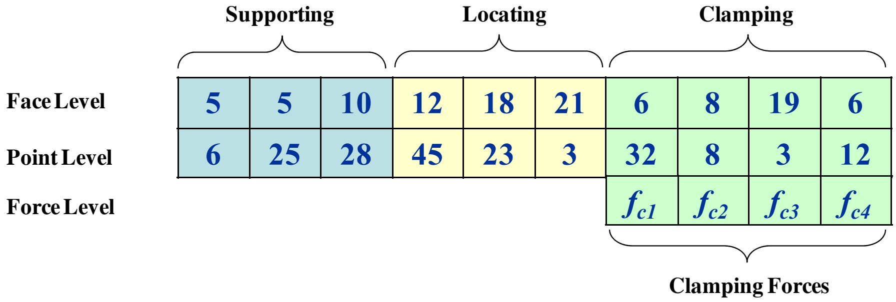



Figure 7.4 Encoding of fixture design with 3-2-1 approach

Decode the particle to get a serial of spatial positions of contact points and interaction forces between the workpiece and fixture elements. In each iteration, when a particle is updated, the spatial positions are obtained discretely and their forces continuously.

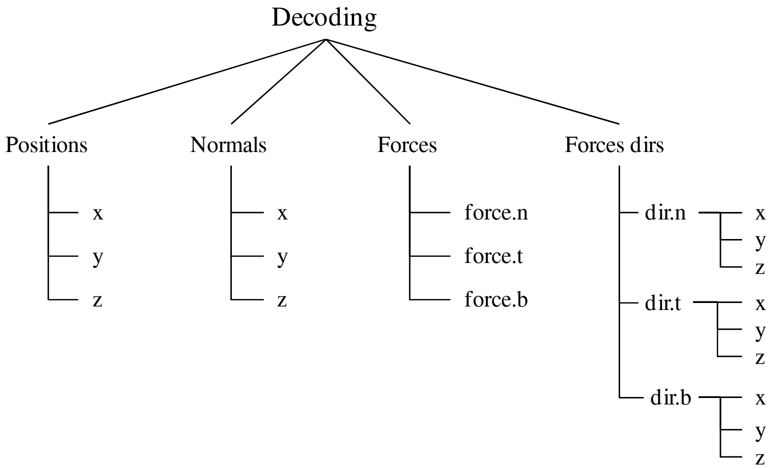



Figure 7.5 Extended fixture design solution encoding for an individual

### 7.3.3 PSO Algorithm Process

A typical procedure of the PSO algorithm can be expressed as follows:

***Initialization:***

*(1) Set parameters for PSO process, e.g. the Swarm Size and the total iteration number;*

*(2) Initialize randomly position and velocity for the particles;*

***Processing:***

*At iteration 0, initialize each particle with feasible random number under the face, point and force constrains;*

*Do loop*

*For each particle*

*Calculate the fitness value*

*If the fitness value is better than the best fitness value (**pBest** $P_t$) in history, set current value as the new **pBest***

*End*

*Choose the individual with the best fitness of all particles as the **gBest** $P_g$;*

*For each particle, calculate velocity with the velocity equation and update the new positions with position equation to generate a particle for next iteration;*

*While the maximum iteration number is reached or stop criteria is satisfied*

***Output:***

*The **gBest** and its fitness will be output as the final result.*

The traditional PSO algorithm is originally developed for continuous problems and works well at the early stage of search process, but less efficient at the final stage. Due to the loss of diversity in the population and moving slowly with low velocities of the particles, the search algorithm cannot explore the whole design space to reach the global optimum and the swarm is prone to be trapped at local optimum. Moreover, pure PSO algorithm works well at early stage and less efficient at final stage.

In order to solve this problem and to enhance the traditional PSO algorithm to reach the global optimum, a modified PSO algorithm is developed by combining with genetic operators, namely crossover and mutation. The workflow of the algorithm is illustrated in Figure 7.6. In order to escape from local optimum during the search process, the genetic operators are applied if the fitness of the global best individual is same in the continuous 10 iterations. The genetic operators in the modified algorithm are similar to those in Chapter 6 and described as follows.

*Crossover.* Two particles in the swarm are selected randomly as parents for crossover operation. Only one type of crossover strategies is applied. A cutting point is random determined at face level only, and each parent chromosome is separated as left and right parts at the cutting point at each level. The face Ids, points Ids and clamping forces in the left part of parent 1 and those in the right part of parent 2 are reorganized to form child 1. Child 2 can be obtained from similar procedure. The velocities associated with positions are also recombined with the point Ids and clamping forces.

*Mutation.* An individual in the swarm is selected randomly for the mutation operation. A position is randomly selected at either face level or point level from the individual. When the gene selected is at face level, a random face ID from supporting or locating surface candidates is chosen to replace this gene. This replacement is based on original selected face belong to supporting or locating surface. If the gene selected is at point level, a random point ID is chosen to replace this gene from node candidates of the surface on which the original point is in order to guarantee the replaced point ID is not out of range.

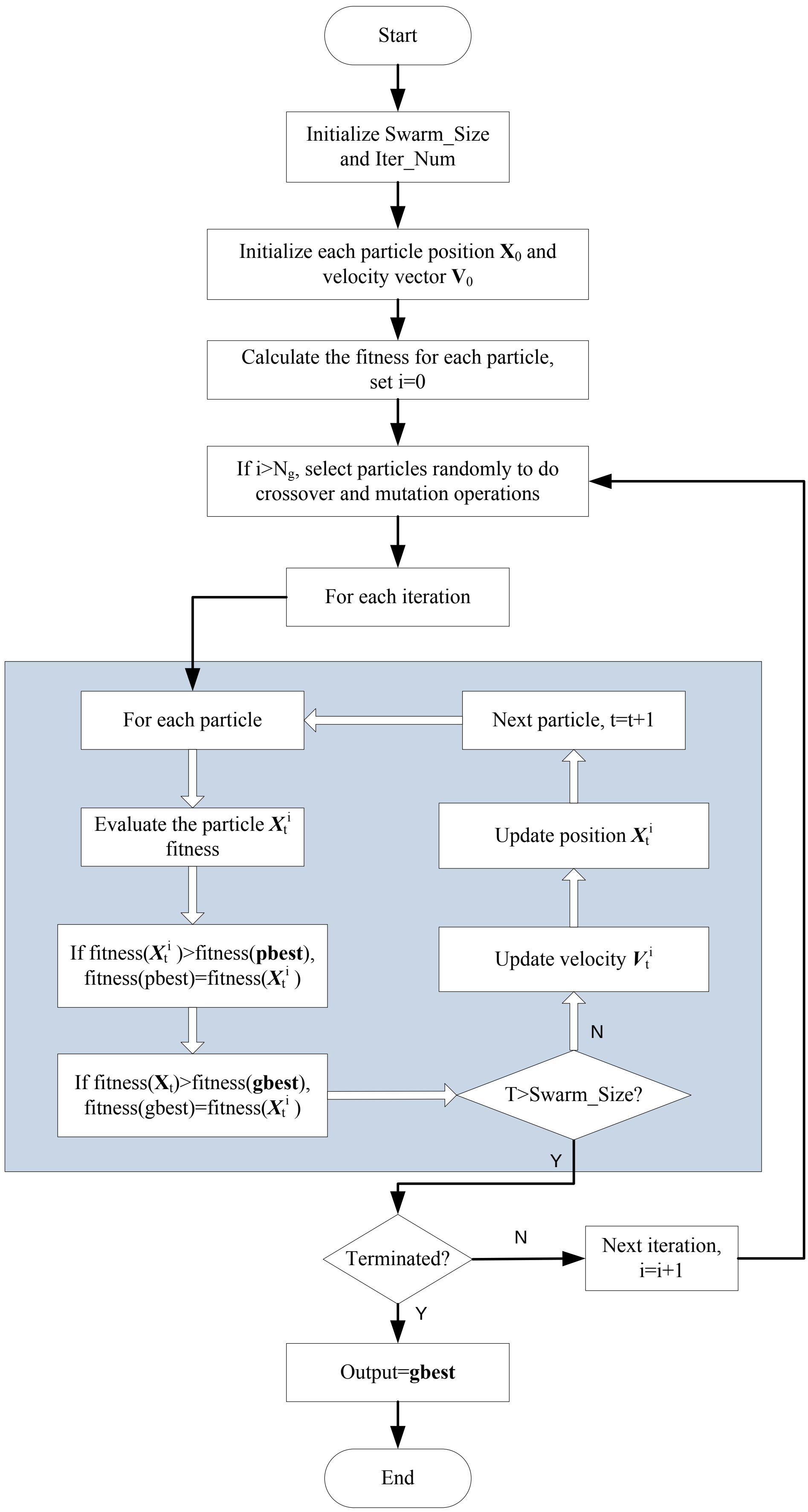



Figure 7.6 Workflow of the PSO algorithm

## 7.4 Case Study

### 7.4.1 Sample Part

A part shown in Figure 7.7 is used as an example to illustrate the computational results of PSO algorithm. This part is an aluminum alloy (*E*=70GPa, ν=0.354) and has a machining feature "Pocket" in the middle. The fixture elements are made of hardened steel (*E*=207GPa, ν=0.296) with flat or sphere tips. The static coefficient of friction for the workpiece-fixture material pair in the range of forces being considered is taken to be 0.2. The details of material properties for the workpiece and fixture elements are lsit in Table 7.1. The candidate points for fixturing are shown in Figure 7.8.

Table 7.1 Material properties

| | Workpiece | Fixture elements |
|---|---|---|
| Material | Aluminum 7075-T6 | Hardened Steel |
| Density (kg/m$^3$) | 2.7x10$^3$ | 7.55x10$^3$ |
| Young's Modulus (GPa) | 70 | 207 |
| Poisson's ratio | 0.354 | 0.296 |
| Coefficient of friction | 0.25 | |

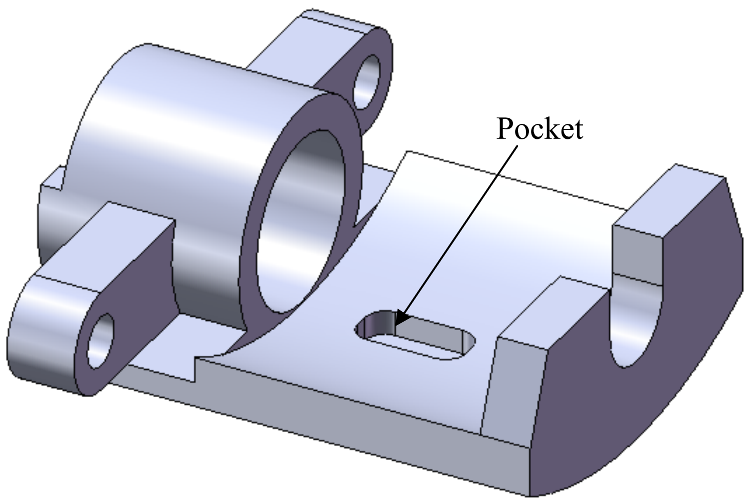



Figure 7.7 A sample part

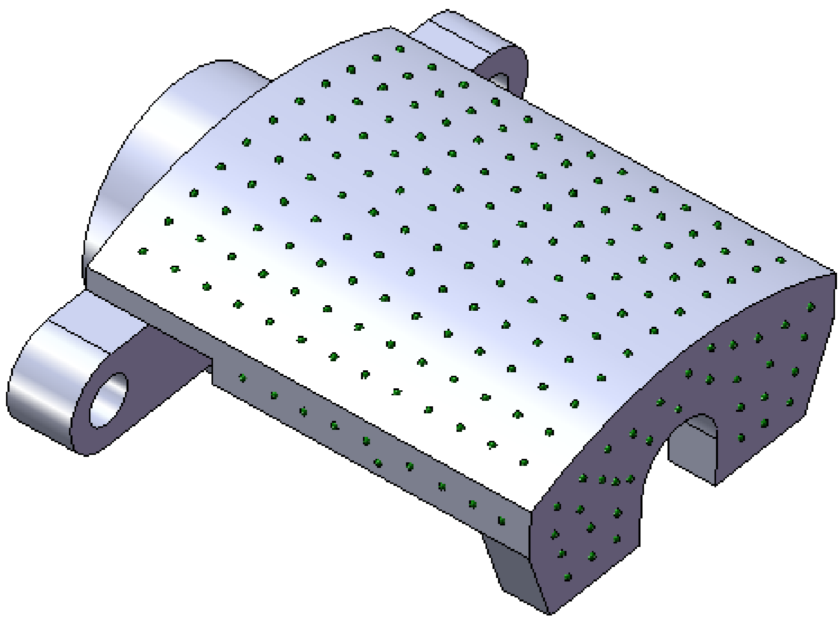


Figure 7.8 Point candidates for fixturing

### 7.4.2 Computation Results

The model for the current case is coded with Matlab 7.5. The design parameters for the model are listed in Table 7.2. At the beginning of computation, it starts with PSO search. After 10 iterations, genetic operations, crossover and mutation, are involved for particle diversity and avoiding local minimum trap. In each iteration, the particles are then evaluated and flown through the problem domain till the stop criteria is satisfied. In the end, the ‘optimal’ solution is obtained and corresponding to the minimum objective function value. Figure 7.9 illustrates the convergence of the hybrid of GA and PSO algorithm for the example process. The contact point coordinates and their reaction forces are listed in Table 7.3. Figure 7.10 shows the contact points for fixturing on the workpiece.

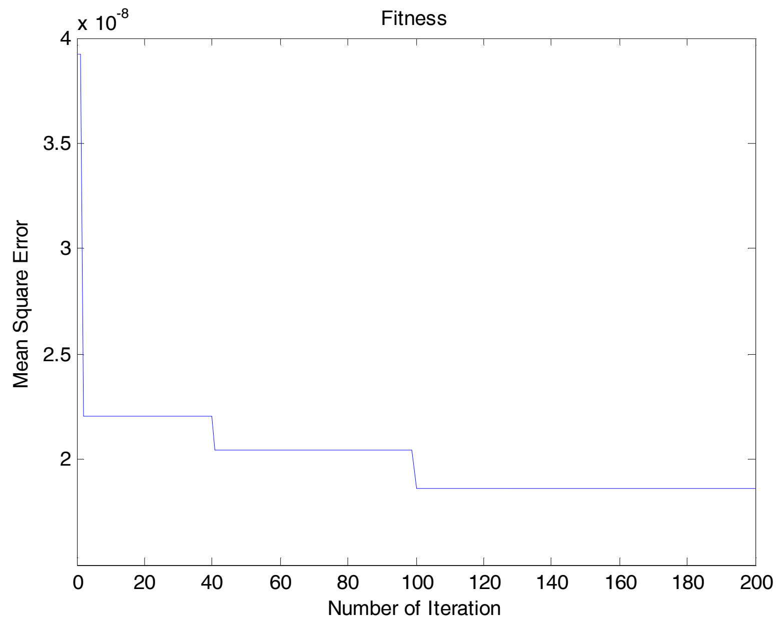



Figure 7.9 Convergence of the developed PSO algorithm

Table 7.2 The parameter values for the case study

| Parameter | Value | Remarks |
|---|---|---|
| Machining force | (-100, 100, -300) | The highest force during machining |
| Clamping force range (*N*) | [100, 1000] | Lower bound 100*N*<br>Upper bound 1000*N* |
| Population size | 30 | Case specific |
| Initial weight ω | 0.4-0.9 | Start at 0.9, and end at 0.4 |
| Coefficient $\varphi_1$, $\varphi_2$ | 2, 2 | Case specific |
| Crossover probability $P_c$ | 0.9 | |
| Mutation probability $P_m$ | 0.1 | |
| Stop criteria | maxIt = 500 | The maximum number of iteration |

Table 7.3 The results for fixturing contact points

| No. | Function | Contact point coordinates | Force |
|---|---|---|---|
| 1 | Support | (-50, -7.7, -40.8) | (52.4, -14.8, 0) |
| 2 | Support | (-50, -7.7, 40.8) | (27.3, -7.7, 0) |
| 3 | Support | (70, -14, -0.1) | (110, -31.1, 0) |
| 4 | Locator | (69.9, 7.6, 60) | (310.4, -38.7, 49.1) |
| 5 | Locator | (-0.9, 7.5, 60) | (281.9, -53.4, 26.2) |
| 6 | Locator | (-60, 26.2, -44.3) | (170, 45.7, -2.3) |
| 7 | Clamp | (80, 6.9, -13.2) | (400, -113.1, 0) |
| 8 | Clamp | (52.5, 7.1, -60) | (500, -10.5, 54.6) |

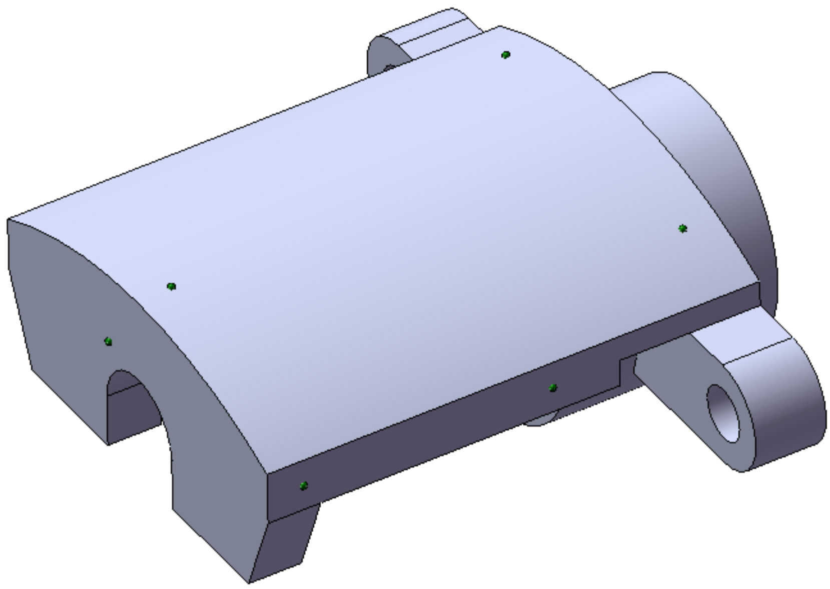


Figure 7.10 Fixturing points on the workpiece

### 7.4.3 Comparison with Other Algorithms

A computational experiment has been conducted to verify and compare the performance of the developed algorithms. The comparison is performed among the modified PSO algorithm, pure PSO algorithm and developed GA based algorithm in Chapter 6. The experiment is based on 500 iterations for each algorithm. The population for all these algorithms are same in this experiment. As shown in Figure 7.11, all algorithms fall rapidly at the initial optimization stage. At the middle stage and final stage, pure PSO algorithm optimizes slowly while the modified PSO and modified GA can get better results.

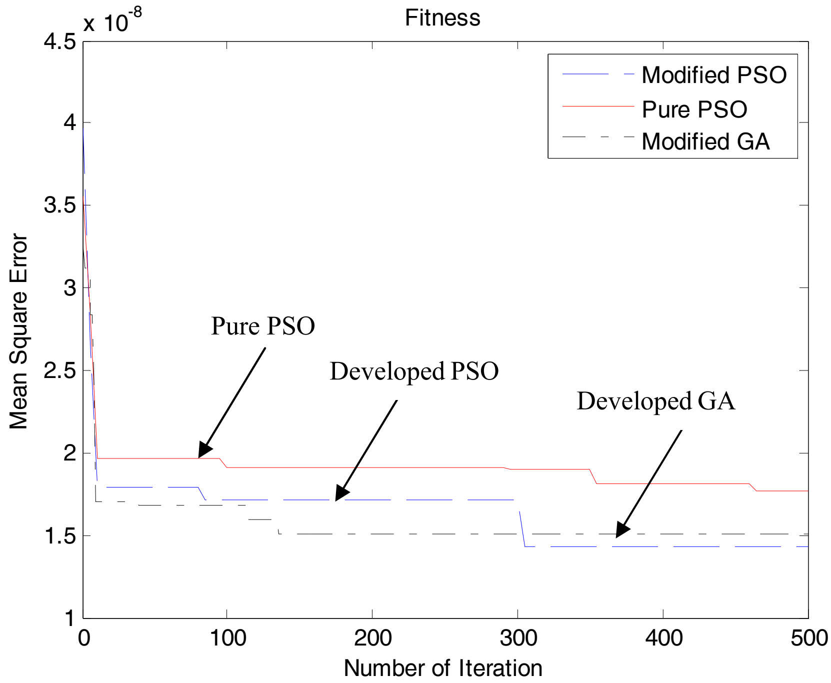



Figure 7.11 The comparison among the modified PSO algorithm, pure PSO algorithm and modified GA

## 7.5 Summary

In this chapter, a modified PSO algorithm for fixturing process is presented. An illustrative example is used to validate the proposed approach. It is shown that the modified PSO algorithm can obtain a satisfactory optimization result for fixture design. Moreover, a comparison is performed among the modified PSO algorithm, pure PSO algorithm and modified GA based algorithm in Chapter 6. It shows that the modified PSO algorithm is outperformed over the other algorithms.

A case study to illustrate the developed fixture design and analysis system incorporating robust design techniques is presented in the next chapter.

# Chapter 8 Case Study

In this chapter, a case study is discussed in order to demonstrate the developed CFDA system and algorithms in this research work. The test case will undergo robust fixture design process to obtain optimal fixturing contact points. Based on these results, a user can design a fixture interactively in the developed CFDA system. The designed fixture is then verified and validated in the analysis module. The analysis result is sent back to the designer for evaluation.

## 8.1 Process for Fixture Design and Analysis

The developed system uses the service-oriented architecture as previously explained in Chapter 3. In this case study, two experts, one in the field of fixture design and the other in FEM, who are located at two different places, involve the collaboration. Both the experts can login to the system simultaneously and invoke the CFDA system. The workpiece for the case study is presented in Figure 8.1. A fixture needs to be arrived for machining the slots on the workpiece highlighted in Figure 8.1. This model is first created by the product designer and stored at the repository. The material properties of the workpiece and fixture elements are same as listed in Table 7.1.

### 8.1.1 The Process in Robust Fixture Design

This process is called by the fixture designer through “Robust Design” module in the CFDA system. The fixturing surfaces are first selected and specified for locating, supporting or clamping by the designer. Figure 8.2 shows that a surface is selected for supporting. For the search of optimal robust contacts for fixturing, the candidate points are first generated with surface meshing program and illustrated in Figure 8.3. The algorithm developed in Chapter 7 is selected for the demonstration. The design parameters for the model are same as the one listed in Table 7.2, except that the machining forces are (700, -300,-200) *N* and (300, -600,-200)*N* for the slots machining respectively. After computation, the convergence diagram and final results are shown in Figure 8.4 and Figure 8.5 respectively.

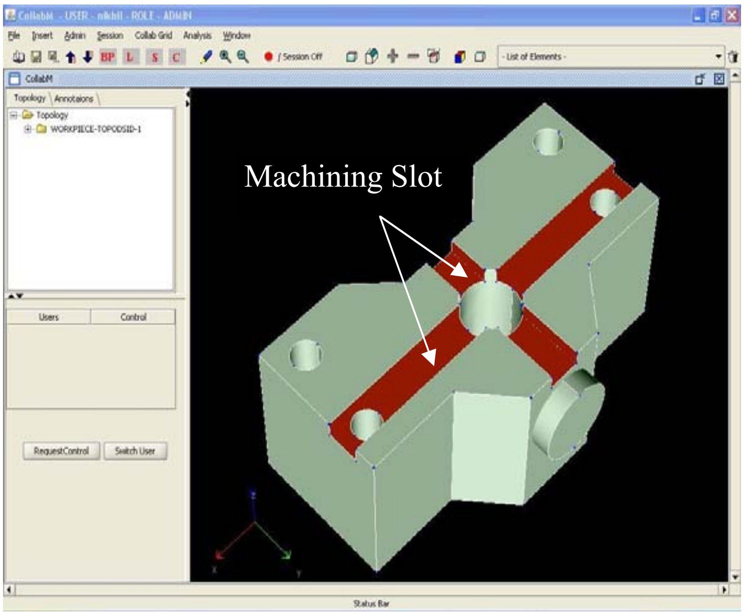



Figure 8.1 A workpiece is imported into the system in the fixture design process

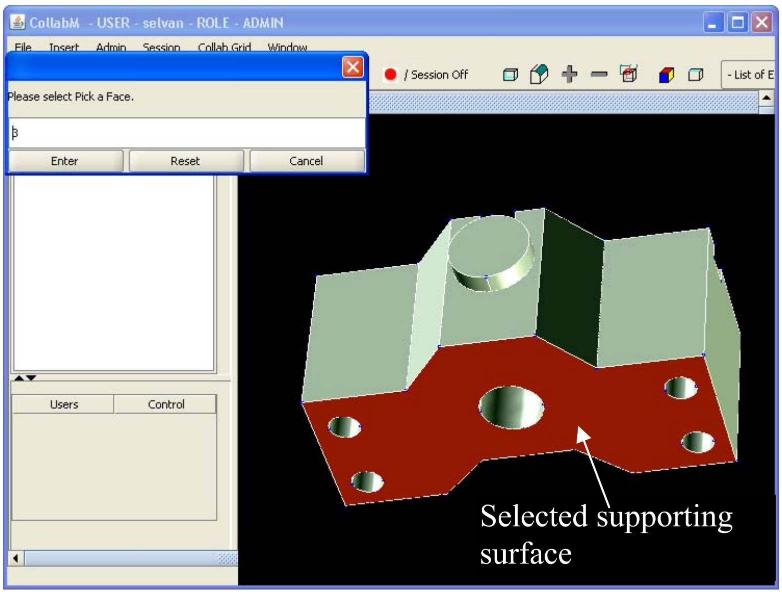



Figure 8.2 A surface is selected for supporting

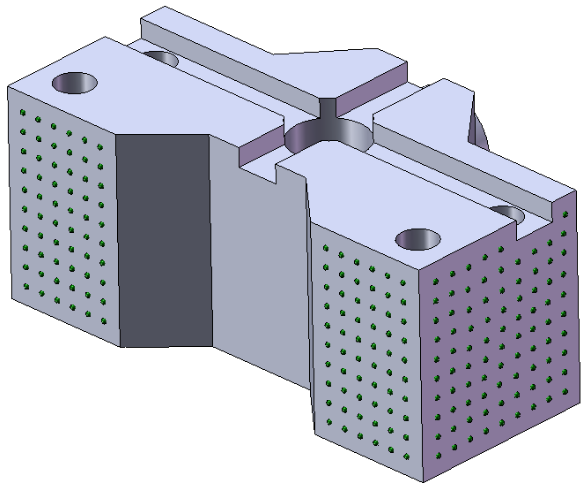


Figure 8.3 The candidate contact points for fixturing

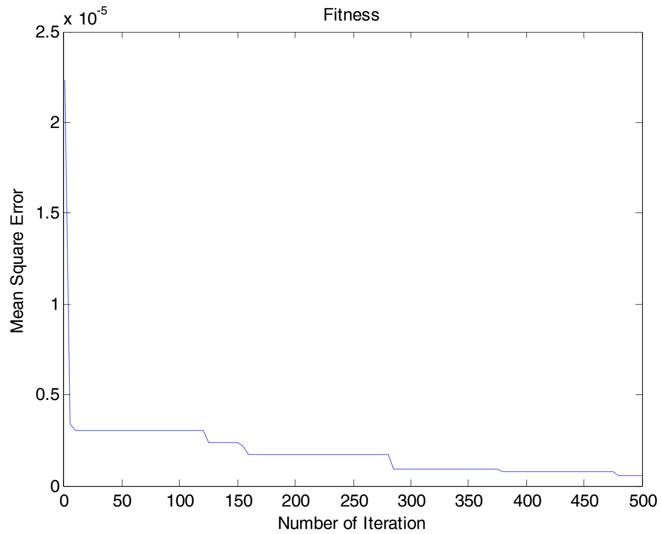



Figure 8.4 The convergence of design process

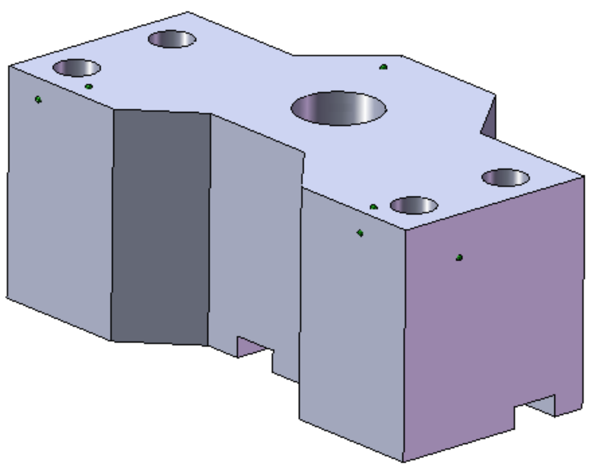


Figure 8.5 The final result for fixturing

### 8.1.2 The Process in Fixture Design

The procedure for interactive fixture design commences with loading a baseplate. Note that the fixture elements are chosen from the commercial IMAO fixture element library. In addition to supporting the workpiece, the baseplate also positions the clamps and locators which are used to restrain the motion of workpiece. By calculating the total area of the selected surfaces, the candidate baseplates for selection (Figure 8.6) are filtered by a rule which is implemented in the system using JBoss Rules.

The workpiece is then located by loading the locators on the baseplate. With the obtained fixturing points from robust design, the user manually chooses a fixture element for each fixturing point and builds a fixture. The final fixture design configuration designed using the developed system is shown in Figure 8.7. The output from the fixture design process is a geometric model file (in STEP format) and a fixture design configuration file which are stored by the fixture designer in the server repository. The example of the fixture design configuration file (FDC) generated by the system in the OWL format is shown in Figure 8.8.

### 8.1.3 The Process in Fixture Analysis

After the fixture design process is complete, the FEM analyst can start to analyze the fixture. The process of fixture analysis can be divided into three steps: (1) generating the boundary condition file; (2) generating the input deck for the solver; and (3) checking the job status and viewing the results. The details are described in the following sections.

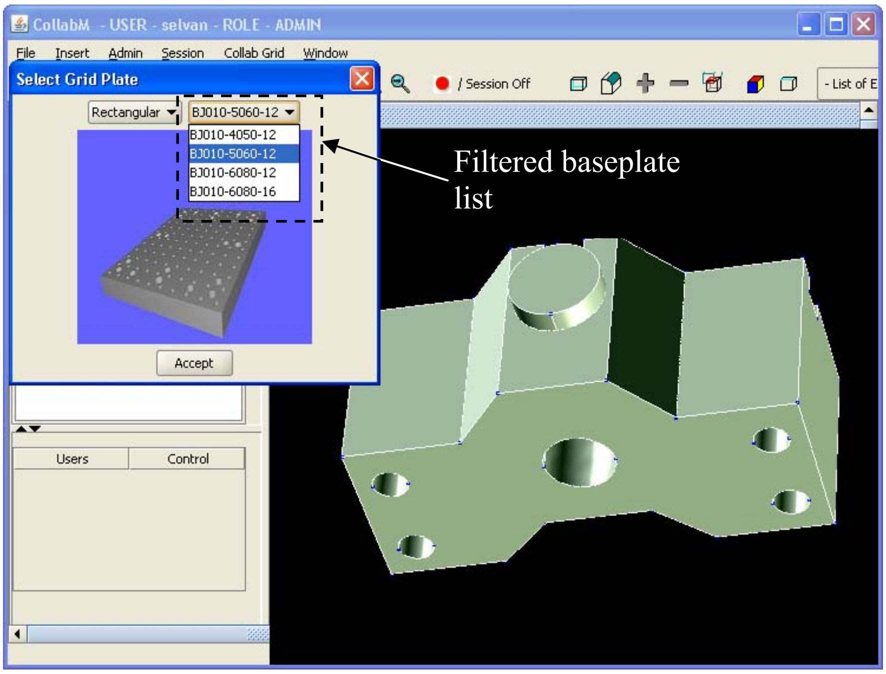



Figure 8.6 Choosing a baseplate from the filtered list in the fixture design process


Figure 8.7 The final fixture design in the fixture design process

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          - <Translation rdf:ID="Translation_107">
              <z rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.1</z>
              <y rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.125</y>
              <x rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.15</x>
            </Translation>
          </hasTranslation>
        </FDO:BJ101-12022>
      </FDO:hasClamp>
    - <hasBaseplateID>
        <BaseplateID rdf:ID="BaseplateID_53" />
      </hasBaseplateID>
      <FDO:contactFace rdf:resource="http://www.owl-ontologies.com/2009/10/part_inst.owl#Surface_50" />
    </FDO:ClampingUnit>
  </FDO:hasClampingUnit>
```


Figure 8.8 Fixture design data file in OWL format

### *8.1.3.1 Generation of the boundary condition file*

The analyst uses the CFDA client (Figure 8.9) to input fixture design data file, machining data file, which has the cutter centre location, assigns material properties to workpiece and fixture elements and specifies the clamping forces obtained. These parameters form the boundary conditions for the FEA process. The machining data file contains details of the cutter geometry, feed rates and cutter tool path for machining. The cutter motion then determines the finite elements to be removed during the machining process in order to simulate the actual machining. A sample of fixture analysis boundary condition file (FAC) in OWL format is shown in Figure 8.10.

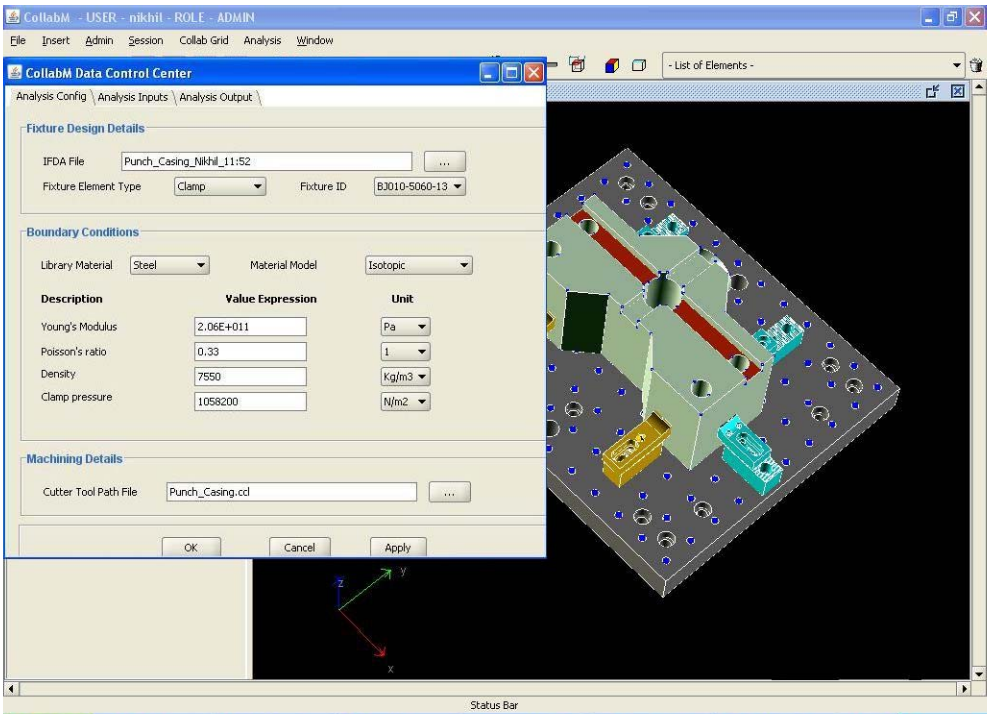



Figure 8.9 User interface for generating boundary conditions

```
- <ADO:GeometryEntity rdf:ID="Workpiece">
  - <ADO:hasMesh>
    - <ADO:Mesh rdf:ID="Mesh_7">
        <ADO:isMeshOf rdf:resource="#Workpiece" />
      </ADO:Mesh>
    </ADO:hasMesh>
  - <ADO:mapGeomtry>
      - <rdf:Description rdf:about="http://www.owl-ontologies.com/2009/10/part_inst.owl
          #Workpiece_1">
        <ADO:mapGeomtry rdf:resource="#Workpiece" />
    - <ADO:mapGeomtry>
        <ADO:GemetryEntity rdf:ID="GemetryEntity_1" />
      </ADO:mapGeomtry>
    - <j.0:hasMaterial>
      - <AO:Aluminum rdf:ID="Aluminum_1">
          <YoungsModulous rdf:datatype="http://www.w3.org/2001/XMLSchema#double">
            79e9 </YoungsModulous>
          <Density rdf:datatype="http://www.w3.org/2001/XMLSchema#decimal">
            2.7e3</Density>
          <PossionRatio rdf:datatype="http://www.w3.org/2001/XMLSchema#float">
            0.34</PossionRatio>
        </AO:Aluminum>
      </j.0:hasMaterial>
      </rdf:Description>
    </ADO:mapGeomtry>
</ADO:GeometryEntity>
```

Figure 8.10 A fixture analysis boundary condition file in OWL format

*8.1.3.2 Generating the input deck for the solver*

After generating the FAC file, the analyst now has all the input files (STEP + FDC+ FAC) necessary to generate the input data for performing the analysis at the server This is done by clicking on the "Analysis input" tab as shown in Figure 8.11. After the user clicks on the "Generate" button, the input deck files for solving, including the batch and session files, are created in real-time. The batch file in conjunction with the session file automates the pre-processing and the solving tasks such as applying boundary conditions, generating mesh, creating the input data file for the solver and sending the job to the solver. As stated before, PCL has been used for automating the FEM processes. The analysis process begins when the user runs the batch file by clicking on the "Apply" button under the "Analysis Input" tab. In order to handle multiple requests from users for analysis, a meta-scheduler has been designed [28]. The meta-scheduler helps in resource discovery and optimal utilization of resources for running multiple jobs. However, its discussion is beyond the scope of this research and its design and implementation can be found by referring to [27-28].

*8.1.3.3 Checking the job status and viewing the results*

The user can check the status of the job through the "Analysis output" tab as shown in Figure 8.12. It contains a list of job being currently run on the server and their status (.sts file). An example of status file ('Punch_Casing_Nikhil_11:52.sts') is shown in Figure 8.13.

Once the analysis job is completed, a report file will be automatically generated with automatic report generation algorithm using PCL. The result file reports the locator reaction forces, maximum stresses generated, workpiece deformation, fixture element displacement, etc. As a part of the result file generated, Figure 8.14 shows the deformation profile while machining, Figure 8.15 illustrates the fixture element reaction forces when the cutter traverses through its path, and Figure 8.16 shows an example of fixture analysis result file in OWL format. All the information helps to determine the quality of the fixture designed. The fixture designer then evaluates the fixture design and the process is reiterated if the fixture requires redesigning or modifications.

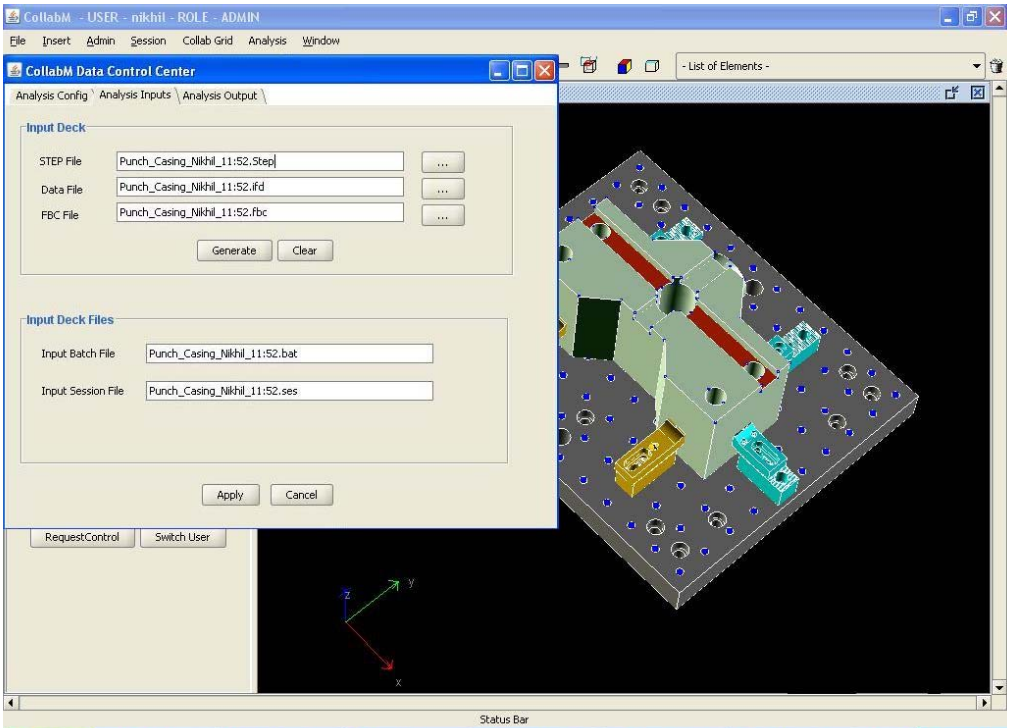



Figure 8.11 User interface for generating input deck for FEM process

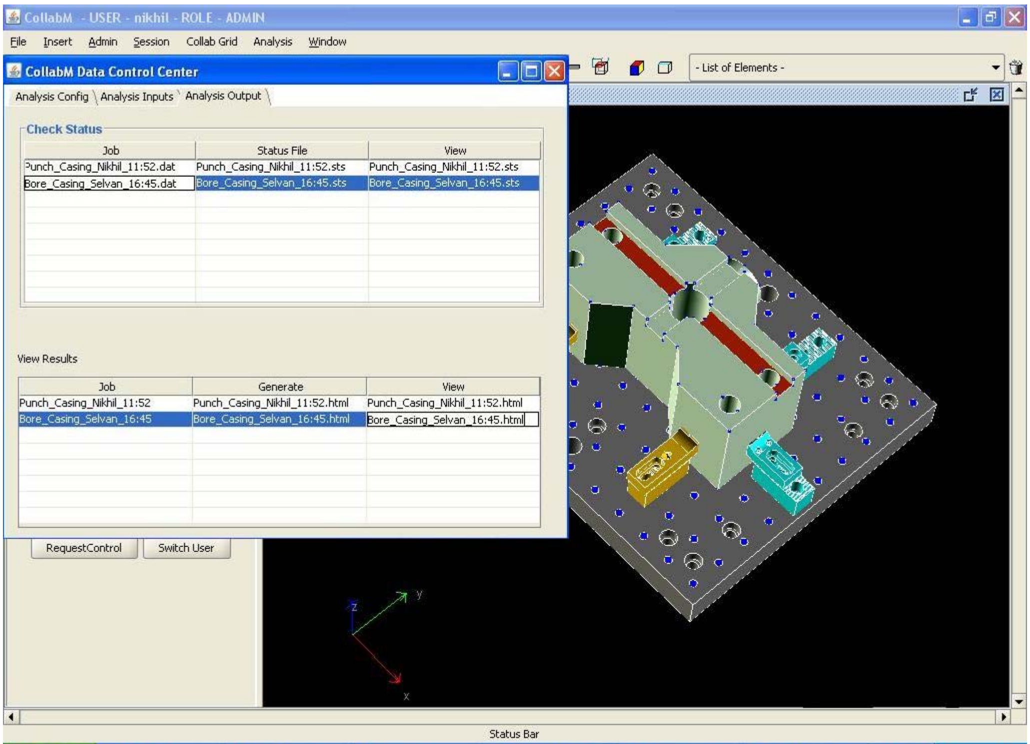
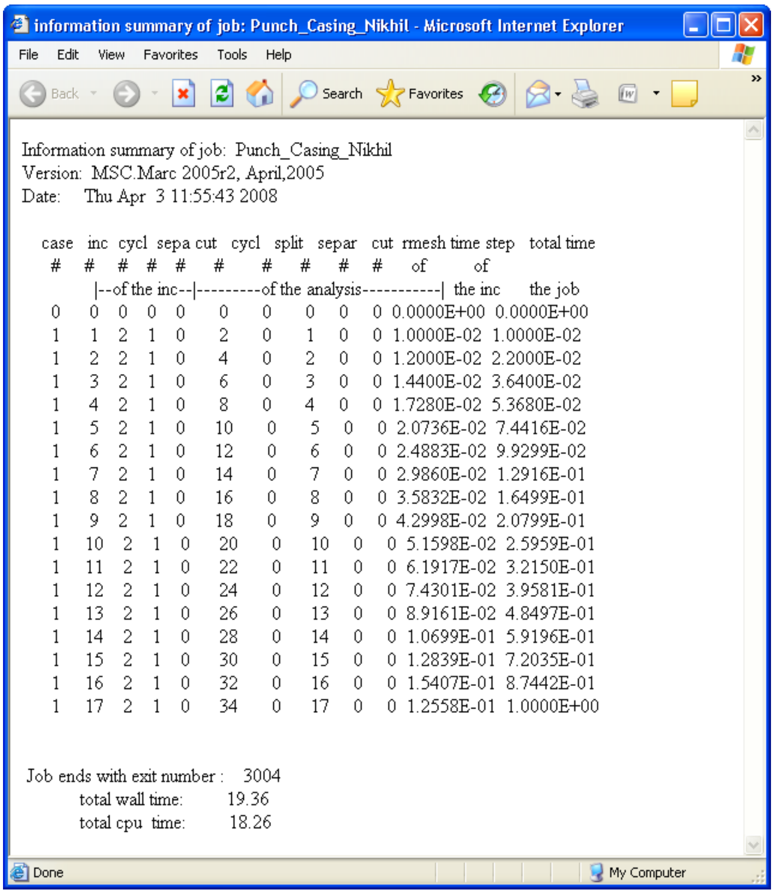



Figure 8.12 User interface for viewing result and status files




Information summary of job: Punch_Casing_Nikhil
Version: MSC.Marc 2005r2, April,2005
Date: Thu Apr 3 11:55:43 2008

| case # | inc # | cycl # | sepa # | cut # | cycl # | split # | separ # | cut # | rmesh # | time step of the inc | total time of the job |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | \|--of the inc--\| | | | | ---------of the analysis---------- | | | | \| | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0000E+00 | 0.0000E+00 |
| 1 | 1 | 2 | 1 | 0 | 2 | 0 | 1 | 0 | 0 | 1.0000E-02 | 1.0000E-02 |
| 1 | 2 | 2 | 1 | 0 | 4 | 0 | 2 | 0 | 0 | 1.2000E-02 | 2.2000E-02 |
| 1 | 3 | 2 | 1 | 0 | 6 | 0 | 3 | 0 | 0 | 1.4400E-02 | 3.6400E-02 |
| 1 | 4 | 2 | 1 | 0 | 8 | 0 | 4 | 0 | 0 | 1.7280E-02 | 5.3680E-02 |
| 1 | 5 | 2 | 1 | 0 | 10 | 0 | 5 | 0 | 0 | 2.0736E-02 | 7.4416E-02 |
| 1 | 6 | 2 | 1 | 0 | 12 | 0 | 6 | 0 | 0 | 2.4883E-02 | 9.9299E-02 |
| 1 | 7 | 2 | 1 | 0 | 14 | 0 | 7 | 0 | 0 | 2.9860E-02 | 1.2916E-01 |
| 1 | 8 | 2 | 1 | 0 | 16 | 0 | 8 | 0 | 0 | 3.5832E-02 | 1.6499E-01 |
| 1 | 9 | 2 | 1 | 0 | 18 | 0 | 9 | 0 | 0 | 4.2998E-02 | 2.0799E-01 |
| 1 | 10 | 2 | 1 | 0 | 20 | 0 | 10 | 0 | 0 | 5.1598E-02 | 2.5959E-01 |
| 1 | 11 | 2 | 1 | 0 | 22 | 0 | 11 | 0 | 0 | 6.1917E-02 | 3.2150E-01 |
| 1 | 12 | 2 | 1 | 0 | 24 | 0 | 12 | 0 | 0 | 7.4301E-02 | 3.9581E-01 |
| 1 | 13 | 2 | 1 | 0 | 26 | 0 | 13 | 0 | 0 | 8.9161E-02 | 4.8497E-01 |
| 1 | 14 | 2 | 1 | 0 | 28 | 0 | 14 | 0 | 0 | 1.0699E-01 | 5.9196E-01 |
| 1 | 15 | 2 | 1 | 0 | 30 | 0 | 15 | 0 | 0 | 1.2839E-01 | 7.2035E-01 |
| 1 | 16 | 2 | 1 | 0 | 32 | 0 | 16 | 0 | 0 | 1.5407E-01 | 8.7442E-01 |
| 1 | 17 | 2 | 1 | 0 | 34 | 0 | 17 | 0 | 0 | 1.2558E-01 | 1.0000E+00 |

Job ends with exit number : 3004
total wall time: 19.36
total cpu time: 18.26

Figure 8.13 Status file viewed via the web browser

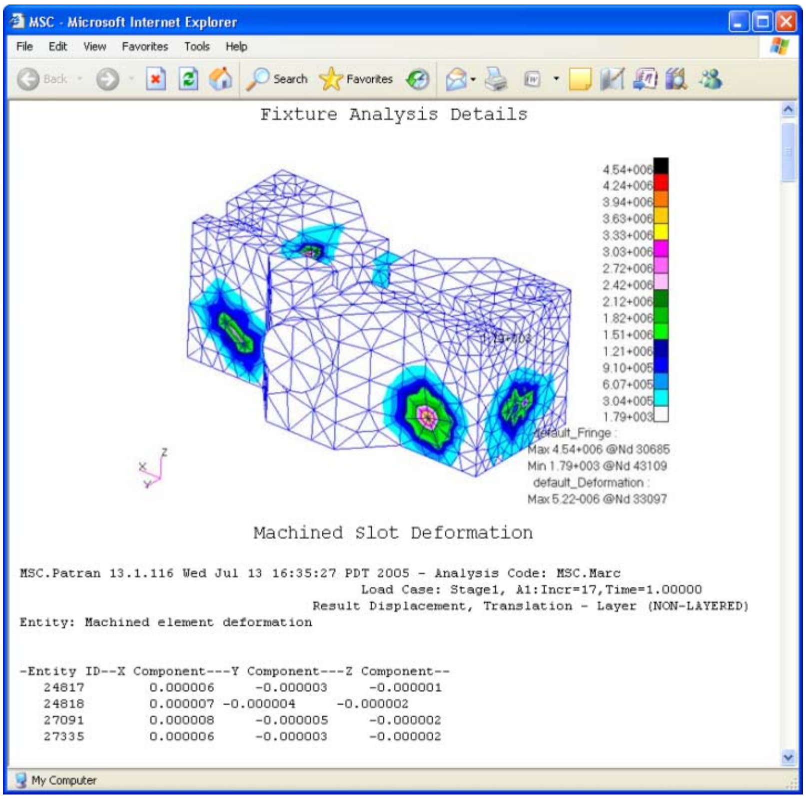



Figure 8.14 The deformation and stress profile as cutting along the slot in the result file

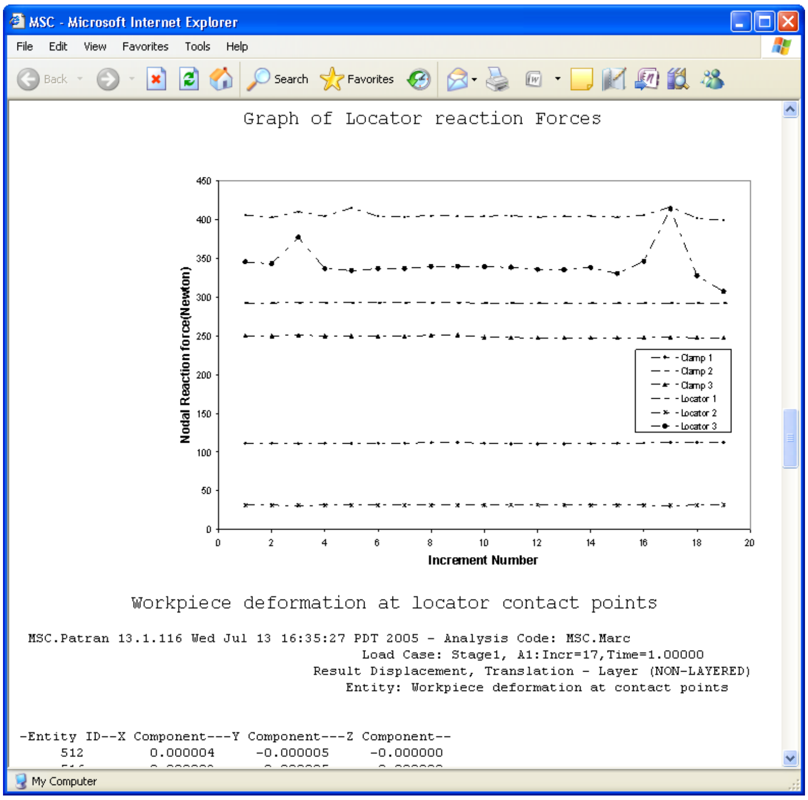



Figure 8.15 The fixture element reaction forces when the cutter traverses through its path in the result file viewed via the web browser

```
- <ADO:LocatorEntity rdf:ID="LocatorEntity_6">
  - <ADO:hasLoadCase>
        <ADO:LoadCase rdf:ID="LoadCase_1" />
    </ADO:hasLoadCase>
  - <ADO:hasContact>
      - <ADO:ContactPoint rdf:ID="ContactPoint_2">
      - <ADO:hasReactionForce>
          - <ADO:NormalForce rdf:ID="NormalForce_36">
              <dataValue
               rdf:datatype="http://www.w3.org/2001/XMLSchema#float">267.6</dataValue>
            </ADO:NormalForce>
        </ADO:hasReactionForce>
      - <ADO:hasReactionForce>
      - <ADO:FrictionalForce rdf:ID="FrictionalForce_37">
            <dataValue
             rdf:datatype="http://www.w3.org/2001/XMLSchema#float">26.0</dataValue>
            <x rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.4</x>
            <y rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0</y>
            <z rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.7</z>
          </ADO:FrictionalForce>
        </ADO:hasReactionForce>
      - <hasNormalDir>
        - <NormalDir rdf:ID="NormalDir_31">
              <z rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0</z>
              <y rdf:datatype="http://www.w3.org/2001/XMLSchema#float">-1.0</y>
              <x rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.0</x>
            </NormalDir>
        </hasNormalDir>
        <ADO:hasLoadCase rdf:resource="#LoadCase_1" />
      - <hasCoordinate>
        - <Coordinate rdf:ID="Coordinate_30">
              <x rdf:datatype="http://www.w3.org/2001/XMLSchema#float">-0.125</x>
              <y rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.13</y>
              <z rdf:datatype="http://www.w3.org/2001/XMLSchema#float">0.1</z>
            </Coordinate>
        </hasCoordinate>
        </ADO:ContactPoint>
    </ADO:hasContact>
```


Figure 8.16 An example of fixture analysis result file in OWL format

## 8.2 Summary

In this chapter, a case study is presented to demonstrate the developed PSO algorithm and the CFDA system based on the Web-service based service-oriented architecture (WSSOA) for fixture design. This system enables designers to collaborate seamlessly across the globe in arriving at a design. The benefits of using WSSOA for the system are interoperability, platform-independence and language neutrality of web services and SOA. The developed algorithm can provide robust fixturing contact points and optimal clamping forces, which are used as guidance and reference for the inactive fixture design stage. In the developed CFDA system, the interactive fixture design system not only can make full use of expertise of rules to guide novice fixture designers in arrival at a fixture design, but also can provide flexibility for expert designers to design more complicated fixtures. The developed fixture analysis system could verify a designed fixture with FEM and send back results to the designer for further evaluation.

The information models were developed using the OWL/XML schema to facilitate exchange of information between fixture design and analysis. This enables integration of two different domains namely design and manufacturing seamlessly and provides a dynamic and efficient environment for information exchange.

The major contributions of this research are presented in the next chapter.

# Chapter 9 Conclusions and Recommendations

## 9.1 Research Contributions

This thesis focuses on the robust design of mechanical fixtures in a distributed collaborative environment. The research objectives shown in Section 2.4.2 have been accomplished. Several issues, such as the ontology-based knowledge representation in fixture design process domain, development of collaborative environment for integrated fixture design and analysis, and robust fixture design for localization and deformation, are studied. The key contributions are concluded as follows.

- Development of a collaborative fixture design and analysis system

  The CFDA system has been developed using Web-Service-based SOA in order to enables designers across the geographical boundaries to collaborate seamlessly to complete a design. The benefits of using WSSOA for collaborative fixture design and analysis system are interoperability, platform-independence and language neutrality of web services and SOA. Using the developed CFDA system, fixture designers can be guided to arrive at a fixture design with the rule engine, and this design can be evaluated by collaborators with fixture analysis module.

- Knowledge representation for fixture design using an ontology

  In order to seamlessly integrate various applications in a distributed collaborative platform, ontology models have been developed to represent fixture design processes at knowledge level. The following ontology models are developed to facilitate the fixture design process: 3D parametric feature-based geometric model, manufacturing related setup planning, fixture synthesis, and FEM-based fixture analysis. The ontology models were developed using the OWL schema to facilitate exchange of information among applications in a dynamic and efficient environment. This enables seamless integration and effective information exchange between upstream applications and downstream applications, viz. fixture design and fixture analysis.

- Development of robust fixture localization using Taguchi's method

  A robust fixture localization approach has been developed with Taguchi's method to explore the effects of surface tolerances, which arises due to dimensional and geometrical variations, on optimal location of a workpiece. It shows that variances on the primary datum surface have more contributions to product quality than those on the secondary and tertiary datum surface.

- Development of evaluation criteria for robust design

  Evaluation criteria for robust fixture design have been developed to measure the product quality based on sum square of point deviation or directional point-wise manufacturing error during domain space exploration. These evaluation criteria are frame-invariant, which means the value is constant and not varied with the change of coordinate system. In addition, in order to balance the product performance and robustness effectively, weighted mean-square-error is employed to evaluate both performance and robustness during simulation processes.

- Development of optimization methods for robust fixture design process

  Two optimization methods, GA and PSO, have been developed for the robust fixture design process. The modified genetic algorithm has been developed by combining with Monte-Carlo statistical method, which is used to simulate the locating process, and the modified PSO algorithm has developed by combining genetic algorithm and particle swarm optimization. Both developed algorithms can be used to explore the 3D surface space and the clamping force range to search for optimal points and force values for robust fixture design. These developed algorithms are also deployed in the developed CFDA system.

## 9.2 Recommendations for Future Work

Despite several of the achievements mentioned above, some problems remain unsolved in the development of this research work. In order to make it better, future works can be focused on following aspects.

Current developed system and conceptualization of the ontology for fixture design knowledge are only developed at lab scale and are not comprehensive enough for real-life industry use. Furthermore, current development is only focused on machined fixture. Assembly and inspection fixture will be covered in the system and ontology models at future development.

Although the current fixture design system can aid in fixture design of fairly complex parts, the automatic analysis procedures are limited to prismatic parts only. Further work needs to be done so that the PCL codes for automatic analysis procedures can be made more robust for handling complex parts and assemblies.

In the current research, the objective functions for evaluation use weighted sum method, which is an effective criterion to combine the mean and the variance in the dual response robust design. However, weighted sum methods can only be used if the Pareto front is convex and fails to produce an even distribution of points from all parts of the Pareto set as weights are varied. In order to avoid this problem, multi-objective method will be considered to treat the mean and variance as two different objectives in the future work. Meanwhile, the domain space can be applied on the continuous surfaces on the workpiece rather than the discrete point sets.

The main drawback of using population-based searching algorithms, e.g. GA and PSO, is the speed to explore the whole domain space. The main weakness of these algorithms is the slow computational speed even with high performance workstations. Research on parallelization with MPI and OpenMP will be studied in the hope to shorten the loading as well as the computational time.

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# Relevant Publication List

## Journals

Fan, L.Q., Senthil Kumar, A., Jagdish, B.N., Anbuselvan, S., and Bok, S.-H. 2010. *Collaborative fixture design and analysis system based on service-oriented architecture*. IEEE Transactions on Automation Science and Engineering (T-ASE), 7(3): p. 617-629

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Fan, L.Q., Senthil Kumar, A., *Development of robust fixture locating scheme using genetic algorithm*, submitted to ASME Journal of Mechanical Design (under review).

Fan, L.Q., Senthil Kumar, A., 2010. *Development of robust fixture locating layout for machining workpieces*, Proceedings of the Institution of Mechanical Engineers, Part B, Journal of Engineering Manufacture. (Online)

## Conferences

Fan, L.Q., Senthil Kumar, A., Jagdish, B.N., Anbuselvan, S., and Bok, S.-H. 2008. Integrated fixture design and analysis system based on service-oriented architecture. in IEEE International Conference on Automation Science and Engineering, 2008 (CASE 2008). p. 656-661.