Computer-Aided Design and Applications

http://www.cadanda.com

Fixture Feasibility: Methods and Techniques for Fixture Planning

Xiumei Kang[1] and Qingjin Peng[2*]

[1]University of Manitoba, umkangx@cc.umanitoba.ca
[2]University of Manitoba, pengq@cc.umanitoba.ca
* Corresponding author

ABSTRACT

Fixture planning is a complex activity restricted by the extreme diversity of workpieces and several environmental factors including machine tools, assembly tools, grasping devices, and cutting tools. This paper reviews methods and techniques for the geometry analysis of fixture feasibility in product development. Fixture synthesis methods including geometrical analysis and fixture assembly planning are surveyed. The implementation of CAD-based and Web-based fixture planning systems is discussed in respect to their reasoning methods, functionality, limits and potentials. A novel fixture planning system is proposed and further research activities are identified.

Keywords: computer-aided fixture planning, fixture feasibility, fixture assembly planning.
DOI: 10.3722/cadaps.2008.424-433

1. INTRODUCTION

Over the decades, substantial research has been conducted to decrease production cost and processing time in manufacturing to meet the competitive market demand. The workpiece handling system, which largely affects the usability of machine tools, is used to clamp, change and store the workpiece in manufacturing [1]. Fixtures play an important role in workpiece handling. Proper fixture planning can dramatically reduce the manufacturing cost, the lead-time, and labor skill requirements in product manufacturing. Also, the integration of fixture planning with computer-aided design and computer-aided manufacturing (CAD/CAM) provides an overall optimal solution for product design and manufacture. However, fixture planning is a highly experience-based activity. There are not many fixture planning tools available for industry applications due to the extreme diversity and complexity of workpieces. New manufacturing technologies, such as computer-integrated manufacturing, flexible manufacturing systems, lean manufacturing, agile manufacturing and internet-based manufacturing, bring new challenges to fixture planning in terms of the planning theory, planning reliability and planning efficiency.

Fixtures are used to locate, hold and support workpieces in manufacturing operations such as machining, inspection, and assembly. A traditional fixture, called dedicated fixture, is designed to hold a specific workpiece. The cost of design and fabricating dedicated fixtures can take up to 10-20% of the total manufacturing system cost. Usually, design and manufacturing of dedicated fixtures are time-consuming due to some workpieces' tight tolerance and restricted machining operations. Flexible and adaptable fixtures dramatically reduce the fixturing cost and lead-time since they are reusable [2]. Using flexible and adaptable fixtures can expect as much as 80% reduction of the fixture cost. Modular fixture, one type of flexible fixtures, is a set of ready-made, re-usable, standard components and combination units. The set includes base plates, supports, locators, clamps and accessories. Modular fixtures provide many fixture configurations for different workpieces by using a variety of fixture element combinations. Much work of fixture planning has been reported based on modular fixtures [3-6].

Computer-aided fixture planning (CAFP) aims to determine fixture configurations and assembly for modular fixtures and dedicated fixtures with the aid of computer techniques. Existing CAFP methods rarely consider integrating environmental factors into fixture planning, which may have a large impact on fixture feasibility. This paper discusses the feasibility of fixture based on geometrical analysis and assembly accessibility. CAD-based CAFD systems and Web-based CAFD systems are compared in respect to their implementation. A novel fixture planning system is proposed with the consideration of environmental factors for fixture feasibility.

2. FIXTURE PLANNING

Fixture planning determines precise locating and rigid clamping of a workpiece according to workpiece's design and process requirements. The locating planning chooses surfaces on the workpiece as locating planes and selects suitable fixture components for locating these surfaces. Locating surfaces are classified as plane, pin-hole and external profiles. Commonly used fixture locating methods include: 1) 3-2-1 point locating for prismatic workpieces, it uses three locators on the primary locating surface, two locators on the secondary locating surface, and one locator on the tertiary locating plane; 2) one plane and two pins locating for general parts with two holes. It uses a primary locating plane, a primary pin, and a secondary pin to restrict the freedom of a workpiece; 3) V-block locating for external cylindrical parts. One wide V-block or two short V-pads may be used to hold the workpiece.

The clamping methods can be summarized as top clamping and side clamping. It is usually used to restrict a workpiece's movement to keep it stable during processing [7]. The clamping planning determines clamping surfaces and points on the workpiece and clamping components, the magnitude of each clamping force, and the clamping sequence when the stability of the workpiece becomes a concern. Some locating and clamping variations may be applied for different part geometrical and processing requirements. Fixture assembly planning determines the fixture assembly sequence and assembly tools used. It can also verify the possible interference of fixture components and workpieces in an assembly process, and the ease of workpieces loading and unloading.

Fig. 1 illustrates a 3-2-1 fixture for a prismatic workpiece called a gearbox body. The workpiece is located by three perpendicular locating planes. The bottom plane of workpiece forms the primary locating plane. The secondary locating plane is the plane contacting two locators. The tertiary locating plane is the left plane with a hole. Four vertical clamps are applied on the sides of the workpiece. The features on the top surface of the workpiece are to be machined.

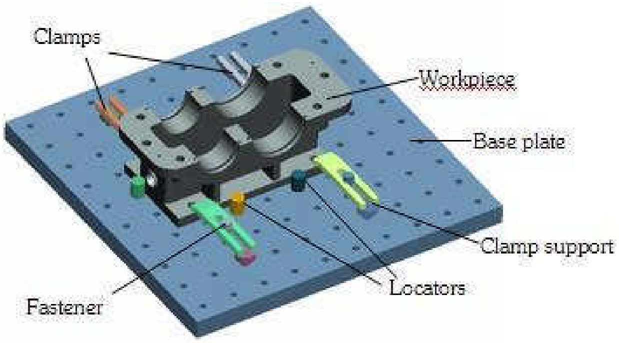

Fig. 1: The 3-2-1 locating method for a gearbox body.

The fixture planning requires workpieces and machining information including geometry, material, dimension and tolerance, processing plan and tool path. To hold a specific part, several design constraints may be applied. Among them, four main constraints in the fixture planning are as follows:

(1) Geometrical constraints: Accurate locating of a workpiece should be ensured to meet machining accuracy requirements of a workpiece.
(2) Accessibility constraints: There should be no interference among fixture components, workpieces, and machining tools during assembly and machining. In addition, it should be easy to load and unload the workpiece.
(3) Force constraints: The fixture should be strong enough to resist the forces and moments produced by clamps and machining tools. A minimum clamp force should be specified for the workpiece stability.
(4) Deformation constraints: The stiffness of a fixture system should be sufficient to keep the workpiece deformation within the design tolerance.

CAFP can be divided into four phases: problem description, fixture analysis, fixture synthesis, and fixture verification [8, 9]. The problem description defines fixture design variables, design constraints and design objectives. In the fixture analysis, a workpiece-fixture interaction model is built in terms of geometry, kinematics, force, and deformation. The analysis result is then used to select the locating, supporting and clamping surfaces and points on the workpiece. The fixture synthesis determines details of the fixture configuration including selecting fixture elements, placing the elements in suitable locations, and generating fixture assembly plan. The fixture configuration is verified in respect to geometrical interference, locating determinant, clamp stability and machining tolerance in the fixture verification phase. If design objectives are not satisfied, the result will be sent back to fixture analysis phase for further improvements. Fig. 2 shows the four fixture planning phases.

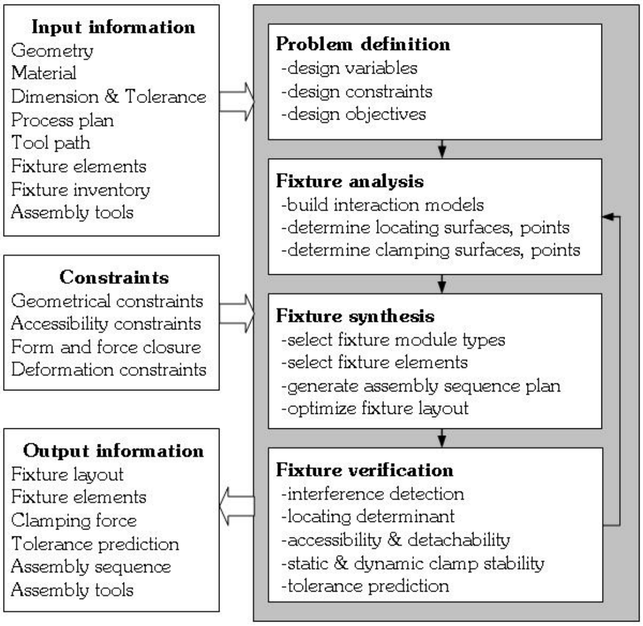

Fig. 2: Four fixture planning phases.

3. APPROACHES TO FIXTURE PLANNING

Several methodologies have been developed for fixture planning to satisfy various constraints. The main methods in four fixture planning phases are summarized in Fig. 3. In the fixture analysis phase, several prominent methods have been developed including geometrical, kinematical, force, and deformation analysis methods, rule-based methods and feature-based methods. The geometrical analysis checks the locating errors and interference among fixture elements, the workpiece and cutting tool paths by spatial reasoning. The kinematical analysis ensures the determinant locating against locating planes, and the easiness of loading/unloading. A sufficient clamp force is determined for static equilibrium under the cutting force based on force analysis. The deformation analysis determines the elastic and/or plastic deformation of the workpiece under the clamping and cutting force, which directly affects the final dimensional tolerance of a workpiece. Finite element analysis (FEA) is usually used for the deformation analysis. Similarly, these methods are used in the fixture verification to justify the generated fixture configuration.

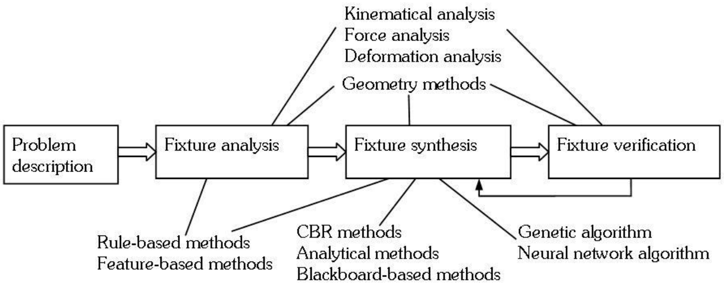

Fig. 3: Summary of CAFP approaches.

In the fixture synthesis phase, the locating, clamping, and supporting layout are determined. Analytical methods, rule-based methods, feature-based methods, blackboard-based methods, geometry methods, and CBR methods can be used for the fixture element selection and fixture layout planning. Optimization techniques such as genetic algorithm and neural network algorithms are integrated into the mathematical model to search for better fixture configurations.

Research in CAFP aims at the automation of fixture layout generation, fixture verification, and fixture assembly planning. The early work includes various interactive and semi-interactive fixture planning systems based on CAD software [2, 10]. Later research investigates the mechanism of fixture-workpiece interactions in respect to their geometry, kinematics, force, and deformation. Trappey [7] reviewed fixturing principles and automated fixture planning theory. Bi and Zhang [8] presented a review of flexible fixture planning and automation. Cecil [11] briefly reviewed current CAFD approaches and indicated the trends of CAFD research to support cross-functional participation and concurrent engineering in a distributed and collaborative manufacturing environment. Recently, Pehlivan and Summers [9] investigated the information support requirement of fixture planning. The geometry methods and assembly planning methods in fixture planning are reviewed as follows.

3.1 Geometry Methods in Fixture Synthesis

The geometry analysis is widely used in fixture synthesis for the fixture layout generation. In two-dimensional (2D) fixture synthesis, it is assumed that three locators and a side clamp are sufficient to fix a part in position. For modular fixture, the planning problem is to find three locating points and a side clamp point coinciding with locating holes on the base plate. Fig. 4 shows a 2D fixture synthesis of a valve body on a modular fixture. The cross center refers to locating holes on the base plate. The part is represented by its 2D silhouette. The circles refer to locators of radius r. If the part's boundary is expanded by locator's radius r, the problem of locating a given part by three round locators can be transferred to find three point-edge contacts at the part's boundary. A clamping point can be generated based on the constraint of form closure. The form closure is a condition when the motion of a workpiece is fully constrained by a fixture. Fixture configuration alternatives are ranked and selected according to certain quality criteria.

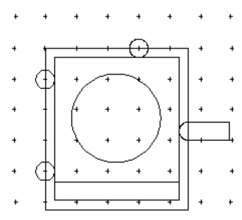

Fig. 4: 2D fixture synthesis of a valve body.

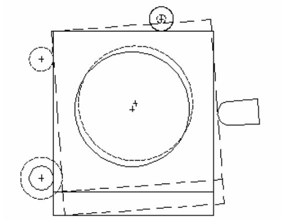

Fig. 5: Locating error caused by locator's geometric errors.

Brost & Goldberg [3] developed an algorithm for the planar fixture synthesis based on the geometric analysis and form closure. In their system, a part is described by its 2D silhouette, and possible locating setups are generated by translating and rotating the part. Clamp placement is then achieved by form closure. Wallack and Canny [12] developed a similar method for a fixture vise with two combined fixture plates. Wu [4] extended the 2D algorithm to cylindrical surfaces and several other kinds of locators for fixture layout design. Wu [5] presented a systematic geometric methodology for fixture planning. The feasibility of a workpiece loading and unloading motion is analyzed based on the concept of visible cone and pivotal locator. Hou and Trappey [13] developed a fixture synthesis algorithm for V-blocks to hold non-prismatic parts by geometric reasoning.

The fixture synthesis for 3D workpieces is complicated and computationally demanding. Six locators and at least one clamp are required for a grasp or fixture in a 3D space. The candidate contact points for fixturing are selected from continuous surfaces of a workpiece. Some candidate surfaces are represented as a set of discrete points. Since it is very complex to select a set of fixturing points from a large number of candidate locations, exhaustive searches are not practical [14]. Optimization techniques are often required as assistant tools in 3D fixture synthesis. The fixture planning criteria and restraints are formulated into optimization objective function and constraints. The optimization algorithms search for an optimal set of locating points under the constraints.

Liu [15] presented a 3D fixture planning/grasp algorithm in which a local search process is combined with a recursive problem decomposition strategy. The optimization objectives are derived from three criteria: the form-closure constraint, minimum locating errors and even load distribution of fixturing points. Liu [16] further extended the algorithm for frictional grasp/fixture planning. Joneja and Chang [6] integrated the fixture planning into setup planning in which a generalized geometric and functional representation scheme for fixture elements was developed.

3.2 Geometry Methods in Fixture Analysis and Verification

The machining accuracy of a workpiece is closely related to its localization accuracy caused by three sources: locators' position variation, locators' geometric errors, and datum planes' geometric variation of the workpiece. In geometry reasoning, a relationship model is built and utilized to verify the locating scheme and tolerance allocation. Moreover, locating errors can be reduced by optimizing fixture locators' layout and tolerances. Fig. 5 shows a workpiece's displacement caused by locator's dimensional variations. The dashed line indicates the locators' dimensional variation and the subsequent position deviation of a workpiece. Three basic ways may be used in tolerance analysis including methods of the worst-case, statistical, and Monte Carlo. The worst-case methods estimate the maximum error. Monte Carlo methods use any probability distribution for individual errors. Statistical methods only use simple probability distributions, such as normal and uniform distributions.

Bourdet and Clement [17] presented a mathematical representation of the localization error using a displacement screw vector. The localization error was minimized utilizing optimization techniques. Choudhuri and DeMeter [18] analyzed the worst case geometric errors of machined features with respect to locators' error and datum planes' geometric error of a workpiece. Carlson [19] presented a quadratic sensitivity analysis of the localization error related to the displacement of the part. Wang [20] investigated the relationship of main sources of localization error and the manufacturing error of a machined surface. The sum of squared error magnitudes of critical points on a machined surface is considered as an evaluation criteria for fixture layout planning. An optimal approach called D-Optimality was proposed. Kang et al. [21] presented a model for the evaluation of machining accuracy caused by the deviation of locators and the workpiece. The machining accuracy is determined by maximum surface deviations at the worst case. The tolerance of locating points is assigned based on a sensitive matrix. Qin [22] proposed a general mathematical model for the determination of the locating scheme and locators' dimension and tolerance. The variance of the position error of the workpiece is minimized and the stochastic characteristic of the locating errors are integrated into the optimization. Rong et al. [23] presented a locating error evaluation algorithm with sensitivity analysis functions for the 3-2-1 locating scheme, pin-hole location scheme and V-block locating scheme. The prototype system was applied to two automobile manufacturing companies. The missing part in the research may be the extraction of the dimension and tolerance information from the CAD model for tolerance analysis, which forms a base of tolerance analysis.

Accessibility analysis in fixture verification consists of two aspects: the fixturing surface of a workpiece is approachable and the fixture elements are inference free. Three types of interference may happen for a fixture: fixture element vs. fixture element, fixture element vs. workpiece, and fixture element vs. cutting tool. Li et al. [24] evaluated the accessibility of a fixture component to a workpiece's surface by testing the obstruction at grid points of the surface. The accessible direction is restricted to the normal direction of the surface. Hu and Rong [25] analyzed the accessibility of machining tools against fixture components in fixture verification by expanding a 2D contour of fixture components and shrinking the tool as a moving dot/line segment. Irrelevant fixture components for the tool path checking are excluded by using grids. Kumar et al. [26] developed an automatic fixture planning system. The interference between machining tools and fixture elements is detected using a cutter swept solid generated by tool motion silhouettes. The static interference test is performed using CAD built-in functions. Ilushin et al. [27] presented a polygon/surface-tool intersection algorithm for the collision detection of multi-axis NC-machining tools based on space division techniques.

Most of the above-mentioned geometry methods were proposed for 2D fixture layout planning of polygonal workpieces. Only a few algorithms were presented for non-polygonal workpieces. In addition, the part design modification has not been integrated into the geometry methods. A general fixture design method for complex shaped workpieces incorporating dynamic design changes is required.

3.3 Fixture Assembly Planning Methods in Fixture Synthesis

Several methods have been developed for fixture assembly planning, such as feature-based methods, fastener-based methods, and geometry-based methods. Bai and Rong [28] developed a method to represent modular fixture elements. A modular fixture element assembly relationship database (MFEARDB) was established based on assembly features and mating relationships. Yi et al. [29] described a fastener-based approach in fixture assembly planning. Part Liaison Graph (PLG) and Fixture Liaison Graph (FLG) were generated to represent the assembly relationships. Dai et al. [30] presented a modular fixture design and assembly system based on geometric analysis. A modular fixture tower database (MFTD) was generated to represent the assembly relationship of fixture elements. The fixture towers were selected and placed in the assembly. Ma et al. [31] presented a computer-aided fixture design system named FIX-DES. Feature-based representation was used to describe the contact surface and the functionality of fixture elements. The assembly relationships between two fixture elements were automatically generated and rules were derived for the reasoning. The output of the system was a list of fixture elements and 3D drawings of fixture design. Kakish et al. [32] proposed a knowledge-based universal modular jigs and fixtures design system (UMJFS). Peng [33] developed a VR-based modular fixture design system in which the user is allowed to manipulate the virtual models in a virtual environment for the fixture design and assembly.

Different methods to represent the assembly relationship of fixture elements were developed in fixture assembly planning, a few of them can automatically generate fixture assembly plan. However, there is a lack of automatic methods for generating the assembly relationship based on geometry analysis. Moreover, the feasibility of assembly tools used in fixture assembly was seldom considered as an evaluation criteria. The fixture assembly has not been thoughtfully investigated in terms of the global accessibility in complex working environments.

4. IMPLEMENTATION OF CAFP SYSTEMS

The CAFD systems can be implemented as CAD-based systems and Web-based systems. Most of the previously mentioned fixture planning systems was implemented based on CAD software. The economic globalization stimulates new research trends towards Web-based fixture planning system.

4.1 CAD-based Fixture Planning Systems

Early fixture planning systems were developed in CAD software which provides an environment for modeling, visualization, positioning, and modification of a fixture. Fixture elements were modeled and stored in a database. Based on the degree of automation, CAFP systems can be classified as interactive [34], semi-automated [30], and automated fixture planning systems [35]. Various functions have been realized in fixture planning systems including automatic fixture layout planning, fixture elements selection, fixture configuration verification, and assembly sequence planning.

Although CAD-based CAFP systems provide various functions to support fixture planning, it has some drawbacks. Firstly, it is not easy to emigrate a CAFP system from one CAD software to another because different CAD software uses different data structures. Secondly, it is troublesome for the inter-enterprise collaboration. The CAFP system often relies on a specific operating system. Manufacturing companies may use different operating platforms, which causes difficulties for the collaboration and information sharing between enterprises. Fixture planning service providers have to spend a lot of time and efforts to solve the information exchanging problems. Web-based fixture planning systems are promising in providing a solution for the information transferring and operation platform independency.

4.2 Web-based Fixture Planning Systems

Research on the Web-based fixture planning is relative new. Most existing systems provide limited functions. Three-tier client-server architecture is generally used with Java as the programming language, Java3D as graphics API, and XML as the file format for information exchange. The user interface and 3D model visualization is commonly applied on the client side. Fixture planning engine and database are implemented on the server side. Wagner et al. [36] implemented a “FixtureNet” fixture planning system over the Internet based on Brost-Goldberg’s algorithm [3].

Web-based fixture planning systems require 3D model visualization and manipulation for the ease of design. Several approaches have been proposed in dealing with model representation in distributed manufacturing environments. Standard file formats such as STEP, WRL or polygonized representation of 3D models are stored on the server side, and the model can be retrieved and viewed on the client side. Mervyn et al. [37] presented an Internet-enabled fixture planning system in which the part and fixture elements are polygonized. The facet data of polygonized models are embedded in the XML file and stored on the server side. The system allows users to interactively select fixturing surfaces and fixture elements on the client side. Heuristic rules are incorporated into the fixture planning process.

An important issue in the Web-based fixture planning is the information integration of fixture planning with other product design and manufacturing systems. On one hand, workpieces’ design information (i.e. geometry and tolerance) is required for fixture planning, and machining information (i.e. surfaces and tool paths) for fixture verification. On the other hand, the fixturability feedback from each setup is needed for product design verification and machining validation. Besides this, the information sharing among different fixture planning phases is also required.

Pehlivan and Summer [9] conducted a literature survey for information representation requirements in CAFP. Mervyn [38] developed CAFD information models for information exchange to support the integration of product design and manufacturing. The model information was stored in XML file. Hunter [39] presented a knowledge model for fixture planning which consists of two stages: the knowledge representation and inference process description. The first stage extracts the knowledge of an object, such as the part geometry, machining process, functional and detailed fixture planning and fixture resources. The second stage describes the fixture planning and interpretation rules. The information was modeled using Unified Modeling Language (UML) and coded in C++. A rule-based method was used. Kang et al. [40] presented a hybrid CBR/KBR (Knowledge-Based Reasoning) system. New designs based on KBR were compared and adapted to existing fixture planning cases to get a satisfied fixture plan. XML was used as the file format for information and knowledge transfer over the Internet.

5. VIRTUAL FIXTURE PLANNING SYSTEM TO INTEGRATE ENVIRONMENTAL FACTORS

Fixture planning is affected by the diversity of workpieces and related environmental factors. These environmental factors include machine tools, assembly tools, grasping devices, cutting tools, fixture components, and workpieces. Although many approaches to fixture planning have been developed, the neglect of environmental factors may lead to mismatch of the fixture analysis with actual fixturing feasibility in machining environments. Moreover, a relative "static" fixture configuration is generated and verified in the sense of not considering the possible motion of a workpiece in the workpiece loading and unloading, as well as the assembly trajectory of fixture components. A "dynamic" fixture planning can integrate fixture assembly motions with various environmental factors simulated in a virtual environment.

The accessibility/detachability in workpiece loading and unloading has been analyzed in the previous work. Although local accessibility of a workpiece has been fully investigated, global accessibility in the fixture assembly, workpiece loading and unloading has not been addressed. There is a lack of global accessibility analysis methods for human hands or robot arms operating in complex manufacturing environments. Motion planning and ergonomics analysis in the fixture assembly are two methods to address the global accessibility problem. Rajan et al. [41] presented a Virtual Reality (VR)-based motion tracking system to evaluate product assembly sequence and jig design. The ergonomic analysis is performed by evaluating the recorded user hand's motion in the assembly. However, this method needs human intervention to assemble the product which takes a lot of time and efforts.

There is also a need to facilitate the fixture planning and information sharing in virtual environments. Fixture planning has to be integrated into concurrent and distributed virtual manufacturing environments. Information sharing among geographically distributive teams of product design, fixture planning, manufacturing and resource management is essential for a rapid response to the dynamically changed market. Web-based distributed fixture planning forms a platform for information sharing of part design, manufacturing, and fixturing. Virtual prototyping and VR techniques provide a viable way towards virtual manufacturing. VR-based fixture planning enables models visualization and manipulation in an intuitive way to allow a collaborative design sharing and modification. There is little work using VR techniques in fixture planning. More research is required on fixture model representation, fixture planning and verification methodologies in virtual environments.

A VR-based fixture planning framework is proposed in this research to improve the automatic analysis of the fixture planning in terms of assembly planning, global accessibility analysis and motion planning. Product design changes are integrated into the fixture planning to provide a supportive platform. VR-based solutions enable a better 3D fixture viewing than CAD software. Fig. 6 shows the system structure of the proposed virtual fixture planning system. The product information in CAD/CAM systems including part design, process plan, NC path, product assembly and logistics is retrieved and sent to the proposed system. The information is used to generate fixture configurations, evaluate the fixturing feasibility, and verify the assembly possibility in the fixturing environment. The fixturing feedback for design and process changes is sent back to CAD/CAM systems.

The proposed system consists of four subsystems including fixture design system, fixture assembly planning, assembly tool verification, and fixture assembly motion planning. The fixture design system generates the fixture configuration, evaluate and optimize the fixture layout in terms of geometry, accessibility, form and force closure, and deformation. The 3D fixture assembly is imported into VR environments. Fixture assembly planning system automatically generates the assembly sequence in respect to geometry and functional constraints. The assembly tools are verified using the assembly tool verification method. The fixture assembly motion planning is to plan the motion of fixture components and workpiece in the assembly process under complex manufacturing environments. The motion may consist of multi-step movements instead of simple one-step translation.

The fixture environmental elements will be considered in the proposed system. Fig. 7 shows a workpiece handling process with the machining fixture and its fixturing environment. The workpiece handling process can be divided into several steps. Firstly, the fixture is designed and assembled at a separate place. Then it is assembled on the worktable of a machine tool. In some cases, it is also possible to assembly the fixture directly on the worktable of a machine tool. Then the workpiece is picked up from the storage area and positioned in the fixture. After the workpiece is clamped for machining, it is processed according to the process plan, such as milling and drilling. Finally, the finished workpiece is unclamped and unloaded from the fixture. A new unprocessed workpiece is picked up. This process is repeated until all workpieces have been processed. The fixturing environments are illustrated in the right side for each step. The related factors include machine tools, assembly tools, human hands or grippers on a robot, and cutting tools. Although some of the current simulation-based software takes some of these factors into account for the collision detection, most merely use these factors as the verification of an existing plan instead of taking them into the fixture planning process.

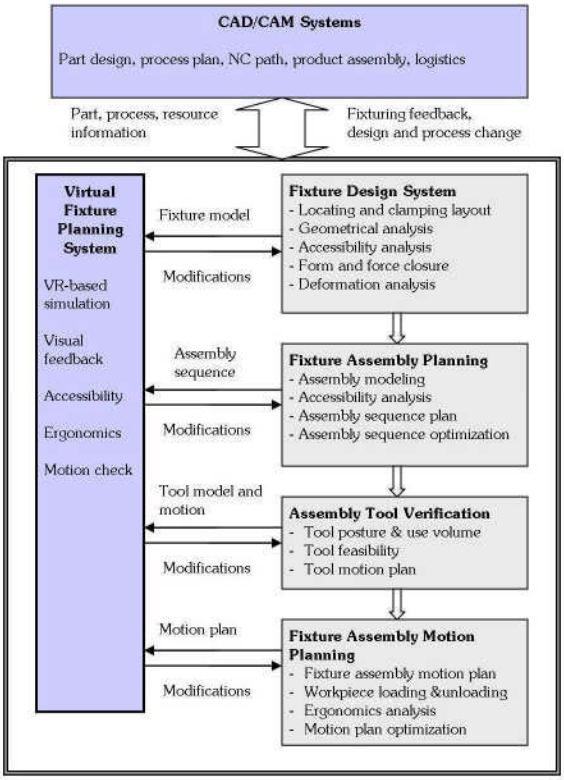

Fig. 6: The architecture of the fixture planning system.

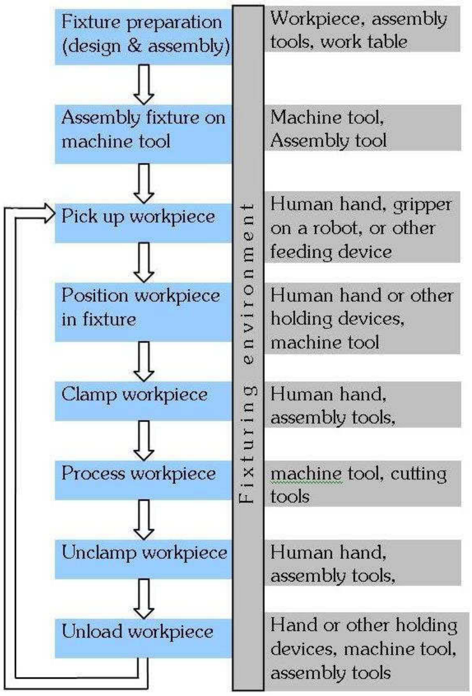

Fig. 7: A workpiece handing process & its fixturing environment

As a part of the proposed system, a Web-based fixture assembly planning system has been developed in our previous research [42] as shown in Fig. 8. The fixture information is listed in the left side of the window. The fixture assembly is illustrated in the middle of the window via a VRML browser. The assembly tool information and its verification are shown in the right side of the window. An assembly tool verification approach was developed by the authors [43-44]. Further research in fixture design and fixture assembly motion planning is still undergoing.

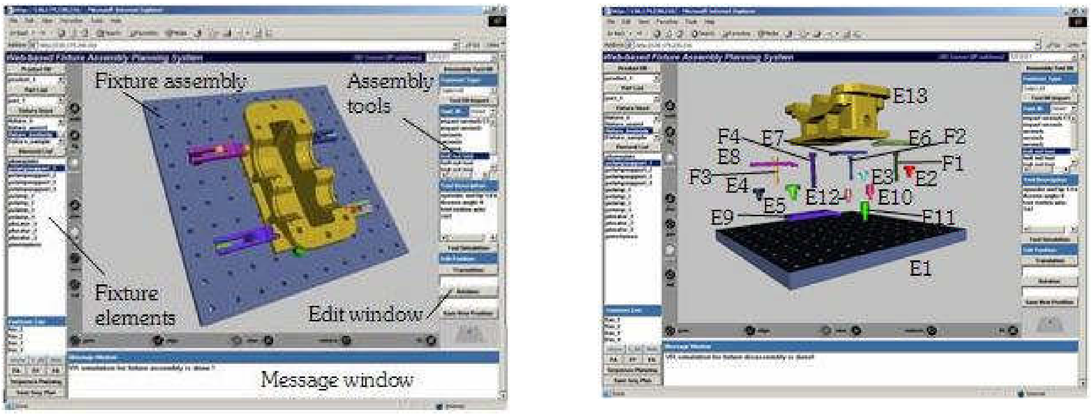

Fig. 8: A web-based fixture assembly planning system.

6. CONCLUSIONS

Fixture planning is a complex activity affected by the extreme diversity of workpieces and several environmental factors. This paper reviewed main methodologies in CAFP. Generally, the fixture planning consists of four phases: the problem description, fixture analysis, fixture synthesis, and fixture verification. Fixture analysis and verification methods are summarized as geometrical analysis, kinematic analysis, force analysis, and deformation analysis. In fixture synthesis, CBR methods, assembly sequence planning methods, and optimization methods are surveyed. The implementation issues in CAD-based CAFP systems, Web-based CAFP systems and information sharing are discussed. A framework of virtual fixture planning system is proposed to integrate environmental factors into fixture planning process. Further research will improve approaches for fixture design and fixture assembly motion planning based on VR techniques in respect to environmental factors.

7. ACKNOWLDGEMENTS

This research is supported by Canadian NSERC Discovery Grants.

8. REFERENCES

[1] Fleischer, J.; Denkena, B.; Winfough, B.; Mori, M.: Workpiece and Tool Handling in Metal Cutting Machines, CIRP Annals - Manufacturing Technology, 55(2), 2006, 817-839.
[2] Hargrove, S. K.; Kusiak, A.: Computer-aided fixture design: a review, International Journal of Production Research, 32(4), 1994, 733-753.
[3] Brost, R. C.; Goldberg, K. Y.: A complete algorithm for synthesizing modular fixtures for polygonal parts, Proceedings of 1994 IEEE on Robotics and Automation, 1, 1994, 535-542.
[4] Wu, Y.; Rong, Y.; Ma, W.; LeClair, S. R.: Automated modular fixture planning: geometric analysis, Robotics and Computer-Integrated Manufacturing 14, 1998, 1-15.
[5] Wu, Y. Y.: The geometric principle of automatic modular fixture planning, Proceedings of the 2001 ASME Design Engineering Technical Conference and Computers and Information in Engineering conference, 1, 2001, 779-787.
[6] Joneja, A.; Chang, T.-C.: Setup and fixture planning in automated process planning systems, IIE transactions, 31(7), 1999, 653-665.
[7] Trappey A. J.; Liu, C. R.: A literature survey of fixture design automation, International Journal of Advanced Manufacturing Technology, 5, 1990, 240-55.
[8] Bi, Z. M.; Zhang, W. J.: Flexible fixture design and automation: review, issues and future directions, International Journal of Product Research, 39(13), 2001, 2867-2894.
[9] Pehlivan, S.; Summers, J. D.: A review of computer-aided fixture design with respect to information support requirements, International Journal of Production Research, 46(4), 2008, 929-947.
[10] Hazen, F. B.; Wright, P. K.: Workholding automation: innovations in analysis, design, and planning, Manufacturing review, 3(4), 1990, 224-237.
[11] Cecil, J.: Computer-aided fixture design - A review and future trends, International Journal of Advanced Manufacturing Technology, 18(11), 2001, 790-793.
[12] Wallack, A. S.; Canny, J. F.: Planning for modular and hybrid fixtures, Algorithmica, 19(1-2), 1997, 40-60.
[13] Hou, J. L.; Trappey, A. J. C.: Methodology for applying V-blocks and clamps to non-prismatic workpart fixtures, International Journal of Computer Applications in Technology, 10(3-4), 1997, 152-167.
[14] Wang, M. Y.: An optimum design for 3-D fixture synthesis in a point set domain, IEEE Transactions on Robotics and Automation, 16(6), 2000, 839-846.
[15] Liu, Y. H.: Optimal Fixture Layout Design for 3-D Workpieces, Proceedings of the 2004 IEEE International Conference on Robotics & Automation, 5, 2004, 5274-5279.
[16] Liu, Y.-H.; Lam, M.-L.; Ding, D.: A complete and efficient algorithm for searching 3-D form-closure grasps in the discrete domain, IEEE Transactions on Robotics, 20(5), 2004, 805-816.
[17] Bourdet, P.; Clement, A.: A study of optimal criteria identification based on the small displacement screw model, Annals of the CIRP, 37(1), 1998, 503-506.
[18] Choudhuri, S.; DeMeter, E.C.: Tolerance analysis of manufacturing fixture locators, ASME Journal of Manufacturing Science and Engineering, 121(2), 1999, 273-81.
[19] Carlson, J. S.: Quadratic sensitivity analysis of fixturing and locating schemes for rigid parts, ASME Journal of Manufacturing Science and Engineering, 123(3), 2001, 462-472.
[20] Wang, M. Y.: Tolerance analysis for fixture layout design, Assembly Automation, 22(2), 2002, 153-162.

[21] Kang, Y.; Rong, Y.; Yang, J. C.: Computer-aided fixture design verification Part 2: Tolerance analysis, International Journal of Advanced Manufacturing Technology, 21(10-11), 2003, 836-41.
[22] Qin, G. H.; Zhang, W. H.; Wan, M.: A mathematical approach to analysis and optimal design of a fixture locating scheme, International Journal of Advanced Manufacturing Technology, 29(3-4), 2006, 349-359.
[23] Rong, Y.; Hu, W.; Kang, Y.; Zhang, Y.; Yen, D. W.: Locating error analysis and tolerance assignment for computer-aided fixture design, International Journal of Product Research, 39(15), 2001, 3529-3545.
[24] Li, J.; Ma, W.; Rong, Y.: Fixturing Surface Accessibility Analysis for Automated Fixture Design, International Journal of Product Research, 37(13), 1999, 2997-3016.
[25] Hu, W.; Rong, Y.: A Fast Interference Checking Algorithm for Automated Fixture Design Verification, International Journal of Product Research, 16, 2000, 571-581.
[26] Kumar, A. S.; Fuh, J. Y. H.; Kow, T. S.: An automated design and assembly of interference-free modular fixture Setup, Computer-Aided Design, 32, 2000, 583–596.
[27] Ilushin, O.; Elber, G.; Halperin, D.; Wein, R.; Kim, M.S.: Precise Global Collision Detection in Multi-axis NC-machining, Computer-Aided Design, 37(9), 2005, 909-920.
[28] Bai, Y.; Rong, Y.: Establishment of modular fixture element assembly relationship for automated fixture design, ASME, Manufacturing Engineering Division, MED, Manufacturing Science and Engineering, 2-1, 1995, 805-816.
[29] Yi, C.; Nekey, G. A.: Assembly planning for modular fixtures, Proceedings of the 1996 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 96, Robotic Intelligence Interacting with Dynamic Worlds (Cat. No.96CH35908), 2(2), 1996, 704-711.
[30] Dai, J. R.; Nee, A. Y. C.; Fuh, J. Y. H.; Kumar, A. S.: An approach to automating modular fixture design and assembly, Proceedings of the Institution of Mechanical Engineers, Journal of engineering manufacturing, Part B, 211(7), 1997, 509-521.
[31] Ma, W.; Lei, Z.; Rong, Y.: FIX-DES: A Computer-Aided Modular Fixture Configuration Design System, International Journal of Advanced Manufacturing Technology, 14, 1998, 21-32.
[32] Kakish, J.; Zhang, P.; Zeid, I.: Towards the design and development of a knowledge-based universal modular jigs and fixtures system, Journal of Intelligent Manufacturing, 11, 2000, 381-401.
[33] Peng, G.; Liu, W.: A novel modular fixture design and assembly system based on VR, 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2006, 2650-5.
[34] Fuh, J. Y. H.; Nee, A. Y. C.; Kumar, A. S.; Teo, J. C. S.: IFDA: an interactive fixture design and assembly environment, International Journal of Computer Application Technology, 8(1/2), 1995, 30–40.
[35] Hou, J. L.; Trappey, A. J. C.: Computer-aided fixture design system for comprehensive modular fixtures, International Journal of Product Research, 39(16), 2001, 3703-3725.
[36] Wagner, R.; Castanotto, G.; Goldberg, K.: FixtureNet: Interactive computer-aided design via the world wide web, International Journal of Human-Computer Studies, 46, 1997, 773-788.
[37] Mervyn, F.; Kumar, A. S.; Bok, S. H.; Nee, A. Y. C.: Development of an internet-enabled interactive fixture design system, Computer Aided Design, 35(1), 2003, 945-957.
[38] Mervyn, F.; Kumar, A. S.; Nee, A. Y. C.: Fixture design information support for integrated design and manufacturing, International Journal of Production Research, 44(11), 2006, 2205-2219.
[39] Hunter, R.; Vizan, A.; Perez, J.; Rios, J.: Knowledge model as an integrated way to reuse the knowledge for fixture design process, Journal of Materials Processing Technology, 164-165, 2005, 1510-1518.
[40] Kang, Y. G.; Wang, Z.; Li, R.; Jiang, C.: A fixture design system for networked manufacturing, International Journal of Computer Integrated Manufacturing, 20(2), 2007, 143-159.
[41] Rajan, V. N.; Sivasubramanian, K.; Fernandez, J. E.: Accessibility and ergonomic analysis of assembly product and jig designs, International Journal of Industrial Ergonomics, 23, 1999, 473-487.
[42] Kang, X.; Peng, Q.: Fixture assembly planning in a Web-based environment, Special Issue on Virtual Manufacturing in Web-based Environments, International Journal of Internet Manufacturing and Service, 2007 (accepted).
[43] Kang, X.; Peng, Q.: Analysis of tool accessibility in fixture setup planning, ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Las Vegas, Nevada, USA, September, 4-7, 2007.
[44] Kang, X.; Peng, Q.: Tool feasibility analysis for fixture assembly planning, ASME Journal of Manufacturing Science and Engineering, 2007 (accepted).