A LITERATURE SURVEY OF FIXTURE-DESIGN AUTOMATION

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This paper gives a review of fixture-design research, most of it done in the 1980s. The major topics of the review are the fixturing principles (supporting, locating and clamping), automated fixture design (configuration, assembly and verification), and fixture hardware design (dedicated, modular and electric/magnetic types).

Keywords: Fixturing principles; Fixture configuration; Modular fixtures; CAD/CAM integration

1. Introduction

Fixture design can be classified as a part of process planning [1]. The taskwise description of process planning [2] specifically states that “fixture design for each workpiece set-up” is an integral planning task. However, the automation of fixture design has been overlooked in most research into automated process planning. In this paper, a wide range of fixture-design literature is studied in order to reveal the progress in the field and the significant contributions to it in the 1980s. The review is presented in the next three sections: Section 2, on fixturing principles; Section 3, on automated fixture design; and Section 4, on fixture-hardware design.

In Section 2, the fixture-design principles are reviewed. Established fixturing techniques and methodology include the supporting and locating principles and the clamping principles. The principles are considered systematically, according to the geometric types of the workpieces (e.g. prismatic or cylindrical parts) for which they are applied. The limitations of the principles are also discussed.
Automated fixture design (AFD) research is reviewed in Section 3. In general, AFD research considers issues such as:

1. **Fixture configuration** – determining the types of fixture elements required, and selecting locating points on the selected elements according to the specified process information.

2. **Fixture assembly** – constructing and assembling modular fixture components. The orientation of each component on the baseplate is determined according to the workpiece set-up. Consequently, the assembly sequence of the fixture components is planned for automatic assembly by robot hand.

3. **Fixture verification** – proving the validity of the fixture configuration with consideration of some operating factors, such as the cutting directions, the acting forces and the machining sequence.

The major emphasis of AFD research is the development of knowledge of how the fixture design works. First, the review of AFD system development deals with the overall automation of the fixture configuration and assembly. Second, special topics in AFD are reviewed, which involve either automation of fixture design for specified application domains (such as the AFD for the assembling workpiece) or solving some selected issues in AFD (such as the verification of workholding).

Section 4 reviews fixture-hardware design, with consideration of automation, flexibility, versatility, cost-efficiency and machining accuracy. Fixture hardware is first introduced as dedicated, modular and hybrid types, and then advanced fixture-hardware designs are studied in chronological order.

Finally, the conclusion in Section 5 expresses a general overview of the field of fixture design.

### 2. Fixture-Design Principles

The fundamental principles of basic fixture design, which have been actually used in manual fixture design, are reviewed in this section. These principles can be categorised into two major types – the *supporting* and *locating* (or vertical and horizontal locating) principles, and the *clamping* principles [3]. Discussion of each of these is further organised according to its applications to different workpiece geometries [4].

#### 2.1. Supporting and Locating Principles

The main purpose of this section is to describe the "fixturing criteria" that ensure the precise locating and rigid supporting of the workpiece under various circumstances. There is a total of 12 \((2 \times 3 \times 2)\) linear and rotational movements along the \(x\), \(y\) and \(z\)-axes, including both positive and negative directions (see Fig. 1). Usually, supporters and locators restrict at least nine movements, with the remaining three possible movements constrained by clamps.
Fig. 1. There is a total of 12 degrees of movement: six linear movements (\(+x\), \(+y\), \(+z\), \(-x\), \(-y\) and \(-z\)) and six rotational movements (clockwise or counterclockwise around each of the three axes).

1. **Prismatic Parts without an Existing Hole**

According to the ANSI dimensioning and tolerancing standard [5], a “datum reference frame” of a part can be defined by three perpendicular datum planes (see Fig. 2). For a prismatic workpiece, the datum planes are sequentially related to the defined datum features of the part. The 3-2-1 locating principles can be used to configure the external locating points [4, 6], which can relate the part to the datum reference frame as shown in Fig. 3. First, the three-point supporting principle is used to assign three supporting points on the first datum plane; these shall be located as far apart as possible to increase the workpiece stability. Five movements will be restricted by following the three-point supporting principle. Second, two points are assigned on the second datum plane and can restrict three possible movements. Third, one point has to be assigned on the third datum plane and can restrict one more movement. Totally, nine movements are bound according to the principles. However, the 3-2-1 principles can only be applied for prismatic-workpiece fixturing, and the three perpendicular datum planes and corresponding features must be well defined.

2. **General Parts with Existing Hole(s)**

For a general part with an existing hole, three supports and a single internal locator may be applied to restrict nine movements at once; this is the most efficient way of locating the workpiece. Certain criteria have to be met, for example:

- The existence of the first datum plane for three-point supporting as described in the previous paragraph
- The hole used for internal locating should be perpendicular to the first datum plane and open towards the datum plane (see Fig. 4)
- The hole in the workpiece must be of a suitable diameter to contain an existing internal locator
Fig. 2. The three datum planes are related to the primary, secondary and tertiary datum features of the part.

Fig. 3. The 3-2-1 supporting and locating principles for a prismatic workpiece.

Otherwise, the internal locating principles cannot be used, and the workpiece is treated as a regular prismatic part applying the 3-2-1 principles for fixture design. If there is another existing hole in the part that can also be used for internal locating, eleven movements are restricted (see Fig. 5).
3. Nonprismatic Parts

Here, external locating principles have to be applied to restrict the possible movements of the workpiece. Several components may be considered for properly supporting and locating the workpiece by following the external locating principles. They are:

- V-blocks for locating or supporting externally cylindrical parts
- Adjustable supports (e.g. threaded type) and locators for supporting and locating nonplanar or rough surfaces

The fixturing techniques for nonprismatic parts are often dependent on the workpiece shape. Because of the complex nature of workpiece geometry, there are no generalised fixture-design principles for nonprismatic parts, especially since multiple choices of design are often available.

For those who are interested in details of fixture-design principles, some of the most commonly used fixturing techniques are described in the book *Jig and Fixture Design* [3].
2.2. Clamping Principles

Clamping is used to restrict the possible movement of a workpiece that is not bound by supports and locators (usually three or fewer degrees of freedom need to be constrained). The general clamping principles are reviewed below according to the clamping direction with respect to the workpiece set-up.

1. Horizontal Clamping

A horizontal clamp is applied on the "horizontal clamping face" which has not been used as the locating face. Also, the clamp is located on the side of the workpiece that is opposite to the second or third datum face in order to counteract the locating force (see Fig. 6). If the horizontal clamping faces are nonplanar faces, multiple horizontal clamps can be applied on one face to ensure the restriction of the movement.

2. Vertical Clamping

A vertical clamp is applied on the "vertical clamping face", which is a face that is the top surface of the workpiece and is on the opposite side of the workpiece to the first datum plane (see Fig. 7). The most rigid area is used as the clamping position to prevent cracking or bending during the machining process. Therefore, locating the vertical clamp on the area directly above a vertical support is the most secure vertical clamping configuration. If that is impossible, the vertical clamp can be located inside the "vertical clamping zone", which is a projective polygon with its vertices defined by the three supporting points, as shown in Fig. 7.

These supporting, locating and clamping principles can be coded as a knowledge base to help decide the proper supporting, locating and clamping configurations and the corresponding faces and positions. The knowledge of fixture-design principles has to be embedded into the fixture-design system to help make the configuration decision. In the next section, the automation of fixture design is reviewed, and the modelling schemata which bring design principles into the AFD system are discussed.

Fig. 6. Horizontal clamps are placed on the opposite sides of the workpiece to their counteracting locators.
3. Automated Fixture Design (AFD)

The major emphasis of AFD is towards eliminating human intervention and increasing computerised automation. The existing research provides essential steps towards completely automating and fully integrating fixture-design systems. First, the literature on AFD system development is reviewed, and then work in some specific areas of AFD is described.

3.1. AFD System Development

The SERF expert system [7] was developed by Ingrand and Latombe at LIFIA in France. This system emphasises the functional perspectives of a fixture in expert rule construction. Ingrand and Latombe were among the first to use a function-oriented expert system for automated fixture design. Fixture set-up functions, such as positioning and fixing, are created as major constraint rules for the refinement of fixture structures. The system configures resting and fixing points (i.e. locating and clamping points) and the corresponding workpiece surfaces (called resting and fixing surfaces). The generic elements (with definition of function, principle of action and nature of contact) are chosen by expert rules to further specify the generic positioning and fixing element classes. Finally, the standard elements (specific fixture components) are selected for fixture assembly. The SERF system was developed for simple prismatic workpieces, and it can be quite difficult to enhance the expert rules to take account of more complex workpiece shapes.

Markus et al., at the Hungary Academy of Science and Budapest Technical University, used the Prolog language to develop an expert system that emphasises modular fixture assembly issues [8]. The automated selection of fixture components is completed with the input of the workpiece shape, the machining operations, and the coordinates of the locators and the clamps, i.e. with human input of the fixture configuration. The major contribution of automation is the selection of feasible sets of fixture components and towers, and the positioning of the fixture components on the baseplate for the fixture assembly. Commonsense rules are created to define the fixture-building logic.
including the shape constraints, and for the evaluation of possible collision for simple box-type workpieces. Strategies for the automated generation of modular fixtures by imitating human fixture-building processes are discussed in further detail by Markus [9]. Since the fixture-locating and clamping configuration, the workpiece shape and the workpiece orientation are given manually, the automation procedure is more approachable by programming technique.

Ferreira et al., at Purdue University, discuss the step-by-step development of an expert system for automated fixture design [10]. The system, called AIFIX, is suitable for general machining operations. Given the raw (prior-to-machining) workpiece information (including the hole-feature attribute for part surfaces), machine and cutting-tool description, and a list of operations, AIFIX is designed to generate and evaluate various fixture designs for several workpiece orientations by using the 3-2-1 principles. The expert system is divided into two major subsystems: one is for generating the suitable workpiece orientations, the details of which are described by Ferriera and Liu [11], and the other is for fixture synthesis. AIFIX was one of the first fixture-design systems to view the fixturing problem from a global perspective, including the conditions of machining sequences, workpiece set-ups and other process criteria. In particular, the effective relationships between the fixture configuration, the workpiece set-up and the machine tool are considered. There are some issues that are not covered in the research domain. For instance, the orientation is derived according to the feature-based approach without use of dimensioning and tolerancing (D&T) information to guide the preference of operation sequences. However, omitting the D&T issue is a common problem in much of AFD research as well as in much of automated process-planning research. Also, the workpiece domain is restricted to those parts that contain the predefined features and are made up of plane surfaces.

Bagchi and Lewis propose a fixture-design system called the computer-assisted fixturing system (CAFS) [12]. The system is implemented as part of a computer-integrated flexible manufacturing system. Four research issues are addressed as the bases for future development of CAFS:

1. Design of the process sheet
2. Part location and part clamping
3. Integration of the robot and fixturing database
4. Determination of the proper clamping force

A rule-based approach is proposed to solve these issues.

Chou et al. adapted a mathematical linear-programming model to generate and verify the equilibrium of cutting force, locating wrench and clamping wrench [13, 14] by using the screw theory [15], i.e. a force-equilibrium representation scheme. Four fixturing requirements have to be satisfied:

1. Workpiece resting equilibrium
2. Deterministic workpiece location
3. Clamping equilibrium
4. Total constraint

Instead of using an expert system or a rule-based system, the mathematical model provides an analysis of the fixture-configuration design. The concept can be applied as a fixture-design verification tool in an automatic or computer-
aided fixturing system. Only prismatic workpieces are considered in this research domain.

Trappey and Liu [16, 17] use the Projective Spatial Occupancy Enumeration (PSOE) approach to simplify the representation of a general shape workpiece (either prismatic or non-prismatic). Therefore, geometric reasoning can be easily conducted and fixture configuration can be found by using a set of cell-search strategies developed according to the PSOE workpiece representation. This approach has enlarged the AFD domain to deal with the general part fixturing not considered by previous researchers. Also, this AFD implementation is developed as a part of a computer integrated manufacturing system. An integrated design shell concept [18], MetaDesigner, is developed to implement the integrated design/manufacturing automation, using the Object Oriented Programming (OOP) technique. In the MetaDesigner system, the AFD sub-system can directly access the CAD database for the workpiece geometric information. The output of the AFD system, for each workpiece fixturing, can also be retrieved by other manufacturing planning activities. The above mentioned work is also applicable in robot workholding.

3.2. Special Topics in AFD

Besides the development of automated fixture-design systems, other special issues, such as developing a fixturing system for a very specific workpiece domain or dealing with some selected issues in fixture design, have been studied by some researchers. Overall, this research has contributed to the development of more sophisticated and more general AFD systems.

Hoshi and his colleagues in Japan emphasise the fixturing design in "thin-walled plate" and box-type simple workpiece machining [19, 20]. The issue of the dynamic rigidity of the workpiece under machining conditions is specifically considered. Measures of natural vibration frequencies and maximum direct compliance on the machined face are applied to ensure the sufficient allocation of supporting points.

Nee et al. [21] in Singapore apply artificial-intelligence (AI) and computer-aided design (CAD) concepts to develop computer-aided fixture design with a human interface. Techniques such as database management, intuitive design rules and computer graphic display are applied to assist fixture-design engineers in creating, retrieving or updating fixture-component selection, location and assembly. This is not a completely automated fixture-design system, although it could be a great help to manual fixture design by using computer technology. Some other computer-aided or computer-graphics-oriented fixture-design tools have been developed by applying existing CAD/CAM technology [22–27]. Because the use of CAD/CAM for fixture design and fabrication can be viewed as a special case of computer-aided part design and manufacturing, the details of computer-aided fixture design and fabrication are not further discussed here.

Fields et al. and Youcef-Toumi et al. at MIT specifically deal with a fixturing system for “sheet-metal drilling operations” [28, 29]. A set of fixture components are designed for easy robot grasping and assembling. The reconfigurable fixturing system is developed and integrated with a CAD/CAM system. The system considers workpiece display, sheet-metal fixturing analyses (stress analysis and layout analysis), fixture-sequence control and fixture assembly. Finite-element analysis (of stress) and geometric reasoning (for collision-
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avoidance) are applied to configure and orient the fixture components, although much more effort has to be devoted to extend the system to the case of a general machining operation and a general three-dimensional workpiece.

Besides specific application-oriented research, another special topic in AFD research is fixture-design verification. Several verification approaches have been developed to ensure sufficient restriction of the workpiece during the fixturing and machining processes [30]. The verification procedure is adapted to two applications:

1. Verifying the user-determined fixture configuration plan in the computer-aided fixture-design system
2. Using the procedures as part of a methodology for the algorithmic development of AFD

The kinematic modelling approach is developed by Asada and By [31]. In their model, the characteristics of the workpiece fixturing, such as the deterministic position, accessibility, detachability and complete restriction, are formulated as geometric constraints. The constraints are structured in terms of the boundary Jacobian matrix and the fixture displacement vector. Asada and By solely consider the relationship between the workpiece boundary and the fixture elements during the fixturing process, and the force impact of the machining process is not included in the analysis. Furthermore, the workpiece boundary domain is restricted to differentiable equations, owing to the needs of the boundary Jacobian matrix.

The naive kinematic approach [32] is applied by Mani and Wilson to construct constraints and to ensure the validity of the fixture configuration [33]. The counterclockwise and clockwise rotational triangles are used to model and prevent the rotational movement. Although this approach is rather easy to implement, the application domain is limited to 2-dimensional prismatic workpieces. The friction factor between the workpiece and the fixture is not considered, i.e. a friction-free surface is assumed.

The reactive force-equilibrium approach is developed by Trappey and Liu to verify the fixture configuration [30]. To ensure the complete motion restriction of a workpiece during machining, assembling, transporting, etc., the resultant force and moment must be zero. The research consists of several considerations, for example:

1. Time-varying acting and reacting force equilibrium
2. Limits of force magnitudes to prevent excessive deflection
3. Constraints of force directions based upon the part geometry
4. Frictional effects

Force elements include the horizontal and vertical locating forces, the horizontal and vertical clamping forces and the machining forces, which are all acting and reacting to each other. Finally, a quadratic programming model is used to implement the general verification system.

4. Fixture-Hardware Design

Fixture-hardware systems can be classified into three types: modular, dedicated and hybrid (of modular and dedicated) fixtures.
The modular fixture system is assembled using different types of modular fixture components on a standard baseplate for the proper positioning and fixturing of a workpiece on the machine tool (Fig. 8). The modular fixture is cost- and time-efficient, particularly for small- to medium-batch production, because it can be assembled, disassembled and reassembled for a variety of workpieces.

The dedicated fixture system is one where a special-purpose fixture is fabricated according to the shape of the workpiece. The cost and time consumed in making the dedicated fixture can only be justified when the quantity of the production is high or the product sales can cover the cost of making the fixture.

The hybrid fixture system is a combination of the modular and the dedicated fixture types. A fixture is assembled using selected modular components if suitable ones are available; otherwise, some special fixture components are fabricated according to the workpiece geometry [34].

Currently, modular fixture systems are more popular than dedicated fixture systems, owing to flexibility considerations, particularly in high-variety small-batch computerised manufacturing environments (DNC, CNC or FMS). The most prevalent modular systems commercially [35] include the Warton Unitool System, the Halder modular jig-and-fixture system, the Bluco Technik modular fixturing system, the SAFE system, the CATIC MFS [36], and the Venlic Block Jig system [37].

Background information about modular fixture systems is first discussed in Section 4.1, and then research into advanced fixture-hardware development is reviewed in Section 4.2.

4.1. Modular Fixture Systems

Two important features of modular fixture systems that must be considered are:

1. How to distinguish modular fixture types, such as the dowel-pin and the T-slot
2. What to consider in modular fixture design [3, 38, 39]

Broadly speaking, there are two types of modular fixture systems currently in use – the dowel-pin system and the T-slot system. Dowel-pin systems have
Fig. 9. (a) Dowel-pin and (b) T-slot types of modular baseplate.

accurately positioned dowel or tapped holes on the baseplate, which are used for fastening and locating fixture components: examples are the Bluco, SAFE and Venlic systems. T-slot systems have several perpendicular and parallel T-slots on the surface of the baseplate: examples are the Warton Unitool and Halder systems. The T-slot system serves the same purpose and provides the same capability as the dowel-pin system (see Fig. 9); the only difference is that the assembly sequence of the fixture components has to be considered more carefully with the T-slot types than with the dowel-pin types, especially when the components are fastened on the same row of slots [29].

Modular fixture design adheres to two basic procedures. First, the functions and shapes of modular fixture components are defined, and the complete versatility of each fixture component is explored. Second, the correct modular components are selected based upon their geometrical and topological characteristics and specific functions for the fixture assembly. The criteria for component selection include the simplicity of the fixture design, the efficiency of manufacturing economy, the complete restriction of the workpiece, the prevention of workpiece bending and cutter collision, the ease of loading/unloading and setting-up, and the machining accuracy. A comprehensive fixture is constructed by using selected components at the right locations, based upon the fixture-design principles described in Section 2.

4.2. Advanced Fixture-Hardware Design

Several ideas for advanced fixture-hardware design have been demonstrated in the United States, Europe and Japan. The hardware improvements are directed towards eliminating manual operation to enhance the fixturing efficiency, automating the fixture assembly by using a robot manipulator, adding electronic sensors or hydraulic devices to control the fixturing process with accuracy, or using a computer to control the fixturing process. This review follows the chronological order of the literature.

Tuffentsammer developed a numerically-controlled (NC) clamping system at the Institute for Machine Tools of the University of Stuttgart in West Germany [40]. In order to speed up the loading and clamping time for small-batch or single-part machining in a flexible manufacturing system (FMS), an “NC clamping machine” is designed to replace the traditional manually operated pallet and modular fixture elements. The NC clamping program (the software)
has to be written for each workpiece shape and provides instructions for selecting fixturing elements and for setting up and positioning the workpiece. The program can be recalled whenever the same workpiece form needs to be machined. The NC clamping machine is set up as part of the FMS layout. Its limitations are the workpiece domain, which includes only simple prismatic parts, and the fact that only one face of the part can be machined per set-up, owing to the hardware restriction of the clamping machine.

A programmable conformable clamping device for turbine blades was designed by Cutkosky et al. at Carnegie-Mellon University [41]. The adaptable turbine-blade clamp contains a row of plungers which can be conformed to support the cross-sectional contour of the blade, and an upper and a lower frame which can be closed and locked to secure the blade rigidly during machining. Generally speaking, the turbine-blade clamp is a dedicated clamp just for the turbine-blade part family. Although it is flexible in that it can be be used for machining a variety of turbine blades, it is not suitable for other workpiece geometries.

Zdor et al. in the Soviet Union have described the design of a three-jaw self-aligning stand (or chuck) and a rotary clamp for prismatic-part fixturing used in automated manufacturing sections [42]. The optical polarisation method is applied to test the mechanical properties, such as stress, for various components under different conditions.

Gandhi and Thompson discussed the utilisation of a two-phase fluidised bed as a fixture-hardware design [43]. This is a most flexible fixturing concept, although the constraints (such as part location accuracy and the rigidity of the fixed workpiece) need to be studied further. Also, the required fixturing force limits may be difficult to obtain in practice.

Reconfigurable and robot-loadable modular fixtures have been specially designed for sheet-metal drilling and routing, as well as for electronic-appliance assembly [31, 44]. A set of modular fixture components, e.g. vertical supporting pins, horizontal guides and horizontal and vertical clamps, are stored in the storage magazine and can be picked up by a robot manipulator and placed on a magnetic chucking baseplate. The magnetic plate is activated to secure the fixture elements.

Colbert at Rensselaer Polytechnic Institute has described a robot-loadable, sensor-equipped and automatically clamped modular fixturing system for prismatic workpieces [34]. This demonstrates a hybrid of modular and dedicated fixturing concepts. Modular design includes the fixture baseplate, the toolpoint unit and the clamp unit. The fixture base is designed as a hydraulic manifold and is equipped with sensors. Toolpoint units are used to locate the secondary and tertiary planes of the workpiece. The primary plane is established by the three toolpoints built into the clamp units. The dedicated fixturing concept is adapted into the design of the specific workpiece mounts for a particular workpiece shape. The specially designed fixture components are relatively few in comparison with the functions and varieties of the existing versatile modular fixture components, although the robot-loadable sensor-equipped automatic fixturing system is a very valuable fixture-hardware design direction.

A configurable clamp has been designed by the Carnegie-Mellon group [45, 46]. The concept of a robot (or machine-tool) loadable (swing) clamp is very similar to the hardware design concept described by Colbert [34]. Furthermore, a variety of automated fixture components (e.g. locators, supports, etc.) should be developed to suit the general machining fixturing purpose.
Reconfigurable assembly fixtures are studied by Gordon and Seering [47], who analyse the part-assembly task with respect to a variety of specific assembly operations. Then the specific reconfigurable assembly fixtures, including the reference baseplate, base-part fixture, active-part fixture and positionable reference fixture, are designed for the purposes of assisting the assembly operations. The fixture component is designed to simplify and automate the assembly process with the flexible assembly concept in mind.

Youcef-Toumi and Buitrago designed a robot-operated adaptable fixture [48]. This fixturing device consists of a conformable surface which can be adapted to the workpiece geometry for near-continuous surface support and location. The major components of the device include an array of conformable pins, an actuator and clamping mechanism, and a modular interface. This concept is similar to the conformable turbine-blade clamp design created at Carnegie-Mellon [41].

5. Conclusion

The aim of this review paper has been to express the contribution of previous research and to emphasise the need for further research in fixture-design automation. The overview reveals that a general and comprehensive automatic fixture-design system has not been completely developed. The rule-of-thumb expert-system approach for fixture design is limited by the application domain owing to the case-oriented expert-rule structure. In order to run the system in reality, a huge rule base has to be constructed to cover a sufficient domain in the expert system. One way to generalise the research domain is to develop the theoretical base by analysing the general and basic principles of the workpiece-fixturing relationship. Furthermore, the development of AFD system software and the fixture-hardware design must be studied together to enhance the overall automation of fixture design.

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References

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