A Rapid Reconfiguration Method of Modular Fixtures Based on Flexible Manufacturing Equipment

Jian Zhang*

CHANGCHUN TECHNICAL UNIVERSITY OF AUTOMOBILE, Changchun, 130012, China.
**Corresponding author: 2018012@caii.edu.cn*

Abstract: *Flexible manufacturing equipment imposes dynamic reconfiguration requirements on the fixture system under the multi-variety and variable batch production mode, while traditional rigid fixtures fail to meet the changeover cycle time constraints due to their long disassembly and assembly cycles and poor interface adaptability. This paper proposes a rapid reconfiguration method based on modular fixtures, and the research is carried out from three aspects: architectural mechanism, interface characterization, and decision-making and regulation. First, the driving constraints of flexible manufacturing equipment on fixture reconfiguration are revealed, the self-similar hierarchical decomposition principle is established, and the spatiotemporal coupling characteristics of the reconfiguration process are described. Second, standardized interfaces with geometric and mechanical decoupling are designed, the modular coded representation and parametric modeling method are proposed, and a combination rule matching algorithm for reconfiguration is constructed. Finally, a heuristic search framework for reconfiguration paths is established, its convergence analysis is conducted, the rigid-flexible coupling response mechanism during the transient switching process is elucidated, and the optimization criteria for reconfiguration schemes under multi-objective constraints are provided. The proposed method offers systematic theoretical support and a technical pathway for the rapid reconfiguration of fixture systems in flexible manufacturing environments.*

Keywords: *flexible manufacturing equipment; modular fixtures; rapid reconfiguration; interface decoupling; heuristic search; rigid-flexible coupling response*

Introduction

Flexible manufacturing equipment drives the evolution of production systems toward multi-workpiece machining capabilities, but the fixture switching speed has become the bottleneck of changeover efficiency. Traditional dedicated fixtures have a one-to-one correspondence with workpieces due to their structural rigidity, and their reconfiguration requires complete disassembly, assembly, and calibration, with the time consumption occupying the major part of the changeover cycle. Although modular fixtures achieve configuration transformation through the combination of standard interfaces, existing research still focuses on the static construction of module libraries and lacks systematic modeling of the reconfiguration process under dynamic constraints of equipment. Fixture reconfiguration involves coupled issues such as interface compatibility, motion sequence planning, transient dynamic response, and multi-objective trade-offs. Starting from the architectural mechanism, this paper establishes the self-similar hierarchical decomposition principle, develops interface standardization and module characterization techniques, designs a decision-making and regulation mechanism combining global optimality and real-time performance, and forms a complete rapid reconfiguration method system.

1. Architectural Mechanism of Modular Fixtures Under Flexible Manufacturing Equipment

1.1 Driving Constraints of Flexible Manufacturing Equipment on Dynamic Reconfiguration of Fixtures

Under the multi-variety and variable batch production scenario, flexible manufacturing equipment imposes non-fixed interface requirements on the fixture system due to the dynamic switching of its machining trajectories, workpiece postures, and clamping spaces. The driving constraints manifest themselves as the compression of the changeover cycle on the time scale and the diversity of clamping positions and postures on the space scale. The acceleration characteristics of the equipment motion system and the timing logic of the tool exchange sequence jointly define the available time window for fixture reconfiguration, and the magnitude of this window is generally smaller than the disassembly and assembly time of traditional rigid fixtures. The reconfiguration process needs to achieve a one-to-one match between the clamping profile and the workpiece features through module replacement, while retaining the basic positioning accuracy. The instantaneous fluctuation of the machining load and the spatial distribution variation of the cutting forces further constrain the stiffness distribution and the force closure condition of the reconfigured fixture.

The mathematical description of the driving constraints can be reduced to the definition of the feasible region for the reconfiguration action sequence. When the control system of the flexible manufacturing equipment outputs a workpiece switching command, the fixture system must complete the conversion from the current configuration to the target configuration within the cycle time determined by this command. During the conversion process, the contact state of the joint surfaces of each module, the preload transmission path, and the repeated positioning error of the locating elements are all affected by the coupling influence of the equipment vibration spectrum and the environmental thermal equilibrium state. These constraints together delineate the high-dimensional boundary of the reconfiguration degrees of freedom of the modular fixture, so that the reconfiguration strategy cannot be based solely on a static module library, but must consider the dynamic matching relationship between the real-time state of the equipment and the machining task[1].

1.2 Self-Similar Hierarchical Decomposition Principle of Modular Fixtures

The self-similar hierarchical decomposition principle holds that the system structure of a modular fixture can present similar combination logic at different scales, that is, the entire fixture is composed of several functional modules, and each functional module can be further decomposed into more basic sub-module units internally. This principle borrows the self-affine property from fractal geometry, and it maps the positioning function, clamping function, and base support function of the fixture to different levels respectively. The top level is the fixture configuration for a specific workpiece family, the middle level consists of standardized interface modules and adapter plates, and the bottom level consists of basic geometric units with interchangeability. This decomposition method ensures that the modules at each level have independent functional integrity, while it allows rapid replacement across levels.

The interfaces between levels adhere to the geometric feature consistency constraint, meaning that the mating surfaces of modules within the same level share the same locating datum system and locking method. The self-similarity manifests itself as the topological isomorphism between the reuse pattern of basic units at the bottom level and the combination pattern of configurations at the top level. When a reconfiguration demand occurs, the system only needs to change the module configuration within a certain level, without redesigning the coupling relationships of the remaining levels. This principle significantly reduces the complexity management cost of modular fixtures and provides a recursively searchable decision tree structure for the reconfiguration algorithm. The granularity of hierarchical decomposition determines the flexibility of reconfiguration and the redundancy of the system, and it requires the establishment of a quantitative trade-off criterion between module generality and functional specificity.

1.3 Description of Spatiotemporal Coupling Characteristics of the Fixture Reconfiguration Process

The fixture reconfiguration process is essentially a coupled dynamic process involving spatial configuration changes and time-sequence control. In the spatial dimension, the reconfiguration manifests as relative displacements between modules, contact establishment, and clamping force application, and these operations change the geometric topology and static boundaries of the fixture system. In the temporal dimension, each reconfiguration action is executed in a specific order, and the parallel or serial relationship between actions directly affects the total reconfiguration time. The spatiotemporal coupling is reflected in the fact that the spatial position adjustment of modules must be completed within a specified time window, while the compression of the time sequence is constrained by the module motion speed, the positioning detection delay, and the response characteristics of the locking mechanism.

The mathematical description of the spatiotemporal coupling characteristics can be achieved by a hybrid modeling method that combines a discrete event system with continuous kinematics. During the reconfiguration process, the motion trajectory of each module constitutes a continuous path in space, while the contact detection and locking commands after the module is in place correspond to discrete events. The timing interleaving of path planning and event triggering determines whether interference or idle travel waste occurs in the reconfiguration process. Spatial constraints (such as the clearance distance between adjacent modules) and temporal constraints (such as the minimum duration of the locking action) together define the boundary of the feasible region for reconfiguration. The quantitative description of this coupling characteristic provides the foundation for designing a rapid reconfiguration algorithm and also provides constraints for the reconfiguration path search and scheme optimization in the following sections[2].

2. Interface and Characterization Methods for Rapid Reconfiguration of Modular Fixtures

2.1 Standardized Interface Design Based on Geometric and Mechanical Decoupling

Standardized interfaces need to achieve independent control of the geometric positioning function and the force transmission function, which means that the geometric constraint surfaces and the mechanical locking surfaces are designed to be structurally separated. Geometric decoupling is realized by arranging the locating datum features (such as conical holes, V-shaped grooves, and spherical pairs) and the clamping force application features (such as threaded holes, wedge-shaped inclined planes, and hook heads) in different spatial regions or on different mating layers. The locating features bear the defined contact stiffness and repetitive positioning accuracy, and their design tolerances are determined according to the repetitive positioning capability of the flexible manufacturing equipment. The mechanical features, on the other hand, focus on providing sufficient preload and shear resistance, and their structures are not coupled with the geometric error chain of the locating features. This separated design allows the locating interface to maintain sub-micron level positional accuracy after multiple reconfigurations, while the elastic deformation generated by the locking action of the mechanical interface is not transmitted to the locating datum surfaces.

Another implication of mechanical decoupling is the predictability of the load path at the interface. After modules are joined, the cutting forces, inertial forces, and locking forces are distributed along specific transmission paths respectively, and the cross-coupling between different paths is blocked by the structural topology of the interface. A typical implementation includes the ball-cone-flat interface based on the three-point positioning principle, in which the positioning ball and the cone groove form a geometric lock, while a separate locking mechanism applies a force along the normal direction of positioning, so that the locking action does not change the contact position of the positioning ball. The dimension series and mating tolerances of the standardized interface need to cover the common workpiece weight range and cutting parameter range in flexible manufacturing equipment, while ensuring interchangeability among modules from different manufacturers. The coating treatment and lubrication condition of the interface surface are also incorporated into the standardization content to reduce the interference of friction variation on positioning consistency during the reconfiguration process.

2.2 Coded Representation and Parametric Modeling of Fixture Modules

The coded representation assigns a unique identifier to each fixture module, and this identifier contains not only the geometric dimensions and material properties of the module but also encodes its functional category, interface type, assembly degree-of-freedom constraints, and the list of compatible adjacent modules. The coding system adopts a hierarchical structure, in which the high-order bits represent the functional level to which the module belongs (base level, positioning level, clamping level, and auxiliary support level), the middle bits represent the interface standard version and geometric characteristic parameters, and the low-order bits represent the serial number and batch number of the module within the same product family. The semantic parsing capability of the code allows the reconfiguration algorithm to extract the geometric constraint information and mechanical thresholds of the module directly from the code string without invoking an external database. The code should also include a reconfiguration history record field for the module, which is used to track the wear state and remaining life of the module after multiple disassembly and assembly operations[3].

Parametric modeling represents the geometric shapes and assembly features of modules as variable parameter sets rather than fixed solid models. The CAD model of each module is defined by a set of driving parameters (such as the base length, the locating hole diameter, and the clamping arm rotation angle range) and the constraint equations among these parameters. A mapping relationship exists between the parametric model and the coded representation, and the geometric feature code segment in the code corresponds to the key parameter values in the parametric model. When the flexible manufacturing equipment processes a new type of workpiece, the new module entity adapted to that workpiece can be generated by modifying several parameters in the parametric model without performing a complete geometric modeling process again. Parametric modeling also supports the concept of module families: modules within the same family share the same topological structure and constraint logic, with only the dimensional parameters linearly scaled, and this provides searchability in a continuous parameter space for the subsequent combination rule matching.

2.3 Reconfiguration-Oriented Module Combination Rule Matching Algorithm

The module combination rule matching algorithm aims to quickly screen out the module subsets that can be combined into a target configuration meeting the current workpiece clamping requirements from the module library. The algorithm inputs the geometric features of the workpiece (the coordinates of the locating datum surfaces, the position and normal direction of the clamping areas) and the machining load conditions, and its outputs are the module sequence and its assembly order. The matching rule base is established based on two types of constraints: geometric compatibility and mechanical compatibility. The geometric compatibility rules require that the interface types of adjacent modules are consistent, the fit of the mating surfaces is within the tolerance range, and the overall assembly profile does not interfere with the workpiece. The mechanical compatibility rules require that the stress level of each module in the combined fixture system under given cutting forces does not exceed the material yield limit, and the overall stiffness matrix is positive definite[4].

The matching algorithm adopts a hierarchical search strategy: it first matches the corresponding base module according to the type of the main locating datum surface of the workpiece, and then recursively mounts the positioning modules and clamping modules on the available interfaces of the base module. Heuristic pruning conditions are introduced in the search process: if the current partial configuration has caused the reachable space of a certain interface to be unable to cover the subsequent required clamping points, the expansion of that branch is terminated. The algorithm also considers the reconfiguration time weight of modules, and the difference in disassembly and assembly time of different modules serves as one of the optimization objectives for matching ranking. The scalability of the combination rules is reflected in the algorithm's support for dynamically adding new modules: as long as a new module is entered with its interface parameters and geometric constraints according to the coded representation format, the algorithm can automatically incorporate it into its combination space. This matching algorithm links with the parametric modeling in Section 2.2: when the standard module library cannot meet specific constraints, the algorithm outputs parameter adjustment suggestions and triggers parametric modeling to generate customized modules.

3. Decision-Making and Regulation Mechanism for the Modular Fixture Reconfiguration Process

3.1 Heuristic Search and Convergence Analysis of the Reconfiguration Path

The heuristic search of the reconfiguration path treats the sequence of module disassembly and installation actions required to convert the fixture from the current configuration to the target configuration as a path in the search space. The action space consists of connection and disconnection operations between modules, with each operation corresponding to unlocking, translation, rotation, and re-locking of the interface. The heuristic function is based on a measure of the module state difference between the current configuration and the target configuration, and it uses Manhattan distance or Hamming distance to evaluate the number of modules that have not yet been matched, while also introducing an action cost estimation term, which is calculated according to the module mass, interface type, and accessibility. The search algorithm adopts the A* framework: when expanding nodes, it preferentially explores the branch with the smallest heuristic function value, and it stores the already visited configuration states in a closed set to avoid repeated loops.

The convergence analysis focuses on whether the algorithm can terminate within a finite number of steps and return the optimal path under the condition that a solution exists. The number of states in the search space depends on the size of the module library and the maximum assembly level of the fixture, and it grows exponentially in the worst case; however, the admissibility of the heuristic function guarantees the optimality and completeness of the A* algorithm. The admissibility condition requires that the estimated value of the heuristic function is not greater than the true minimum action cost from the current configuration to the target configuration, and this condition is satisfied by multiplying the module difference amount by the lower bound of the unit action cost. When the reconfiguration time window given by the flexible manufacturing equipment is smaller than the total time cost of the optimal path output by the algorithm, a time penalty term can be added to the heuristic function to guide the algorithm to prioritize searching for a feasible solution with a shorter time cost rather than the globally optimal solution; in this case, the convergence analysis needs to introduce the ε-optimality relaxation condition[5].

3.2 Rigid-Flexible Coupling Response During Transient Switching of Fixture Configurations

During the transient switching process of fixture configurations, the relative motion between modules and the sudden change of the contact state excite the rigid-flexible coupling dynamic behavior of the system. The rigid modules behave as concentrated masses and inertia tensors during motion, while the elastic elements at the interfaces (such as disc springs and rubber gaskets) and the distributed flexibility of the modules themselves constitute the channels for elastic potential energy storage and release of the system. At the moment the locking mechanism acts, the preload jumps from zero to the rated value, and this step excitation generates wave propagation and reflection phenomena in the module structure, causing an instantaneous deviation of the positioning reference point. The magnitude of the deviation depends on the position of the locking force application point relative to the module mass center, as well as the elastic modulus and damping ratio of the module.

The quantitative analysis of the rigid-flexible coupling response adopts a combined modeling approach of the modal superposition method and contact mechanics. The fixture system is regarded as a discrete elastic body consisting of rigid modules connected through flexible interfaces, and the stiffness and damping characteristics of the interfaces are obtained through experimental identification or mesoscopic finite element simulation. The displacement response during the transient switching process can be decomposed into a quasi-static deformation part and a dynamic oscillation part, and the dominant frequency of the dynamic oscillation part is governed by the lowest natural frequency of the system. When the time interval between multiple locking operations in the reconfiguration action sequence is smaller than the oscillation decay time constant of the system, a response superposition effect occurs, which may cause the repeated positioning accuracy of the modules to exceed the design tolerance. The regulation mechanism introduces a time delay compensation strategy: according to the damping characteristics of each module, a waiting duration is inserted between adjacent locking actions, so that the oscillation generated by the previous action decays to the allowable threshold before the next action is executed.

3.3 Optimization Criteria for Reconfiguration Schemes Under Multi-Objective Constraints

The optimization of reconfiguration schemes under multi-objective constraints needs to simultaneously consider four evaluation dimensions: reconfiguration time, positioning accuracy retention capability, module utilization rate, and system stiffness margin. These dimensions have different units of measurement and usually have conflicting relationships with one another. For example, shortening the reconfiguration time may require reducing the locking waiting duration, which deteriorates the positioning accuracy caused by the rigid-flexible coupling response. The optimization criteria are established on the basis of the Pareto optimal solution set, in which all non-dominated solutions constitute the candidate set, and each solution in this set is superior to other solutions in at least one objective while not inferior to other solutions in the remaining objectives[6].

The selection of a single execution scheme from the Pareto solution set requires the introduction of preference information, and this preference information is determined by the current machining task characteristics of the flexible manufacturing equipment. For high-volume production scenarios of the same workpiece type, the weights of positioning accuracy retention capability and stiffness margin are higher than that of reconfiguration time; for multi-variety and small-batch scenarios, the priority of reconfiguration time is increased. The weight coefficients are determined through the pairwise comparison matrix in the analytic hierarchy process, and the matrix elements are valued according to the workpiece tolerance requirements and the cycle time constraints. The final ranking of the schemes adopts the technique for order preference by similarity to an ideal solution, which calculates the distance of each candidate scheme from the positive ideal solution and the negative ideal solution, and selects the scheme with the largest relative closeness. The optimization criteria also embed a robustness check, which requires that the selected scheme can still maintain the positioning function under disturbance conditions such as module wear or interface contamination; this check is realized by mapping the deviation covariance matrix of modules to the position uncertainty of the locating datum points.

Conclusion

This paper addresses the rapid reconfiguration problem of modular fixtures under flexible manufacturing equipment, and it proposes a systematic solution covering the architectural mechanism, interface characterization methods, and decision-making and regulation mechanism. At the architectural mechanism level, this paper clarifies the driving constraints of flexible manufacturing equipment on the reconfiguration process, establishes the self-similar hierarchical decomposition principle to reduce system complexity, and quantitatively describes the spatiotemporal coupling characteristics of the reconfiguration process. At the interface and characterization method level, this paper designs a standardized interface structure with geometric and mechanical decoupling, realizes the coded representation and parametric modeling of fixture modules, and constructs a combination rule matching algorithm based on geometric and mechanical compatibility. At the decision-making and regulation mechanism level, this paper proposes a heuristic search algorithm for the reconfiguration path and proves its convergence, analyzes the rigid-flexible coupling response under transient switching and introduces a time delay compensation strategy, and establishes the optimization criteria for reconfiguration schemes under multi-objective constraints. Future research directions include: introducing machine learning methods into the strategy learning of reconfiguration paths to achieve adaptive heuristic function generation based on equipment state perception; exploring intelligent interface structures with active damping characteristics to suppress oscillation responses during transient switching; and establishing a digital twin system of modular fixtures to realize the linkage of offline simulation and online optimization of the reconfiguration process.

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