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

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Abstract: *The fixture system of the flexible manufacturing equipment needs to be changed dynamically for the production of many different kinds of products in small batches; traditional rigid fixtures are not suitable for this purpose because of a long disassembly-and-assembly cycle time, and they also have poor interface adaptability. A way to quickly move the modular fixtures is proposed in this paper, and the three parts of the study are the architectural mechanism, interface characterisation and decision-making and regulation. First, determine the reasons for changing the arrangement of fixtures in flexible manufacturing; then introduce the idea of self-similar hierarchical decomposition; finally explain the spatiotemporal coupling characteristics of the reconfiguration process. Second, the periodically added interfaces have been separated in terms of geometry and mechanics; thus, a modular coded representation and a method for parametric modelling have been introduced, and a rule-matching algorithm for reconfiguration has also been developed. Finally, a heuristic search framework for reconfiguration paths has been put forward, the convergence analysis of this framework has been carried out, the response mechanism of rigid-flexible coupling during transient switching has been explained, and the optimisation objectives for reconfiguration schemes under all kinds of constraints have been listed. The above way can offer some theoretical support and technical ideas for the development of fixture systems in flexible production.*

Keywords: *Flexible Manufacturing Equipment, Modular Fixtures, Rapid Reconfiguration, Interface Decoupling, Heuristic Search, Rigid-Flexible Coupling Response*

Introduction

Flexible Manufacturing Equipment has been employed to construct production systems for multi-workpiece machining, but now the speed of fixture changeover is a bottleneck in the development of this field. The old special fixtures are one-to-one matched with the workpieces because they have good structural rigidity, and any changeover needs to be fully disassembled, reassembled and calibrated; thus, a considerable amount of time is lost during the changeover period. Modular fixtures can be built with the help of standard interfaces, but most of the research so far has only focused on the static construction of module libraries and has not systematically modelled the reconfiguration process under dynamic constraints of equipment. The problems of fixture reconfiguration are interface compatibility, motion sequence planning, transient dynamic response and multi-objective trade-off. Based on the above architecture and mechanism, this paper puts forward the idea of self-similar hierarchical decomposition; interface standardisation and module characterisation techniques have been developed, a decision-making and regulation mechanism that balances global optimality with real-time performance has been designed, and finally, a complete rapid reconfiguration method system has been built.

1. Architectural Mechanism of Modular Fixtures for Flexible Manufacturing Equipment

1.1 Driving Constraints for Flexible Manufacturing Equipment in Dynamic Reconfiguration of Fixtures

In multi-variety and multi-variable batch production, as the machining paths, workpiece locations and clamping areas are all different, the interface requirements for the fixture system of flexible manufacturing equipment are not fixed. The reason is that the changeover cycle time has been shortened and the number of clamping positions and postures in space has been increased. The acceleration characteristics of the equipment motion system and the timing logic of the tool-change sequence will determine how long the fixture reconfiguration time window is; generally speaking, this window is shorter than the disassembly and assembly time of traditional rigid fixtures. At this time, one needs to replace the modules according to the clamping profile and characteristics of the workpiece one by one, and the original positioning accuracy must be maintained. Fluctuations in the machining load at a certain time and changes in the spatial distribution of cutting forces will affect the stiffness distribution and the force-closure condition of the modified fixture.

The mathematical expression of the driving constraints can be simplified to define the feasible set of the reconfiguration action sequence. When the control system of the flexible manufacturing equipment issues a workpiece change command, the fixture system needs to be moved from its current position to the new position in time with the cycle time of this command. At this time, the contact condition of the joint surface of each module, the preload transmission path, and the repeated positioning error of the locating element are all influenced by the coupling effect of the equipment vibration spectrum and the thermal equilibrium state of the environment. The above constraints together set an upper bound on the degrees of freedom for the reconfiguration of the modular fixture; thus, the reconfiguration scheme cannot be based solely on a fixed module library, and at the same time, the dynamic matching relationship between the current state of the equipment and the machining task also needs to be considered[1].

1.2 Self-Similar Hierarchical Decomposition Principle of Modular Fixtures

The first is the principle of self-similar hierarchical decomposition; that is to say, the system structure of a modular fixture can have the same combination logic at different scales, and that is to say, the whole fixture consists of several functional modules, and each functional module can be further divided into more basic sub-module units internally. Given that a fractal is self-affine, the positioning function, clamping function and base support function of the fixture can be mapped to different levels according to this rule. At the top is the fixture configuration for a particular group of workpieces; in the middle are the standard interface modules and adapter plates; at the bottom are the basic geometric units and interchangeable parts. Decomposition is employed to divide the components at each level, so changes in one part will not affect the others.

All interfaces at all levels should meet the requirement of geometric feature consistency; that is to say, the mating surfaces of modules in the same level must have the same locating datum system and locking method. Self-similarity is shown by the topological isomorphism of the reuse pattern of basic units at the bottom level and the combination pattern of configurations at the top level. If it needs to be reconfigured, only the module configuration at that level needs to be changed; the coupling relationships of the other levels do not need to be redesigned. First, we will reduce the operating expenses of the module facilities and build a recursively searchable decision tree for the reconfiguration algorithm. The Degree of Granularity in Hierarchical Decomposition Affects the Reconfigurability and Redundancy of a System; Therefore, a quantitative trade-off index for module generality and functional specificity should be developed.

1.3 Description of Spatiotemporal Coupling Characteristics of the Fixture Reconfiguration Process

In fact, the process of moving fixtures is both a change in position and a change over time. Space reconfiguration refers to the relative positions of modules, the formation of contacts and the application of clamping forces; that is to say, changes in the shape and fixed boundaries of the fixture system. At a certain time, all the steps in the organisation need to be taken; if some of these steps can be carried out concurrently, the total time for the organisation will be reduced. Spatiotemporal coupling refers to the requirement that the spatial position adjustment of modules must be realised in a certain amount of time, and the compression of the time sequence is limited by the speed of module movement, positioning detection delay and the response characteristics of the locking mechanism.

Both a discrete-event system and continuous kinematics can be used to obtain the mathematical description of spatiotemporal coupling. At the time of organisation, the motion trajectory of each module is a continuous path in space, and the contact detection and locking commands after the module is placed are discrete events. The Division of Time for Path Planning and Event Triggering will show whether there is interference or idle travel waste in the reconfiguration period. Spatial Constraints (e.g., the clearance distance of adjacent modules) and Temporal Constraints (e.g., the minimum duration of the locking action) together form the boundary of the feasible region for reconfiguration. A quantitative description of the coupling characteristic can be used to design a rapid reconfiguration algorithm, and it will also provide constraints on the search path for reconfiguration and optimisation of the scheme in the following sections[2].

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

2.1 Standardized Interface Design Based on Geometric and Mechanical Decoupling

The Standardised Interfaces should be able to control the geometric position function and the force transmission function independently; that is to say, the geometric constraint surface and the mechanical locking surface do not need to be structurally linked. To achieve geometric decoupling, the position of the datum feature (e.g., conical hole, V-groove, spherical pair) and the location of the feature that carries the clamping force (e.g., threaded hole, wedge-shaped inclined plane, hook head) should be different or on different mating planes. The required characteristics of the Position should be that it has a certain contact stiffness and repetitive positioning accuracy, and their design tolerance will be determined by the repetitive positioning capability of the flexible manufacturing system. At the same time, the mechanical properties should be to provide a large enough preloading force and shear resistance, and their structure should not be linked to the geometric error chain of the locating features. After some modification, it is possible to keep the sub-micron position accuracy of the locating interface, and the elastic deformation caused by the locking action of the mechanical interface will not be transferred to the locating datum surfaces.

The other is that the path of the load at the interface is more uniform. Connect the modules, and then the cutting force, inertial force and locking force will be distributed along the transmission path; cross-coupling among the different paths will be avoided by the structural topology of the interface. A typical construction is a ball-cone-flat joint based on the three-point positioning method; that is to say, the positioning ball and the cone groove are geometrically fixed, and a separate locking device applies a force in the normal direction of positioning so that the locking operation does not change the contact position of the positioning ball. The series dimension and mating tolerance of the standardised interface should cover the common workpiece weight range and cutting parameter range of flexible manufacturing equipment, and it should be possible to interchange with modules produced by different enterprises. The coating treatment and lubrication conditions at the interface of this part will also be specified in the standard to reduce the effect of friction change on the positioning accuracy during reconfiguration.

2.2 Coded Representation and Parametric Modeling of Fixture Modules

A code is used to assign a single index to each fixture unit, and this index contains not only the size and material of the unit but also information about its function group, connection method, constraints on the freedom of motion, and a list of connected units. The code system is hierarchical; the high-order bits indicate the functional level of a module (such as the base level, positioning level, clamping level and auxiliary support level), the middle bits show the interface standard version and geometric characteristic parameters, and the low-order bits are the serial number and batch number of the module in the same product family. The semantic parsing function of Code can directly extract the geometric constraint information and mechanical threshold of a module from the code string for reconfiguration, and it does not need an external database. The code should also have a reconfiguration history record field to keep track of how much wear has occurred in the module and how long it can still be used after several disassemblies and assemblies[3].

Parametric modelling is the shape and connection information of modules in the form of changeable parameters, not fixed solid models. All the CAD models of the modules can be obtained by using a small number of driving parameters (e.g., base length, locating hole diameter and range of clamping arm rotation angle) and the constraint equations among these parameters. There is a map from the parametric model to the coded form, and the geometric feature code segment in the code corresponds to the key parameter values in the parametric model. When the flexible manufacturing equipment produces a new kind of workpiece, a new module entity for that workpiece can be created by changing only a few parameters in the parametric model, and full geometric modeling does not need to be repeated. Parametric Modelling can be used to achieve the idea of module families; that is, modules in the same family have the same structure and constraints, and only the size parameters are varied linearly to provide a continuous parameter space for searchability and subsequent application of combination rules.

2.3 Reconfiguration-Oriented Module Combination Rule Matching Algorithm

The rule-matching algorithm in the module combination can quickly filter out a small number of modules that can be combined to form the desired structure under the current clamping conditions of the workpiece from the module library. According to the geometric features of the workpiece (coordinates of the locating datum surfaces, position and normal direction of the clamping area) and machining load conditions, the algorithm will output the module sequence and its assembly order. The two kinds of constraints in the matching rule base are geometric compatibility and mechanical compatibility. In accordance with the rules of geometric compatibility, the interface type of adjacent modules must be the same, the fit of the mating surfaces should be within the tolerance, and the overall assembly profile should not obstruct the workpiece. According to the rules of mechanical compatibility, the stress at each module of the combined fixture system due to the cutting force should not exceed the yield strength of the material, and the entire stiffness matrix must be positive definite[4].

The matching algorithm has a hierarchical search method; first, it matches the corresponding base module according to the type of the main locating datum surface of the workpiece, and then it recursively mounts the positioning modules and clamping modules on the available interfaces of the base module. Heuristic pruning conditions are employed in the search process; that is to say, if the current partial configuration has made it impossible to cover the next required clamping point with the reachable space of a particular interface, then the expansion of that branch is stopped. The algorithm is also given the reconfiguration time weight of the modules, and one of the optimisation goals for matching rank is the difference in disassembly and assembly time among different modules. The Scalability of the combination rules is that new modules can be added to the algorithm dynamically; as long as the interface parameters and geometric constraints of a new module are in coded form, it can be automatically added to the combination space by the algorithm. The matching algorithm is based on the parametric model in Section 2.2; if the standard module library does not meet some requirements, then parameter modification will be carried out and parametric modeling will be used to create a custom module.

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

3.1 Heuristic Search and Convergence Analysis of the Reconfiguration Path

Heuristic search for the reconfiguration path considers the sequence of module disassembly and installation operations needed to change the state of the fixture from its current state to the desired state as a path in the search space. The Set of Operations is to connect and disconnect modules, and each operation is equivalent to unlocking, moving, rotating and relocking the interface. The heuristic function is based on the measure of the difference in module state between the current configuration and the target configuration; Manhattan distance or Hamming distance is used to determine the number of modules that have not yet been matched, and at the same time, an action cost estimation term that depends on the mass of the module, interface type and accessibility is also added. First, we will use the A* algorithm to find a branch with a small heuristic function value, and to avoid an infinite loop, all visited configuration states will be stored in a closed set.

Convergence analysis determines whether the algorithm can be stopped after a certain number of iterations, and assuming that a solution exists, it finds the best path. The number of states in the search space is determined by the size of the module library and the maximum assembly level of the fixture; it can be very large in the worst case, but due to the admissibility of the heuristic function, the A* algorithm will still find the optimal and complete solution. The admissibility condition is that the estimated value of the heuristic function should not exceed the actual minimum action cost from the current state to the goal state, and this condition can be met by multiplying the amount of module difference with the lower bound of the unit action cost. If the reconfiguration time window of the flexible manufacturing equipment is smaller than the total time cost of the optimal path found by the algorithm, a time penalty term can be added to the heuristic function to obtain a feasible solution with a shorter time cost than that of the global optimum; in this case, the convergence analysis needs to be based on the ε-optimality relaxation condition[5].

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

At the time of transient switching of fixture configurations, there is relative motion among the modules and a sudden change in the contact state; thus, the rigid-flexible coupling dynamic behaviour of the system is excited. It is assumed that the rigid module has a concentrated mass and an inertia tensor in motion, and the elastic elements at the joints (such as disc springs and rubber gaskets) and the distributed flexibility of the modules themselves are the ways in which elastic potential energy is stored and released in the system. When the lock mechanism is working, the preload will increase from 0 to the nominal value; at this time, excitation will generate waves and reflections in the module structure and cause an immediate displacement of the positioning reference point. The size of the deviation is determined by the position of the locking force relative to the centre of mass of the module, as well as the elastic modulus and damping ratio of the module.

In addition to the method of modal superposition, contact mechanics is also employed to determine the effect of rigid-flexible coupling. It is assumed that the fixture system is a discrete elastic body with rigid modules and flexible joints, and the stiffness and damping characteristics of these joints can be obtained from experiments or mesoscopic finite element simulation. The displacement response in the transient period can be divided into a quasi-static deformation part and a dynamic oscillation part, and the main frequency of the dynamic oscillation part is determined by the lowest natural frequency of the system. If the time interval of several lock operations in the sequence of the reconfiguration action is shorter than the oscillation decay time constant of the system, then a response superposition effect will occur and the repeated positioning accuracy of the modules may exceed the design tolerance. A time-delay compensation scheme has been added to the regulation mechanism; according to the damping characteristics of each module, after the previous lock operation, a waiting time is added to allow the oscillation caused by the previous operation to decay to a certain extent before the next operation is carried out.

3.3 Optimisation Objectives for Reconfiguration Schemes Under Multiple Constraints

The four factors that need to be considered in the optimisation of reconfiguration schemes are reconfiguration time, retention of positioning accuracy, module utilisation rate and system stiffness margin. The dimensions have different units of measurement and do not need to be in the same unit. For example, in order to reduce the time of reorganisation, one needs to decrease the lock-waiting time; thus, the positioning error caused by the rigid-flexible coupling response will increase. The optimisation criterion is based on the set of Pareto optimal solutions; all non-dominated solutions form the candidate set, and each solution in this set is better than other solutions in at least one objective and no worse than other solutions in the remaining objectives[6].

One chooses an execution scheme from the set of Pareto solutions based on preference information, and this preference information should be determined by the characteristics of the current machining task for flexible manufacturing equipment. For the mass production of a single kind of workpiece, more weight should be given to the retention ability of positioning accuracy and stiffness margin than to reconfiguration time; for multiple kinds and small-batch production, reconfiguration time is relatively more important. The weight coefficients are obtained from the pairwise comparison matrix in the Analytic Hierarchy Process, and the elements of this matrix are set according to the tolerance requirements of the workpiece and cycle time constraints. The final order of the schemes is determined by the method of order preference based on similarity to an ideal solution; that is to say, the distance of each candidate scheme to the positive ideal solution and the negative ideal solution is calculated, and then the scheme with the largest relative closeness is selected. The other is a robustness test; that is to say, after selecting a scheme, it should still have a positioning function in the presence of disturbances, such as module wear or interface contamination, and this test is carried out by mapping the deviation covariance matrix of the modules to the position uncertainty of the locating datum points.

Conclusion

The problem this paper addresses is the rapid change of modular fixtures in flexible manufacturing systems, and many general solutions have been put forward, such as an architectural mechanism, an interface characterization method, decision-making and regulation mechanisms, etc. At the level of the architectural mechanism, this paper provides the driving constraints for flexible manufacturing equipment in the reconfiguration process, puts forward the principle of self-similar hierarchical decomposition to reduce system complexity, and quantifies the spatiotemporal coupling characteristics of the reconfiguration process. At the level of interface and characterisation method, this paper proposes a general interface structure with geometric and mechanical decoupling; obtain a coded representation and a parametric model of the fixture module, and build a combination rule matching algorithm based on geometric and mechanical compatibility. Heuristic Search Algorithm for Reconfiguration Path at the Level of Decision-making and Regulation is proposed in this paper; its convergence has been verified, the response of the rigid-flexible coupling under transient switching has been studied, a time-delay compensation strategy has been added, and optimisation criteria for reconfiguration schemes under multi-objective constraints have been established. In the future, machine learning will be employed to learn the strategies of reconfiguration paths in the adaptive generation of heuristic functions based on equipment state perception; intelligent interface structures with active damping properties will be developed to reduce oscillations during transient switching; and a digital twin system integrating offline simulation and online optimisation of the reconfiguration process will be constructed for modular fixtures.

Fund Projects

2025 university-level research project of Changchun Automobile Vocational and Technical University, "Research on Modular Design and Rapid Changeover of Automotive Hinge Fixtures" (Project No. XJKY202530).

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