**ORIGINAL ARTICLE**

# Reconfigurable machine tools design for multi-part families

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## Abstract

Reconfigurable machine tools (RMT) are the core facility of reconfigurable manufacturing systems (RMS), and structure design is the fundamental research involving RMT. The existing prototypes of RMT are limited to a specific part family, which suffers from reconfiguration difficulty and module sustainability issues. Therefore, a design philosophy of RMT for multi-part families with new design principles based on reconfigurability is proposed in this paper. Modularity and integrability are the basic principles, scalability, convertibility, and customization are the primary design principles, and reusability and symmetry are the auxiliary design principles. By implementing the new design principles, a two-step design method of RMT is proposed. First, a basic three-main-module structure, including the base, function arm, and workstation, is created. Second, customized components are selected to customize the functions for a specific part family, which can be reconfigured to meet the demand of other part families using other customized components. A prototype of RMT illustrates the proposed design philosophy to specify the basic three-main-module structure. The basic configurations of the RMT prototype are given, as well. The reconfigurability of the RMT prototype is analyzed from the perspectives of scalability, convertibility, and reconfiguration time. Based on topology optimization, the performance of the RMT prototype is improved. The case study implements milling and turning functions, demonstrating the practicality of the proposed design philosophy, where the processing of typical parts is also analyzed. Furthermore, the reconfiguration process among multi-part families is discussed in the case study.

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## 1 Introduction

Reconfigurable manufacturing system (RMS) is a new manufacturing paradigm with adaptable production capacity and functionality to cope with fluctuant market demands quickly and precisely in a cost-effective manner when needed [1–8]. RMS has become increasingly popular since it was first proposed by Koren et al. in 1999 [1], and the research focus varies from system design [9–12] to equipment study [13, 14]. The main components of RMS for machining are CNC machines and reconfigurable machine tools (RMT) [15]. Compared with CNC machines-based RMS, RMT-based RMS is more economical and flexible. Therefore, RMT has attracted considerable attention from researchers [16–18].

The existing studies on RMTs include prototype design, configuration design and optimization, and system integration and control [19]. The prototype design is fundamental research on RMTs. Prototype design involves designing an overall structure of the RMT. Modular architecture and integral architecture are two typical structures investigated in the

existing literature. In the studies of modular architecture, the first RMT with modular architecture was designed by Koren and Kota in 1999 [15]. Landers et al. [13] presented three design examples of modular architecture RMT considering part change, feature change, and cycle time change. Kannan and Saha [20] proposed an approach of generic setup planning (GSP) for RMT configuration synthesis. Padayachee and Bright [17] focused on mechanical design and control system supporting modularity and reconfigurability. Asghar et al. [21] focused on the optimum machine capabilities for RMS based on the co-evolution of process planning and machine configurations through the application of multi-objective genetic algorithms. Benderbal and Benyoucef [22] studied the machine layout problem of RMT by considering the product family evolution based on a two-phase archived multi-objective simulated annealing (AMOSA) algorithm. Gauss et al. [23] introduced the module-based machinery design method to support the conceptual and system-level design of modular machine families for RMS. Wang et al. [24] proposed a methodology of setting module groups for the design of RMT to cope with various changes in the products or parts to be manufactured. In studies on integral architecture, reconfigurable parallel-kinematic machine (PKM) tools [25, 26] and arch-type RMT [16, 27] are developed. RMS is built around a part family [28–30], which determines the part-family–oriented RMT research. Katz [31] introduced design principles for reconfigurable machines. Those design principles emphasize the necessity of designing a reconfigurable machine around a specific part family. The arch-type RMT (integral RMT) is a successful paradigm for implementing those design principles. However, the existing designs of RMT were restricted to a specific part family. It is difficult to reconfigure this kind of RMT to meet the requirements of another part family. Obviously, the RMT designed for a specific part family deviates from the original intention of reconfiguration, and a more flexible RMT is needed to solve this problem. Although Aguilar et al. [32] attempted to solve this problem through designing a reconfigurable lathe-mill machine tool, the integral structure limits the configuration diversity of the lathe-mill machine tool (only one lathe configuration and one mill configuration). In contrast to the limited workspace of integral RMT, modular RMT also has a larger workspace. Therefore, the new design principles of designing for multi-part families considering reconfigurability based on modular structure is proposed in this paper, which will help to fill the gap of designing for a specific part family. Moreover, the proposed design principles of RMT with modular structure aims at solving the following problems: (1) complexity of reconfigurations, (2) low module reusability, and (3) unfavorable mass distribution. The RMT design based on proposed design principles can handle multiple part families, which makes it easy for reconfiguration and prolongs the service life of machine tools. The modular structure of an RMT has more

reconfiguration flexibility, which enriches the configurations and enhances the practicability. A prototype of RMT is designed to implement the proposed design principles.

The remaining part of this paper is structured as follows: first, the design philosophy is introduced, including the design principles and two-step design method. In Section 3, based on the proposed design principles, a prototype of an RMT is designed to illustrate the proposed design philosophy. In Section 4, from the perspectives of scalability, convertibility, and reconfiguration time, the reconfigurability of the RMT prototype is analyzed. Section 5 improves the performance of the RMT prototype using topology optimization. Section 6 presents function implementation cases of the RMT prototype. Section 7 concludes this paper.

## 2 Design philosophy

### 2.1 Design principle

An RMS is designed at the outset for rapidly responding to sudden demand changes within a part family, and machine tools (CNC machine tools and/or RMT) are designed or selected for this specific RMS [33]. Similar to RMS, an RMT can be designed for a specific part family; the design principles for which were given by Katz [31]. The necessary principle is designed around a specific part family. The primary principles are that an RMT is designed only for customized flexibility, easy and rapid convertibility, scalability, and certain other motivations. However, if an RMT is only designed for a specific part family, it is difficult to reconfigure the RMT to satisfy another part family. The RMT will be abandoned after finishing production of the specific part family, which departs from the goals of reconfiguration. In this study, the concept of designing for reconfigurability of RMT is proposed. Compared with designing for a specific part family, an RMT designed for reconfigurability focuses more on reconfigurability, which aims at coping with multiple part families. The high reconfigurability of an RMT makes it easy to reconfigure to serve various part families [34]. The design principles of design for reconfigurability are given below.

From the reconfigurability perspective, the basic principles are modularity and integrability, which is realized through module and interface, respectively. So, module and interface are the cornerstones of an RMT. Various combinations of modules enrich the functions of an RMT. Standard interfaces facilitate the integration of modules to reconfigure an RMT rapidly. Moreover, the modular structure with standard interfaces makes it possible to pursue a "Plug & Produce" architecture. The "Plug & Produce" architecture is capable of introducing a new manufacturing device into a manufacturing system quickly and efficiently [35]. The primary principles are scalability, convertibility, and customization. Scalability is the

ability to change the capacity of an RMT. Convertibility is the ability to change the functionality of an RMT. The design of an RMT should reserve spaces for scalability and convertibility. Customization includes functionality and flexibility customizations. The functionality customization means that the functions of modules can be customized. A group of customized modules satisfying the functional requirements of a part family exhibits the flexibility customization, which the corresponding RMT is restricted to a specific part family. The combination of functionality customization and flexibility customization provides the possibility of designing an RMT for more than one part family with more flexibility. The auxiliary principles are reusability and symmetry. The module redundancy problem should not be ignored in the process of RMT design, and reusability is applied to promote the reuse of the module. Symmetry is used to deal with unfavorable mass distribution.

The basic principles are the cornerstone of RMT design determining the basic structure of RMT and connection methods between modules. The primary principles decide the direction of RMT design to achieve reconfigurability in a cost-effective and rapid way, while the auxiliary principles are proposed to make the machine structure better within the reconfiguration restriction.

## 2.2 Design method

Based on the design principles mentioned above, a standardized three-main-module structure of RMT is proposed, which is customized with various components, as shown in Fig. 1. The standard three-main-module structure consists of a base, functional arm, and workstation. The three-main-module structure simplifies and fixes the module division of an RMT, which helps the standardization of interfaces between main modules. The components within each main module customize the functions of the corresponding main module. The main modules are autonomous, and the physical interfaces are standard and uncouple from energy/information interfaces (this paper focuses on physical interfaces only). It is convenient to install or uninstall these main modules. Therefore, the proposed RMT with standardized three-main-module structure is a "Plug & Produce" architecture, where

the main modules can be removed/reinstalled easily and quickly.

The design process of the RMT with standard main modules and custom components for each main module is divided into two steps, as shown in Fig. 2. In step 1, the standard main modules are designed. The designer only needs to focus on the structure design of the main modules and their interfaces considering reusability and symmetry, which can seek an optimal solution for scalability and convertibility. In step 2, the customized components are designed or selected. According to the customized demands of a part family, the specific functional components are designed or selected to realize the function customization of the corresponding part family. The symmetric structure is also the best choice of components if possible. The main modules stay unchanged once they are complete. However, the components design/selection is a continuous process to update the function of the main modules, which can achieve customized flexibility (flexibility limited to part family) in a certain situation and be updated to gain another customized flexibility (flexibility limited to another part family) if needed. In addition, efforts should be devoted to reusing the existing components.

## 3 RMT prototype design

Based on the proposed design philosophy, a typical RMT prototype is designed to implement the basic three-main-module structure with customized functional components, as shown in Fig. 3. Due to the changeable demands of functional components, the section focuses on the basic structure design of the RMT prototype, and the design details of the three main modules are given below.

### 3.1 Base

The first main module is the base shown in Fig. 4. The symmetric base is divided into three areas. Areas 1 and 3 are designed to hold the function arms, and area 2 is designed to hold the workstation. The screwed hole is chosen to connect the main modules. A screwed-hole pair consists of two screwed holes at a distance of $l$. Four screwed-hole pairs are

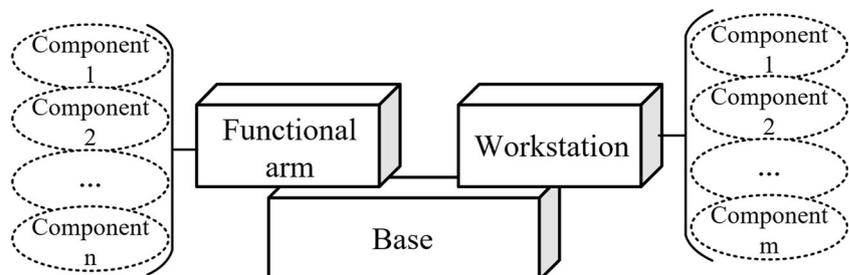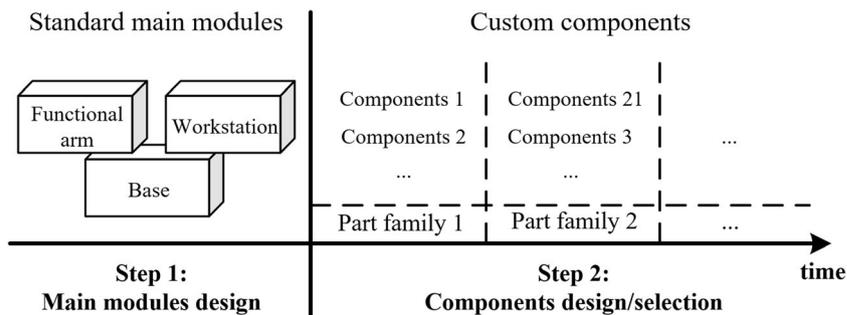**Fig. 1** Three-main-module structure with customized components

**Fig. 2** Two-steps design method

Standard main modules

Custom components

Functional arm

Workstation

Base

Components 1 | Components 21
Components 2 | Components 3
... | ...
Part family 1 | Part family 2 | ...

time

**Step 1:**
**Main modules design**

**Step 2:**
**Components design/selection**

equidistantly distributed at distance $l$ in areas 1 and 3, and five screwed-hole pairs are equidistantly distributed at distance $l$ in area 2. Every two adjacent screwed-hole pair forms a base-workstation/functional arm interface. The solid and dashed square boxes are two examples of base-functional arm interfaces in area 1. The screwed-hole pair in the interaction of solid and dashed square boxes are reused in these two interfaces, which increases the number of interfaces under a limited number of screwed holes. More than one interface is designed in base reserve for scalability and convertibility. Furthermore, there is only one structural type of interface on the base facilitating reconfiguration.

### 3.2 Functional arm

The second main module is the functional arm shown in Fig. 5a and b. Seen from Fig. 5a, the functional arm consists of asymmetric column and functional components. The functional components are added on the side of the symmetric column (*zy* plane). The side-add way of functional components increases workspace in the *y*-direction and decreases the unfavorable mass distribution. Two similar interfaces (screwed-hole pair) are designed at both ends of the column, including the functional arm–base interface and arm–arm

interface. The functional arm–base interface matches with base–functional arm interface. Arm–arm interface is designed to connect two functional arms together, that is, the inverted "L" shape functional arm, shown in Fig. 5b. The inverted "L" shape functional arm reuses the functional arm and readies convertibility for the RMT. Due to the screwed-hole pair of the interface, there is also one interface type of functional arm. In addition, the functional components are designed or selected according to a part family and added on the column of the functional arm to attain the specific function of the part family.

### 3.3 Workstation

The third main module is the workstation shown in Fig. 6. The basic workstation consists of the symmetric platform and part holder. The part holder is a customized component designed for a specific part. A workstation–base interface matching with base–workstation interface is designed using a screwed-hole pair, as well. In fact, the same screwed-hole pair is chosen to constitute the interfaces between main modules in this RMT prototype. The interfaces are standardized to one structural
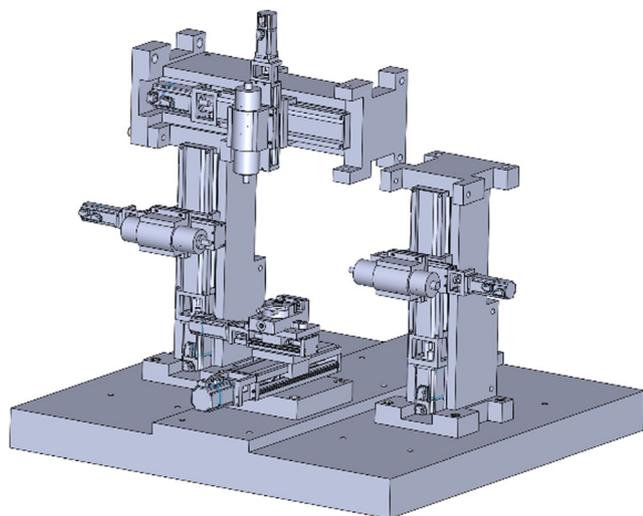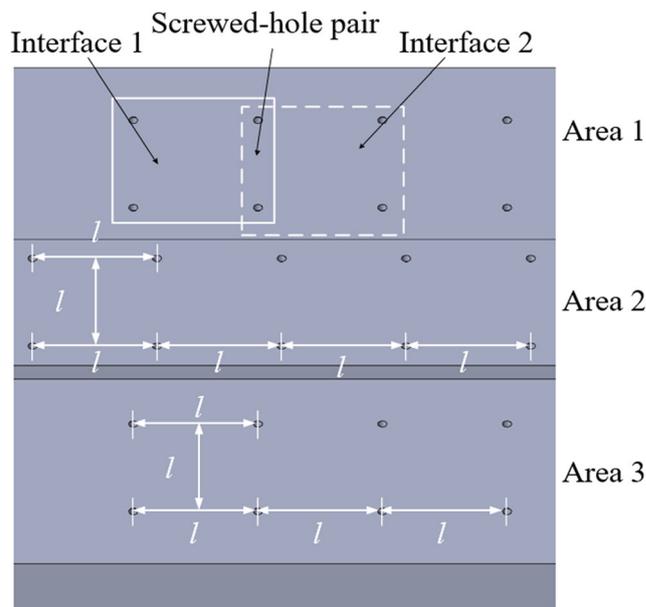


**Fig. 3** Typical RMT prototype



Interface 1

Screwed-hole pair

Interface 2

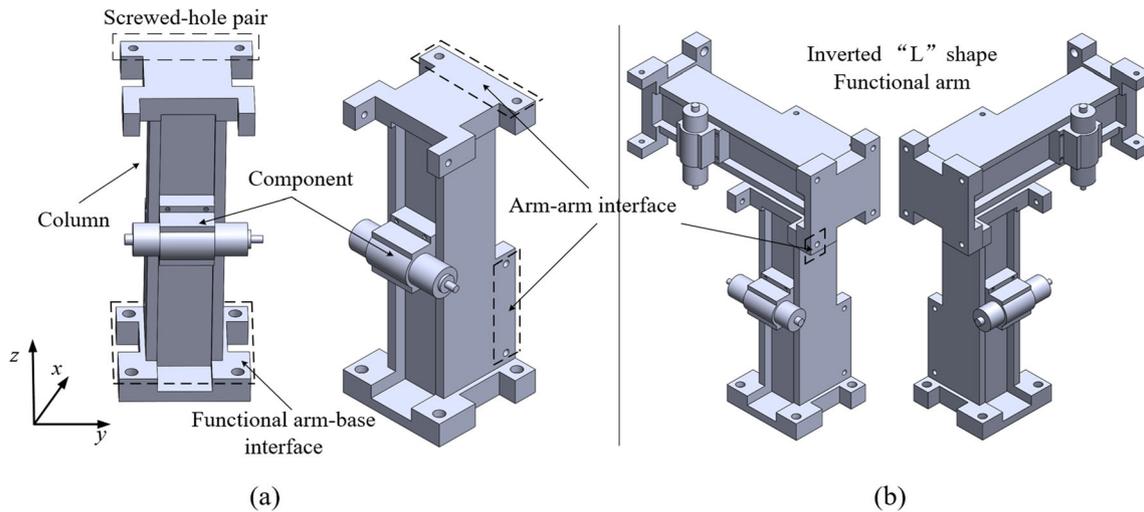Area 1

Area 2

Area 3

**Fig. 4** Base of RMT

**Fig. 5** Function arm of RMT

type decreasing the reconfiguration complexity. Although the connectors of components can be customized, the design of connectors may obey the design principle as far as possible.

### 3.4 Basic configurations

The proposed three-main-module structure simplifies an RMT into three modules and one structural type of interface, but it does not decrease the richness of machine configurations. As to the proposed RMT prototype, no more than four functional arms (two types: regular functional arm and inverted "L" shape functional arm) or two workstations can be installed onto the base. The variants of the proposed prototype without the customized components are shown in Fig. 7 to elaborate the configuration richness. There are up to 12 variants. The actual configurations of the proposed RMT prototype will be considerably more than 12 considering the customized components of functional arm and workstation. It is obvious that the configuration richness of the proposed RMT prototype is capable of meeting actual demands. Moreover, Fig. 8 provides configuration examples of the RMT prototype. Configuration a can process two side surfaces and one upper surface of part, configuration b can process the end surface of the revolving part, configuration c can process two different parts

simultaneously, and configurations d, e, and f can process the revolving surface of the part.

## 4 Reconfigurability analysis of the proposed RMT prototype

The scalability and convertibility of the proposed RMT will be analyzed to show the reconfigurability advantages of the proposed three-main-module structure adequately. In addition, reconfiguration time is an important evaluation index of reconfiguration effectiveness that will be discussed in this section as well.

### 4.1 Scalability analysis

Scalability allows RMS throughput capacity to be rapidly and cost-effectively adjusted to abrupt changes by adding or subtracting manufacturing resources [9, 36]. In terms of RMTs, the scalability of RMT is the ability to easily modify production capacity by adding or removing modules/components. There are two approaches to achieve scalability, as summarized by Putnik et al. [37]: (1) A single element is scaled by up/downsizing its characteristic parameters, that is, changing
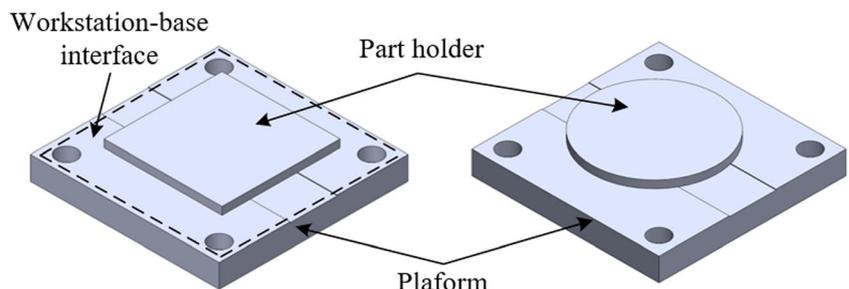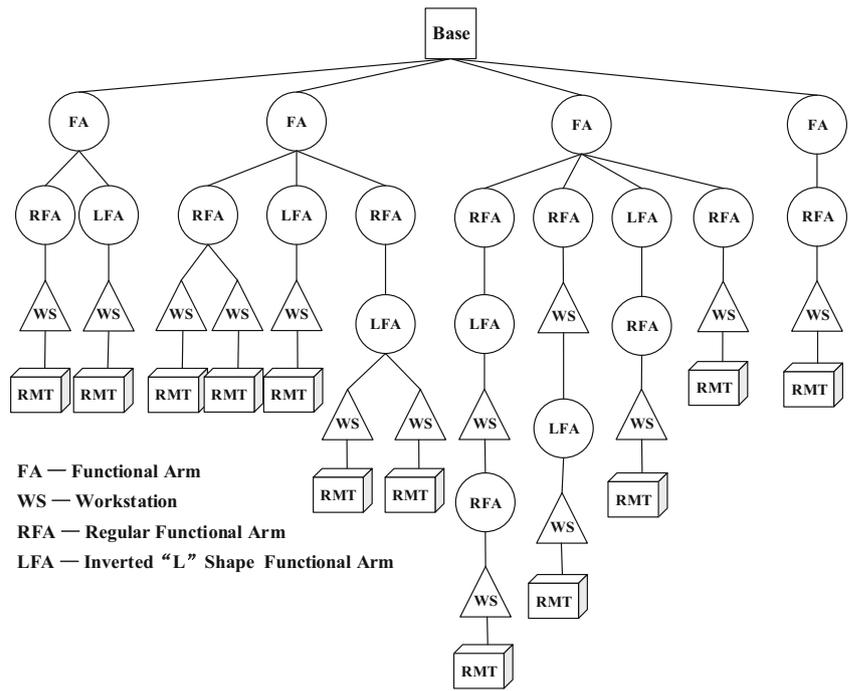
**Fig. 6** Workstation of RMT

**Fig. 7** Variants of the three-main-module structure



FA — Functional Arm
WS — Workstation
RFA — Regular Functional Arm
LFA — Inverted "L" Shape Functional Arm

spindles with different powers in an RMT [13]; (2) Identical elements are linked together to provide scaled performance, that is, changing same-function module numbers of RMT. Although the proposed RMT can adjust its capacity by changing the power of spindle (first approach), the second approach is used to demonstrate the advantages of the proposed three-main-module structure, as shown in Fig. 9. The vertical coordinate represents the capacity of the RMT, and the horizontal coordinate represents the function of RMT. It can be seen from Fig. 9 that the capacity of an RMT with different functions

(horizontal direction) can be scaled by adding/removing same-function functional arm–workstation pair (vertical direction). These main modules (functional arm/workstation with customized components and base) can be reused in the scale-up process.

From the quantity perspective, the scalability of an RMS consisting of CNC machine tools can be defined as [38, 39]: scalability = 100 × (1 − smallest incremental capacity/existing capacity)% where the smallest incremental capacity is one machine tool. If the smallest incremental capacity that can
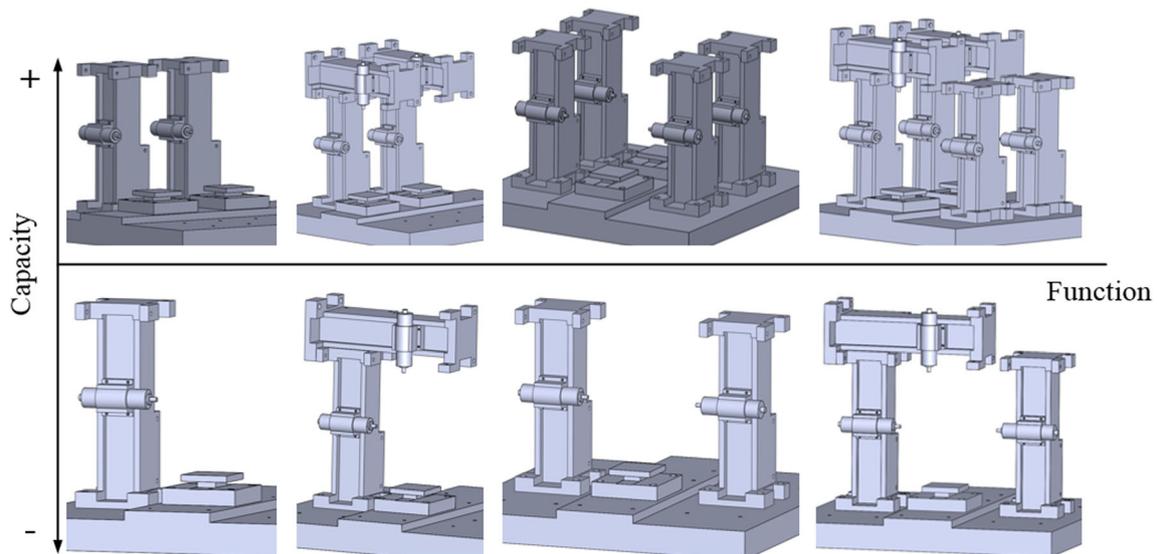
**Fig. 8** Configuration examples
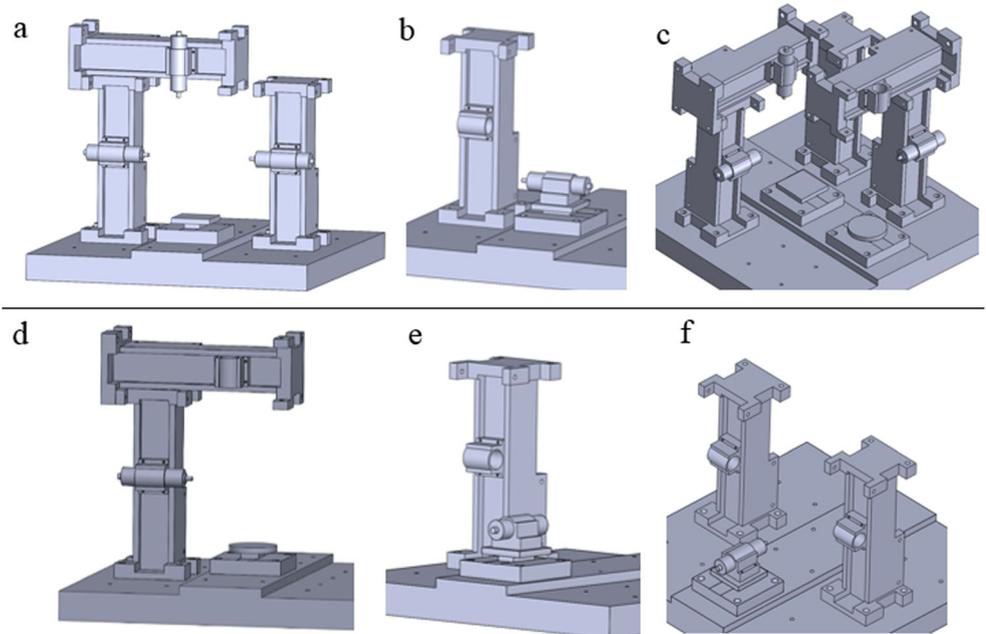
**Fig. 9** Capacity adaption of RMT

be adjusted to meet new demand is small, then the system is highly scalable. However, there are reserved spaces for adding new machines and keeping the system's setup plan unchanged, which increases the initial capital investments. If an RMS is constructed using the proposed RMT, the smallest capacity increment/decrement changes from one machine tool to one functional arm–workstation pair. This approach can not only avoid major adjustments of the system setup plan but can also save the investments of reserved spaces. The different scalabilities of an RMS with CNC machine tools and RMTs are shown in Fig. 10. Obviously, the proposed RMT enhances the scalability of the RMS.

## 4.2 Convertibility analysis

Convertibility is the ability to rapidly adjust system functionality in response to new demand with minimal effort [40, 41]. Unlike the changeable capacity of scalability, convertibility focuses on the functionality changeover, as shown in Fig. 11. There are many ways to change the functions of the proposed RMT: (1) replacing the existing

module with a different function module (when converting from configuration $a_1$ to configuration $b_1$); (2) installing the same/different module in different positions (when converting from configuration $b_1$ to configuration $b_2$, the same function module is installed in a different position; when converting from configuration $b_3$ to configuration $b_4$, a different function module is installed in a different position. The results are that they all obtain a new RMT configuration with different functions); or (3) only changing the installation direction of the existing module (when converting from configuration $a_1$ to configuration $a_3$, the installation direction of the workstation is changed). One thing that should be stressed here is that the basic three-main-module structure is reused in the conversion process. It is a functionality updating process mentioned in Section 2.2. In addition, the replacement of components can gain a new function as well, but this approach is spurned in this study. The components are customized with nonstandard connectors. The replacement of components may encounter an unpredictable situation. The proposed three-main-module structure is a "Plug & Produce"
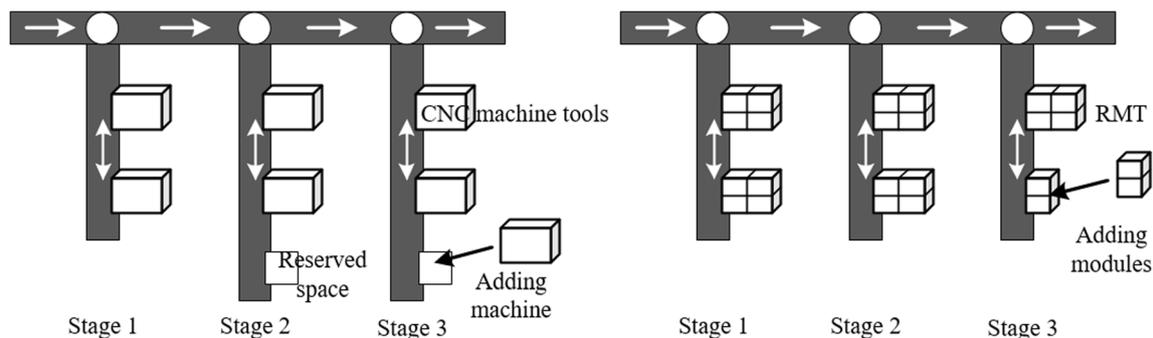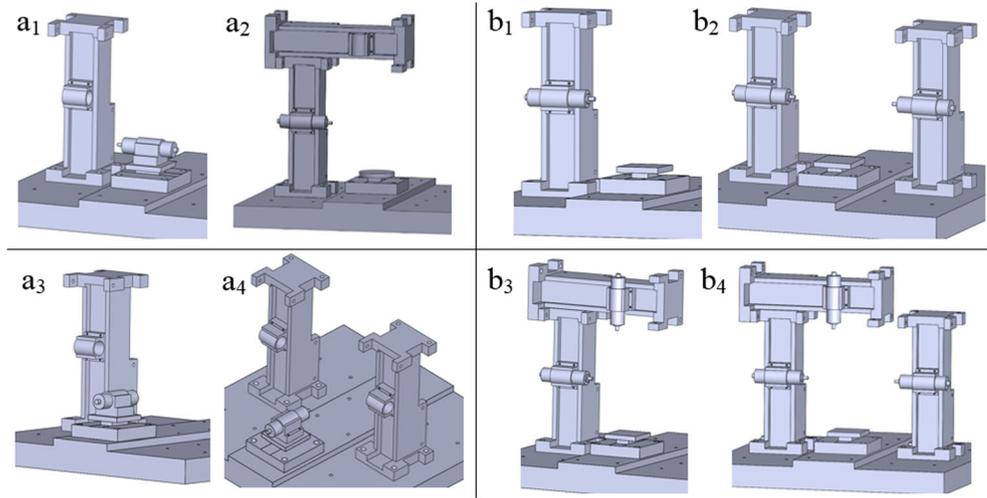


**Fig. 10** Scalability of RMS with CNC machine tools and RMT

**Fig. 11** Function changeover of modular RMT



architecture. It is a reliable and time-effective way to convert an RMT by changing the main modules. This will be discussed in the next subsection.
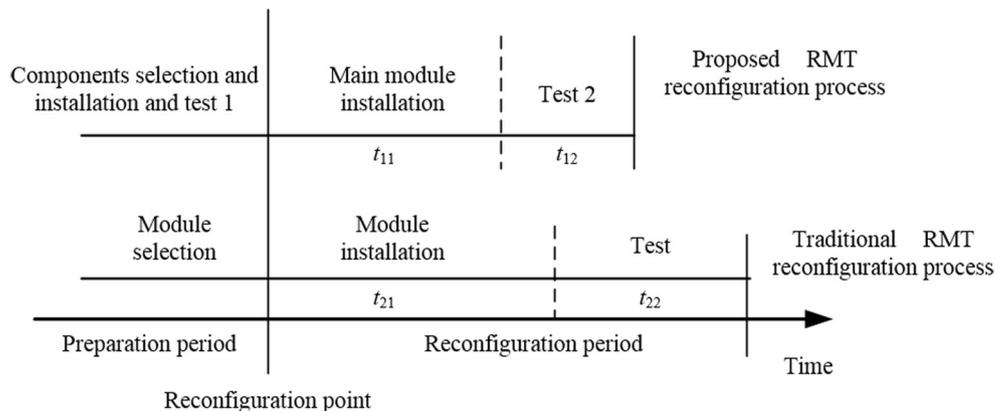
### 4.3 Reconfiguration time

The analysis of scalability and convertibility of the proposed RMT shows that the RMT is designed under the guidance of a proposed design decreases reconfiguration effort. Moreover, the three-main-module structure provides more flexibility to prepare for reconfiguration, which saves reconfiguration time. As shown in Fig. 12, the RMT reconfiguration process includes a preparation period and a reconfiguration period separated by the reconfiguration point [42].

In the traditional RMT reconfiguration process, modules needed for new demands are selected in the preparation period and installed in the reconfiguration period. The new RMT is tested after the installation of new modules. In the proposed RMT reconfiguration process, components needed for new demands are selected and installed into the main module. Test 1 is executed to ensure that the components installed into the main module work well. If there are multiple main

modules needed to be prepared, the preparation work can be conducted simultaneously in order to save preparation time. After the preparation of main modules with new components, the reconfiguration of the proposed RMT begins with the installation of the main module and ends with test 2. Similarly, test 2 is executed to guarantee the reconfigurable effectiveness of RMT. Compared with traditional RMT, the proposed RMT involves more work in the preparation period; in particular, test 1 ensures that the components are prepared well for reconfiguration. Therefore, test 1 will reduce the time required for test 2, that is, $t_{12} < t_{22}$. Moreover, benefiting from the standard interfaces and preinstall during the preparation period, the installation time of the proposed RMT is less than that of the traditional RMT, that is, $t_{11} < t_{21}$. Thus, we can obtain $t_{11} + t_{12} < t_{21} + t_{22}$. The result shows that the times of the main module installation and test 2 in the reconfiguration period of the proposed RMT are less than that of traditional RMT.

Actually, the time-effective reconfiguration process benefits from the "Plug & Produce" idea. The work in the preparation period and the three-main-module structure with standard interfaces of proposed RMT prepare the main modules well for "Plug & Produce". It is a new reconfiguration mode

**Fig. 12** Reconfiguration time comparison between the proposed RMT and the traditional RMT

that brings forward many works to the preparation period, thereby saving reconfiguration time.

# 5 Structure analysis and optimization of the proposed RMT prototype

To ensure the performance of the proposed RMT, structure stiffness is discussed in this section, including static stiffness analysis and dynamic stiffness analysis. Structure stiffness is the physical property of structures and materials [43], which is a key index for the performance of an RMT. Based on the analysis results, structural optimization is applied to avoid resonance problems and improve the overall performance.

## 5.1 Structural stiffness analysis

The static stiffness and dynamic stiffness of machine tools are crucial to producing high-quality products. A typical configuration with three spindles of the proposed RMT prototype is analyzed (Fig. 3), in which the regular functional arm and inverted "L" shape functional arm are installed on the same base. The finite element method (FEM) is employed using the ANSYS workbench to analyze the static and dynamic stiffness of the proposed RMT. The material parameters settings are listed in Table 1. All modules/components are fixed, except the three spindles moving along the slot of the column. The finite element model with hexahedral mesh dividing of RMT is shown in Fig. 13, where the cell number is 254251, and the node number is 962331.

### 5.1.1 Static stiffness analysis

Static stiffness is used to analyze the deformation of machine tools under given load conditions, such as cutting force and other external forces. In high-speed machining, the spindle speed is higher than 10000 r/min [44], and the corresponding force loading on the spindle is 724.8 N. Therefore, the force loads on the three spindles are set as $F_1 = F_2 = F_3 = 724.8$ N, and the analysis result is shown in Fig. 14. The top functional arm of the inverted "L" shape functional arm is deemed as the most unstable structure. The most prominent deformation appears at the end of the top functional arm (0.0221 mm).

**Table 1**　Material parameters and constraints

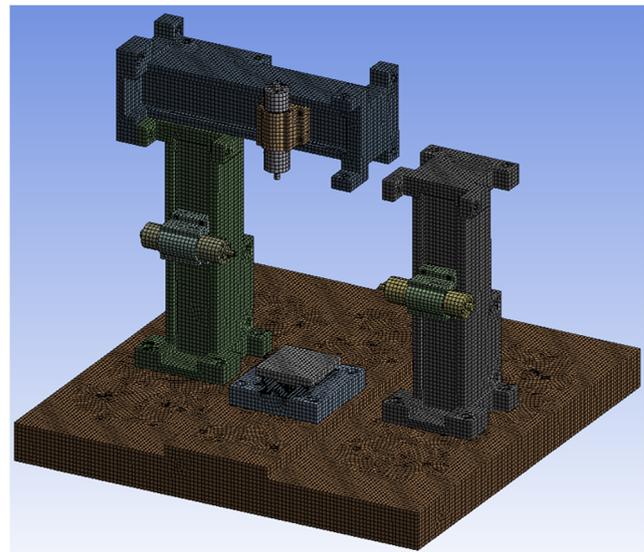| Structure | Base | Other structures |
|---|---|---|
| Material | Gray cast iron | Constructional steel |
| Density (kg/m^3) | $7.2 \times 10^3$ | $7.85 \times 10^3$ |
| Young's modulus (Pa) | $1.1E + 11$ | $2E + 11$ |
| Poisson's ratio | 0.28 | 0.3 |



**Fig. 13**　FEM model for structural stiffness analysis

### 5.1.2 Dynamic stiffness analysis

High rotational speed causes severe vibrations that decrease machine accuracy. For dynamic motions and rigidity, the most important parameter is the first natural frequency. Modal analysis is employed to investigate the vibration performance of the proposed RMT. The structural vibration can be expressed as the linear superposition of the different modes of vibration. The lower order modes, which determine the dynamic characteristics of the structure, are more important than the higher ones. Therefore, the first six order modes and corresponding frequencies are intercepted, as shown in Fig. 15. The frequency ranges from 82 to 310 Hz (generally, the frequencies of turning and milling are 2.5–5 Hz and 100–750 Hz, respectively [45]. Therefore, resonance may appear on the proposed RMT. To avoid this and guarantee the stabilities, further
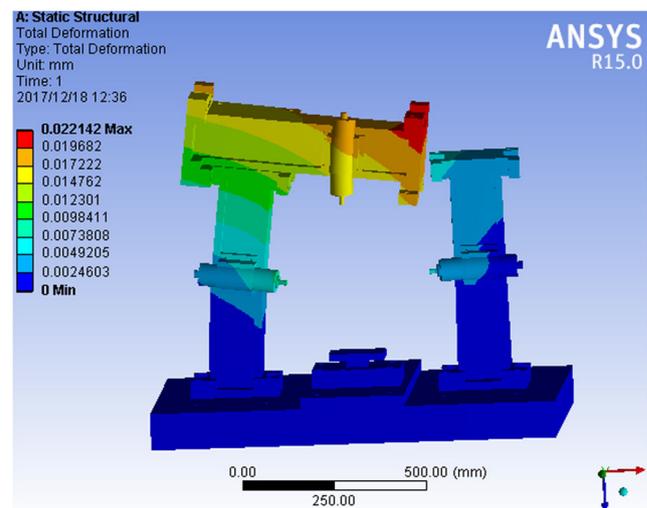


**Fig. 14**　Static stiffness

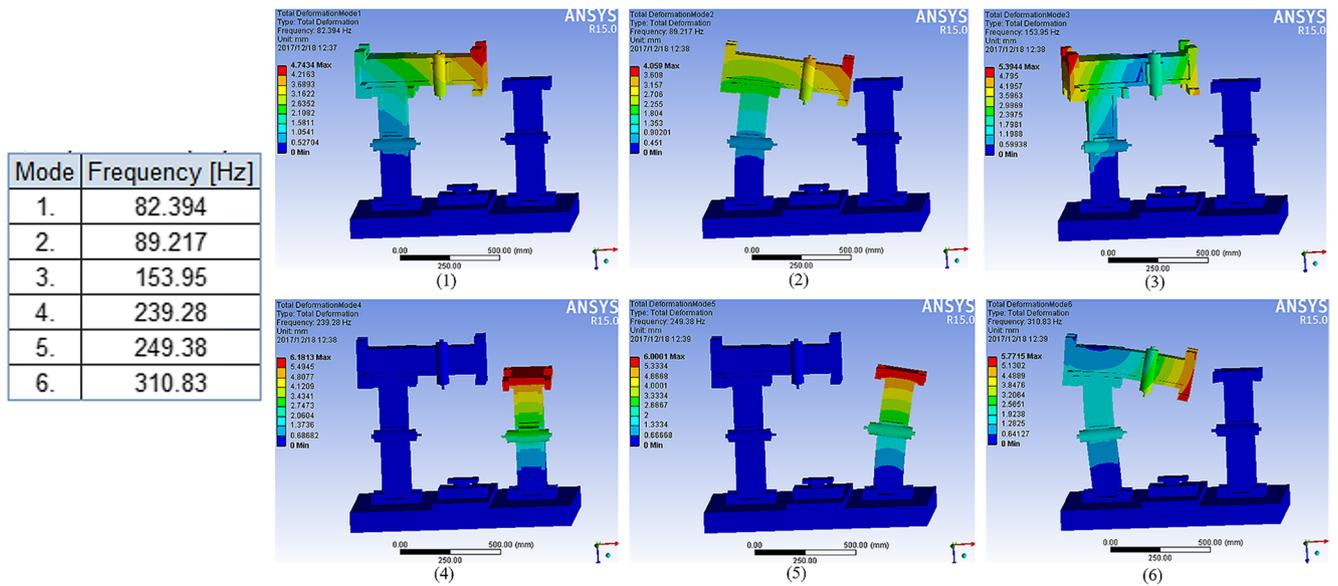| Mode | Frequency [Hz] |
|------|----------------|
| 1.   | 82.394         |
| 2.   | 89.217         |
| 3.   | 153.95         |
| 4.   | 239.28         |
| 5.   | 249.38         |
| 6.   | 310.83         |

Fig. 15 Overall modal analysis

optimization is required. This will be presented in subsection 5.2. As to the mode of vibration, the 2nd- and 6th-order modes show up-and-down vibration, the 3rd-order mode shows in-and-out vibration, the 5th-order mode shows left-and-right vibration, and the vibrations of the other two orders (1st- and 4th-order modes) of mode are unremarkable.

## 5.2 Structure optimization

This section will solve the resonance problem found in the dynamic stiffness analysis, in which the natural frequencies partially overlap the frequency range of milling. The resonance is detrimental to achieving a stable structure. Structure optimization (natural frequency modification) of the proposed RMT is necessary to solve the resonance problem.

Given that there are multiple configurations of the proposed RMT, each one would have a different natural frequency. The overall system varies, and therefore no singular optimization can be made at the system scale. Under such conditions, the functional arm, as the key component in this system, should be the target of optimization. In addition, avoiding resonance of the RMT configuration with the inverted "L" shape functional
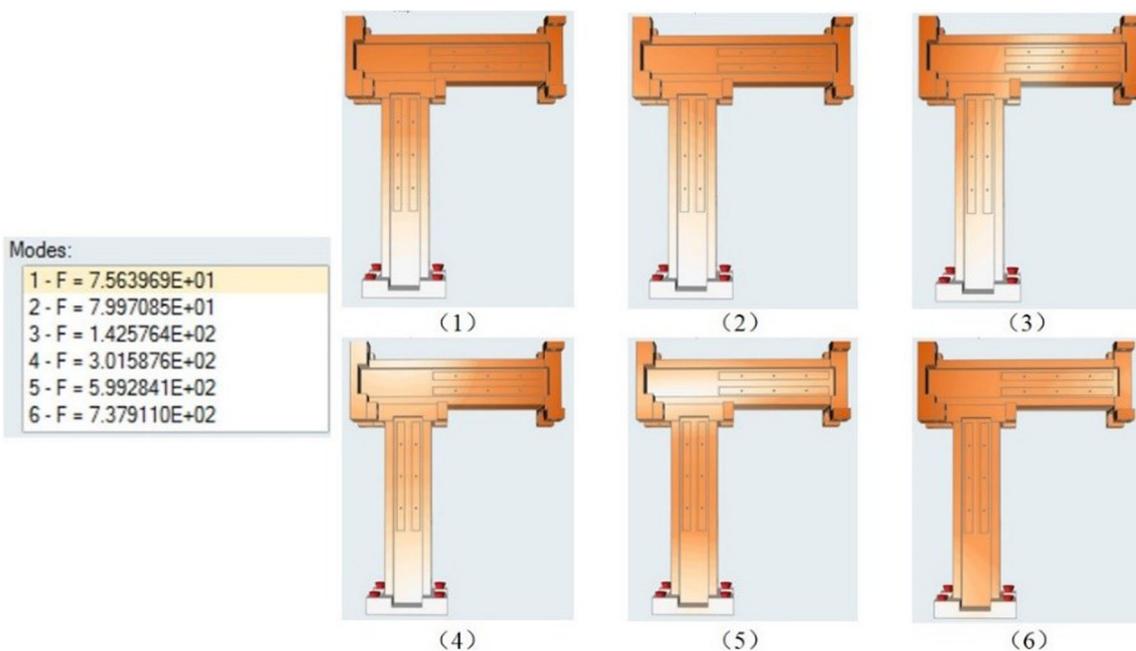
Modes:
1 - F = 7.563969E+01
2 - F = 7.997085E+01
3 - F = 1.425764E+02
4 - F = 3.015876E+02
5 - F = 5.992841E+02
6 - F = 7.379110E+02

Fig. 16 Model analysis of the inverted "L" shape functional arm

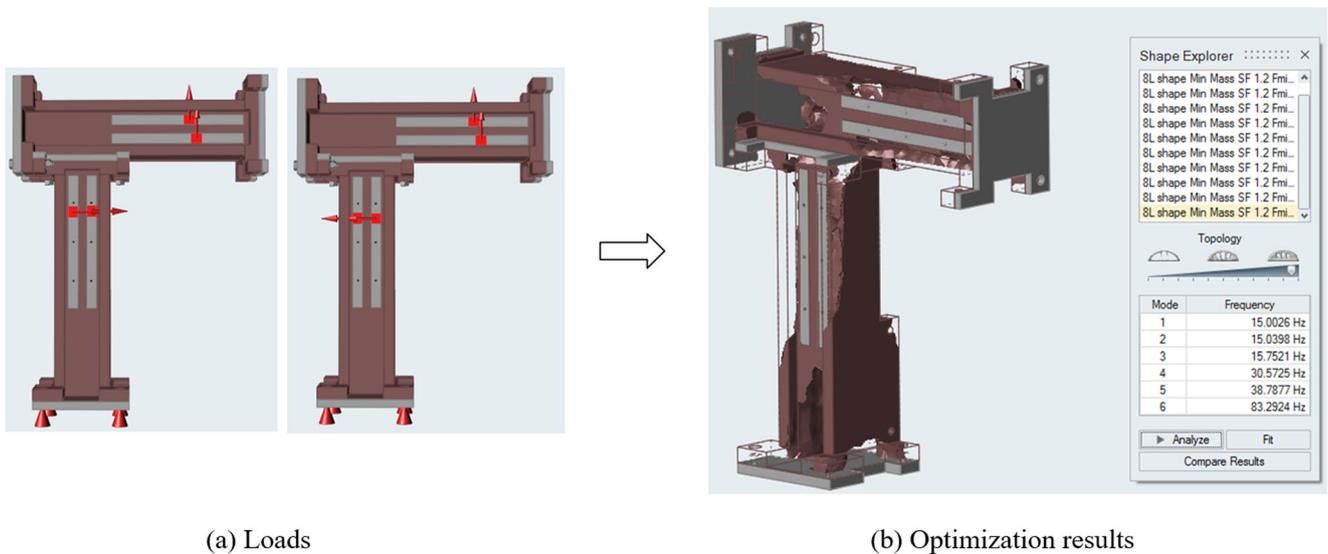(a) Loads                                        (b) Optimization results

**Fig. 17** Loads and optimization results of the inverted "L" shape functional arm

arm should be a primary aim in the optimization, because the vibrations, if any, will cause the largest displacements at the end of top functional arm under such a configuration and lead to the most serious errors, compared with other positions in other kinds of configurations. The analysis result according to *solidThinking* shows that the resonance will appear in the inverted "L" shape functional arm: the first 6 modes of frequency are shown in Figure 16 (where the deeper color indicates the larger extent of displacements, and the largest displacement, 22.45 mm, occurs in mode 5). Apparently, the frequency range from 7.56 Hz to 737.91 Hz also overlaps the frequency range of milling, which is wider than the overall RMT, ranging from 82.39 Hz to 310.83 Hz. Moreover, the vertical part of the inverted "L" shape functional arm bears more forces, implying higher stiffness requirements compared to the single vertical arm state. Based on this, a fair choice of the structure

optimization is to improve the structure of the single functional arm for the aim of modifying the natural frequency of the inverted "L" shape functional arm. As to the optimization method, topology optimization [46, 47] provides convincing results using partial differential equations, based on specified material properties, and can achieve a fair result satisfying multiple requirements, such as the objective of stiffness or mass, under the constraints of volume, mass, frequency and manufacturing control. Thus, topology optimization is selected to optimize the functional arm.

The structure optimization of the inverted "L" shape functional arm using topology optimization method is executed in *solidThinking Inspire 2018*. The objective of the optimization is minimizing mass. The first 6 modes should not overlap the frequency of turning (2.5–5 Hz) and milling (100–750 Hz). Two load cases are applied for topology as shown in Fig. 17a,

**Fig. 18** Optimized regular functional arm
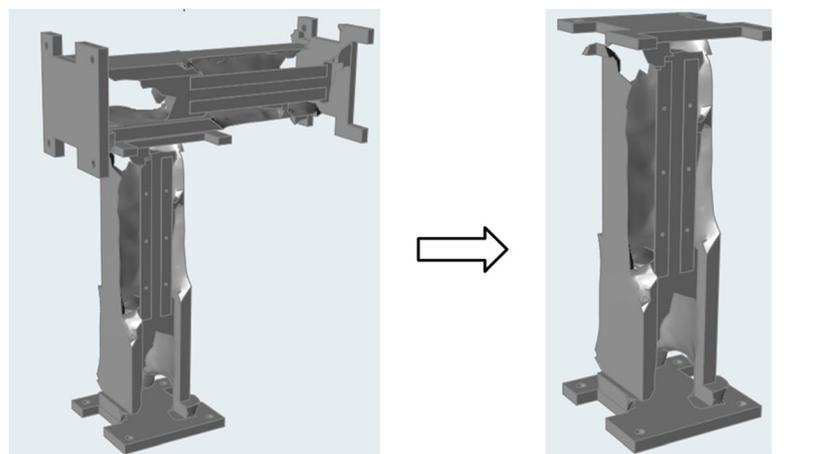


Optimized inverted "L" shape functional arm                    Optimized regular functional arm
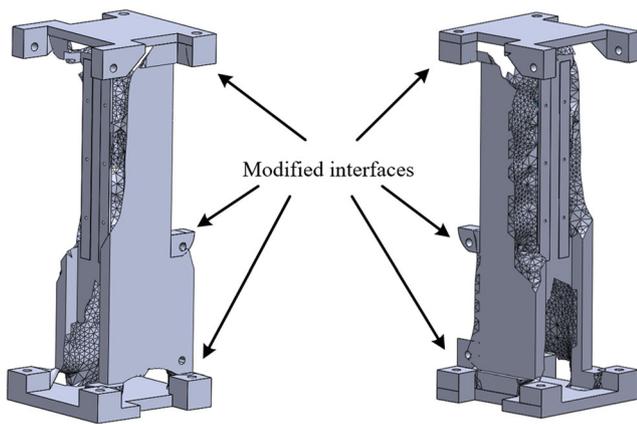
**Fig. 19** Modifying the interfaces to maintain the original interface design

to simulate the most common loading condition, the force's magnitudes are equal, and the foot of vertical arm is fixed to the ground. The gravity is not shown in Fig. 17a but considered during optimization. The gray part is reserved as a nondesign domain for maintaining the interface structure that will not be optimized. The optimization result is shown in Fig. 17b. The first 6 mode frequencies of the optimized inverted "L" shape functional arm range from 15.00 to 83.29 Hz, which achieves stagger frequency to milling and turning. Therefore, the resonance problem is solved through structure optimization. Actually, the optimized structure can be divided into two similar parts, which obeys the proposed design philosophy, as shown in Fig. 18. In addition, the interfaces of the optimized functional arm are modified to maintain the original interface design, as shown in Fig. 19. Moreover, the mass is reduced by 64.88% in the meantime, which will reduce material cost.

# 6 Case study with functions implementation

Milling and turning are the two typical machining functions of machine tools, which are chosen to show the applications of the proposed design philosophy. Based on the three-main-module structure, the core process of function implementation is components selection or design. Therefore, the KK series of single-axis robot from Hiwin Technologies Corp. are selected as movement components executing linear motion, as presented in Table 2. Next, milling/turning spindles with tools are installed on the selected KK series robot to attain the corresponding functions. Moreover, different parts/part features machined by the example RMT are analyzed in this case study.

## 6.1 Milling implementation

The plane and slot that are the two most common part features can be milled using milling machine tools. Generally, disc-mill cutter and shank cutter are used to machine plane and slot separately. There is an exception; shank cutter can be used to mill oblique plane. The two types of milling tools selected and an example part with special features (two type planes and two type slots) are presented in Table 3.

To complete the machine tasks of the example part, an RMT with milling function is implemented, as shown in Fig. 20. Seen from Fig. 20, one regular functional arm with one shank cutter and one inverted "L" shape functional arm with one disc-mill cuter and one shank cutter are installed on the base. The regular functional arm is used to machine the right oblique plane. The two functional arms of the inverted "L" shape functional arm are used to machine the left plane and the top slots respectively. First, the left plane and top through-slot can be milled simultaneously, during which the sliding blocks of the KK86 robot installed on workstation/ inverted "L" shape functional arm (left functional arm and top functional arm) move in their own tracks (x-axis direction, z-axis direction, y-axis direction respectively). Next, the KK86 robot and KK60 robot installed on the right functional arm work together (move in z-axis and y-axis respectively) to mill the right oblique plane. Finally, without changing the part setup, the KK60 robot with shank cutter and the KK86 robot of top functional arm work with the KK60 robot of the workstation

**Table 2** Selected KK series single-axis robots

| Model | Width | Rail length | Motor | Image | Installed on |
|-------|-------|-------------|-------|-------|--------------|
| KK86 | 86 mm | 340 mm | AC400 | | Functional arm, workstation |
| KK60 | 60 mm | 200 mm | AC100 | | KK86 on functional arm |
| KK60 | 60 mm | 150 mm | AC100 | | KK86 on workstation |

**Table 3** Milling tools and example part

| Disc-mill cuter | Shank cutter | Part 1 |
|---|---|---|

(moving in *y*-axis, *z*-axis, and x-axis respectively) to mill the top blind-slot.

## 6.2 Turning implementation

The turning function is usually used to machine the rotary part including turning end surface and turning rotation surface. This case provides three turning configurations of the proposed RMT to machine three different rotary parts, as listed in Table 4. The first part (part 2) is a regular type with normal diameter and normal length. The second part (part 3) is a lengthy type with normal diameter and long length. The third part (part 4) is a lathy type with small diameter and long length. When turning the regular part, the spindle installed on single-axis robot (KK60-200) of the functional arm is used to hold and rotate the part and the turning rest installed on the single-axis robot (KK60-150) of the workstation holds the turning tool. The end surface and rotary surface of the regular part can be machined by changing the installation direction of the turning tool, as shown in Fig. 21a. When turning the lengthy part, two spindles are used to hold and rotate the part, as shown in Fig. 21b. The first spindle is installed on the left functional arm, and the second spindle is installed on the right functional arm. The turning tool setting is the same as the regular part. When turning the lathy part, the spindle installed on the top functional arm and the holder installed on the

workstation are used to hold and rotate the part, and the turning tool is installed on the left functional arm to turning the part, as shown in Fig. 21c.

## 6.3 Reconfiguration process among multi-part families

As mentioned previously, the three-main-module design structure with autonomous modules and decoupled standard physical interfaces have the flexibility to prepare the main modules of new configuration suitably, which decreases the difficulty of main module installation and shortens the ramp-up time [48], which is a process of "Plug & Produce" realization. An example is given to show the reconfiguration process of the proposed RMT with specific functions, as shown in Fig. 22. When reconfiguring the proposed RMT from milling configuration to turning configuration, the turning functional arm and workstation are prepared first. The turning components installed on the functional arm and workstation are selected. These components are installed to update the functions of the corresponding functional arm and workstation. The work states of the new functional arm and workstation are tested on the test platform (test 1). Second, the main modules with milling function are uninstalled from the milling RMT. Third, the new main modules with turning function are installed to complete the reconfiguration. Finally, test 2 is executed to ensure the performance of the new RMT and ramp up the capacity. Compared with the lathe-mill RMT of Aguilar et al. [32] with only one turning configuration and one milling configuration, the turning–milling conversions (reconfiguration) of the proposed RMT are a many-to-many process with multiple configurations. As to main module reusability, the uninstalled main modules can be
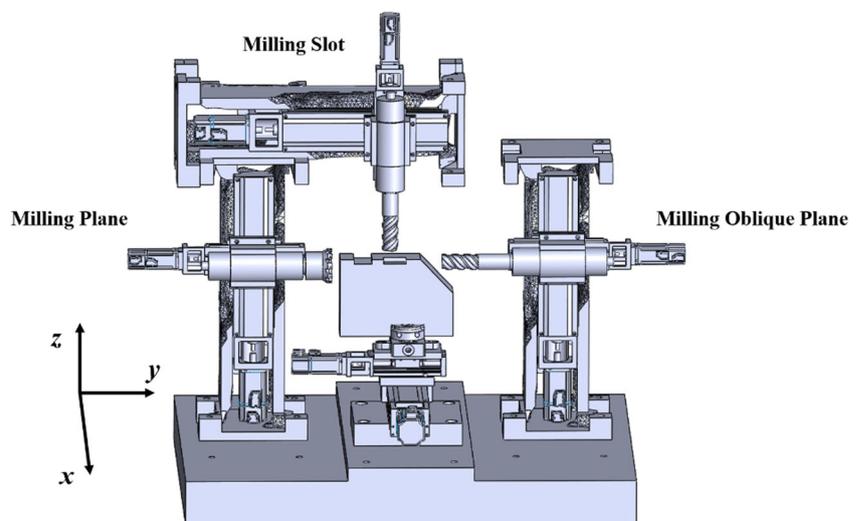
**Fig. 20** Milling RMT

**Table 4**   Three examples turning part

| Part 2 (Regular) | Part 3 (Lengthy) | Part 4 (Lathy) |
|---|---|---|
|  |  |  |



(a)                                                            (b)                                                            (c)
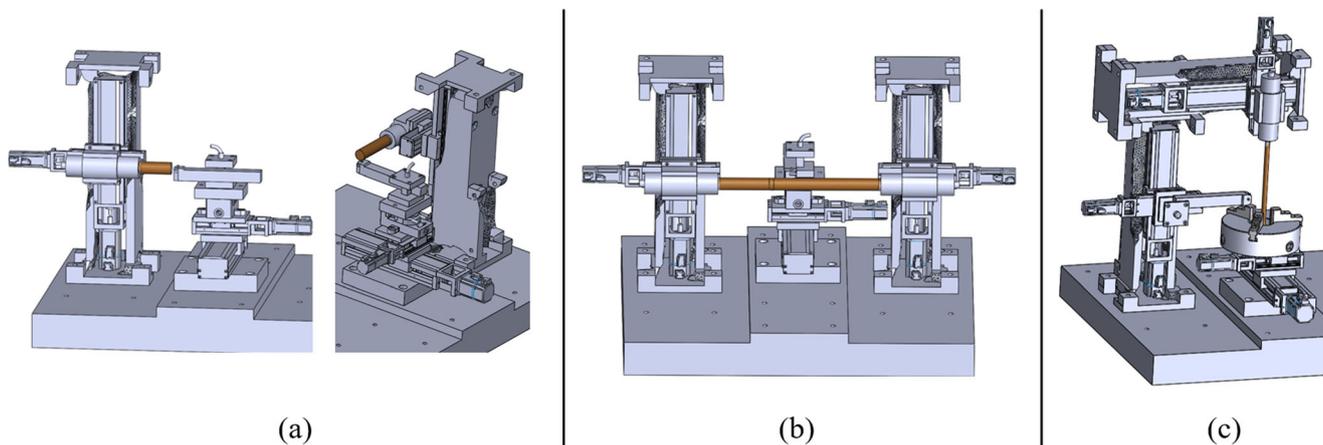
**Fig. 21**   Turning RMTs

reused to construct new main modules by deleting/adding/replacing components.

Given that the machining features of the example parts listed in Tables 3 and 4 are notably different, these parts can be divided into two part families, i.e., part family 1 = {part 1}, part family 2 = {part 2, part 3, part 4}. Assuming that the manufacturer needs to handle part family 1 first, the process sequence of part 1 in part family 1 (the only part) is {milling top slot, milling left plane, milling right oblique plane}. Two RMTs are adopted to execute this process sequence, as shown in Fig. 23. Taking advantage of the inverted "L" shape functional arm, milling top slot and left plane can be completed in

the same RMT, as shown in Fig. 23a, followed by milling right oblique plane to avoid processes concentrated, as shown in Fig. 23b. After completing the production task of part family 1, these two RMTs can be reconfigured to meet the demand of part family 2. The process sequences of the three parts in part family 2 are {turning end surface, turning outer cylinder}, {turning outer cylinder}, and {turning outer cylinder} respectively. Actually, the two RMTs in Fig. 23 can be reconfigured to produce the three parts in part family 2 owing to its high flexibility. Without loss of generality, for example, according to the reconfiguration process of Fig. 22, the RMT in Fig. 23(a) is reconfigured to produce part 2 in part family 2; as shown
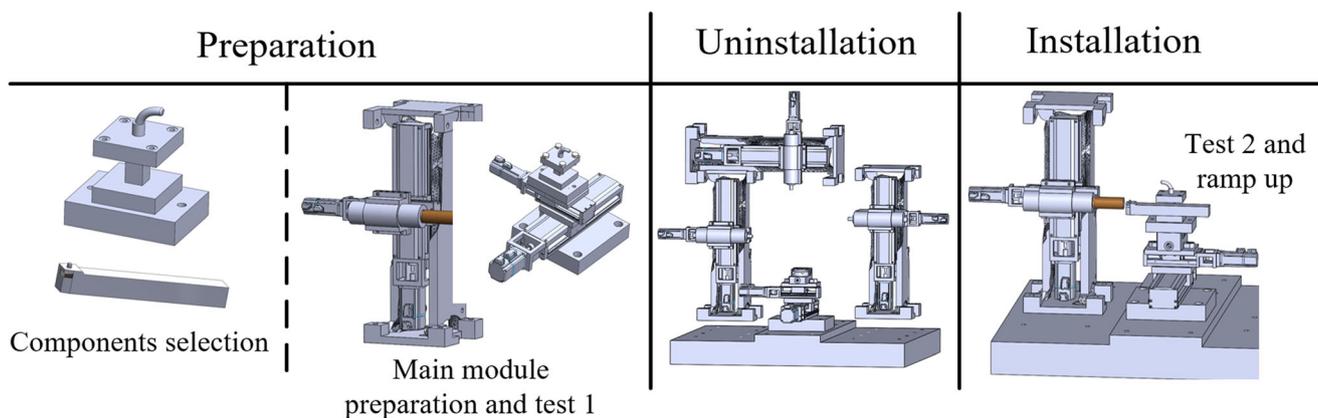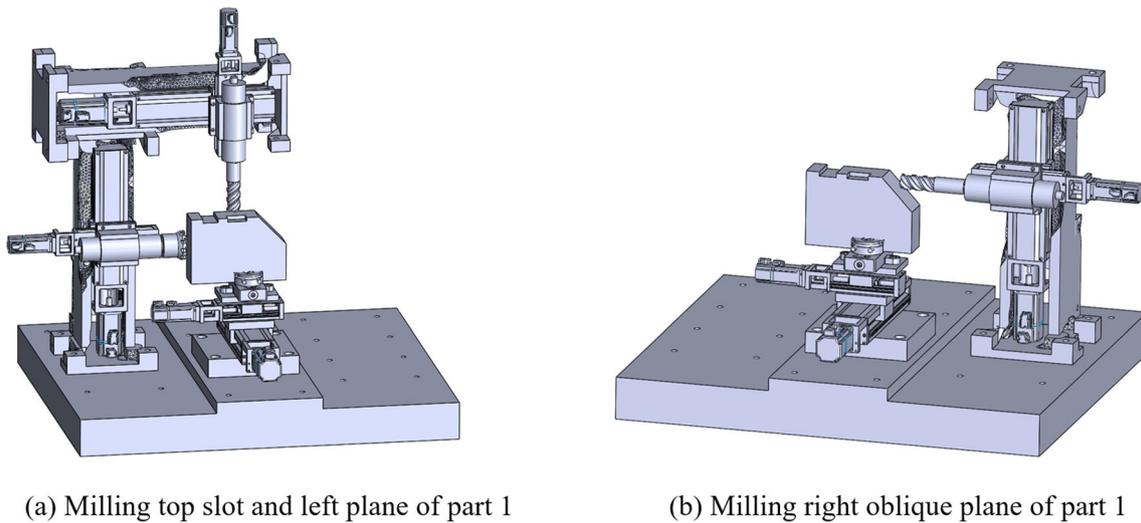


| Preparation | | Uninstallation | Installation |
|---|---|---|---|

Components selection

Main module preparation and test 1

Test 2 and ramp up

**Fig. 22**   Turning-milling conversion process

(a) Milling top slot and left plane of part 1          (b) Milling right oblique plane of part 1

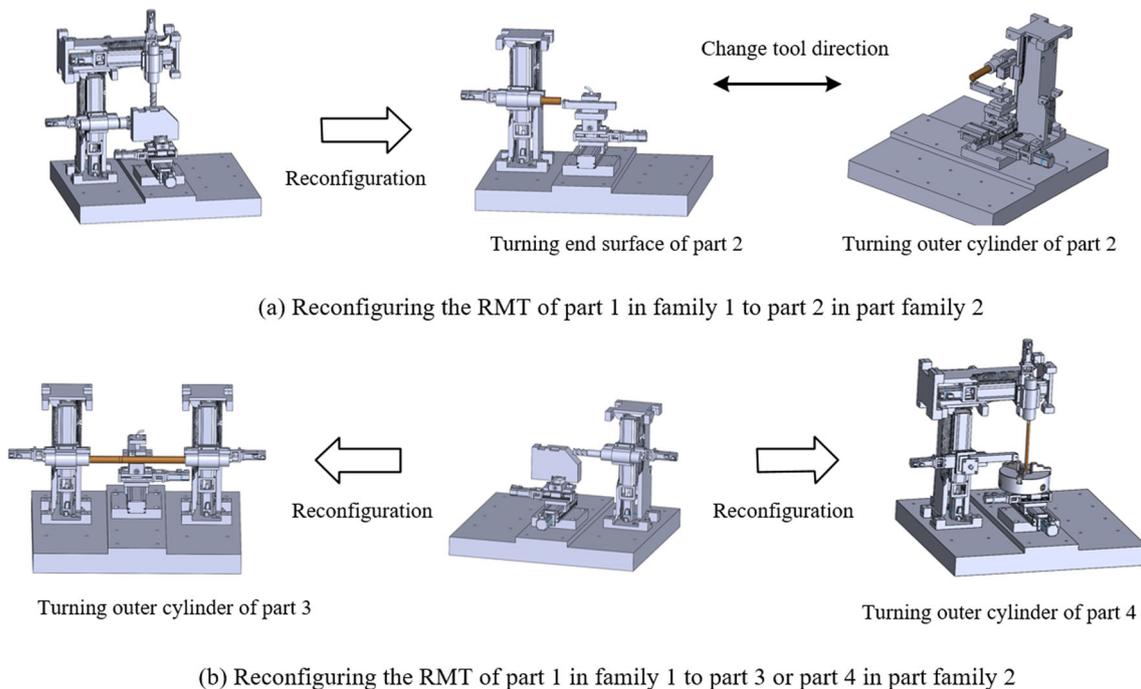**Fig. 23** RMTs for producing part family 1

in Fig. 24a, the RMT in Fig. 23b is reconfigured to produce part 3 or part 4 in part family 2. Furthermore, the turning end surface and turning outer cylinder of part 2 can be completed in the same configuration by changing its tools direction directly, as shown in Fig. 24a.

## 7 Conclusions

RMTs are the core facility of RMSs, and the structure design of an RMT is the fundamental step in the implementation of an

RMS. The idea of designing an RMT around a specific part family is an expedient before the development of reconfigurable technology (module, interface, and other parts) reaching perfection. Inspired by "Plug & Produce" architecture, more attention is paid to the module and interface, and the design philosophy of an RMT for reconfigurability is proposed first. The idea of designing for multi-part families can slip the leash of design around a specific part family, which intends to serve more one part families.

A two-step design method is proposed based on the proposed design philosophy, in which the RMT can be



Change tool direction

Reconfiguration

Turning end surface of part 2          Turning outer cylinder of part 2

(a) Reconfiguring the RMT of part 1 in family 1 to part 2 in part family 2



Reconfiguration          Reconfiguration

Turning outer cylinder of part 3          Turning outer cylinder of part 4

(b) Reconfiguring the RMT of part 1 in family 1 to part 3 or part 4 in part family 2

**Fig. 24** RMTs for producing part family 2 reconfigured from RMTs of part family 1

customized to various part families if needed based on the standardized three-main-module structure. Then, a prototype of an RMT with abundant configurations illustrates the design philosophy. The autonomous main modules and standardly decoupled physical interfaces are developed for "Plug & Produce," which can reconfigure the RMT quickly and easily (decreasing the complexity of reconfiguration). Moreover, the special column structure of the functional arm in the prototype increases the reusability of modules, and the inverted "L" shape functional arm is the best illustration. The reconfigurability analysis shows the full implementation of the proposed design principles. The performance is improved by applying the topology optimization on the most crucial main module, that is, the functional arm. The case study implements milling and turning functions based on the proposed RMT, which shows the flexibility of the proposed RMT. Various parts can be machined in the example milling and turning configurations. The reconfiguration process between part family 1 and part family 2 demonstrates that the proposed RMT prototype can decrease the reconfiguration complexity. Above all, the proposed design philosophy and the RMT prototype solve the problems faced in the existing studies well. Future works may focus on the manufacturability and the control system of the proposed RMT prototype.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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