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Design of Reconfigurable Planar Micro-Positioning Stages Based on Function Modules

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ABSTRACT Micro-positioning stages, which are capable to meet the emerging industrial trend for performing various kinds of micro-manipulation and micro-assembly tasks are the crucial tools to miniaturize the products under ultra-high precision. The current main practice is to specifically tailor a monolithic positioning stage design for one kind of micro-manipulation application. However, the design and fabrication of such a specific flexure-based micro-positioning stage are expensive in both the time and financial investment. In order to increase the flexibility and functionality of micro-positioning stages, this paper proposes a novel reconfigurable planar micro-positioning stages platform based on different function modules. A functional model-based approach is developed to divide one micro-positioning stage into a set of functionally independent sub-models, which allows flexible composition resulting in an adjustable new stage. The robustness of the proposed platform is demonstrated using some typical micro-positioning stages benchmarking cases. The effectiveness of assembly using flexible function modules is verified to show the benefits of the proposed design platform for reconfigurable micro-positioning stages.

INDEX TERMS Reconfigurable micro-positioning stage, function modules, modular, low cost.

I. INTRODUCTION

Flexure-based micro-positioning stages, integrated with piezoelectric actuator (PEA), have been extensively utilized in applications ranging from cell manipulation, fiber alignment to non-circular precision manufacturing due to their remarkable performances [1]–[6]. A flexure-based mechanism is a flexible structure that delivers the desired motion and force by undergoing elastic deformation which possesses the advantages of no wear, no friction, no need for lubrication and maintenance [7]–[9]. As a result, flexure-based mechanisms have been developed rapidly for exploring their diverse prevalent applications in medical instruments and precise mechanical devices [10]–[13].

With growing demands for micro-positioning stages, performance requirements and cost reduction are emergency issues should be addressed. Currently, the process to design and manufacture a compliant micro-positioning stage requires high investment in time and cost. Meanwhile, monolithic micro-positioning stages are tailored to specific tasks with constant performances, working range, and overall size [14], [15]. When one of the set of flexure hinges is out-off order or the requirements of micro-positioning stage are to be modified, another new monolithic micro-positioning stage need to be fabricated for replacement or redesigned to meet the updated requirement, respectively. Such scenario cost non-negligible waste of resources. Therefore, the performance requirements as well as economic factors must be taken into account simultaneously for designing micro-positioning stages.

The main purpose of this paper is to present a new concept of reconfigurable planar micro-positioning stage which allows to rapidly design or to modify only a small part of the whole stage to change its performance. Reconfigurable micro-positioning stages assembled by different function modules can better improve the flexibility and functionality of micro-positioning stages compared with monolithic stages. This approach can be compared to Lego robotics, which are both choosing finite number of bricks to create the desired machine [16], [17]. For Lego robotics, all provided bricks are required to assemble the desired machine. However, for reconfigurable micro-positioning stages, the pre-given modules are optional, which depends on the user's requirement. Overall, the configuration of reconfigurable micro-positioning stages can be modified to meet different performance requirements (functional and non-functional), such as directional stiffness, dynamic performance, motion range, resolution, light weight and size of structure by changing modules, also the self-repair ability can be realized in this way [18]. The rest of the paper is arranged as follows: Section II answers why we need reconfigurable micro-positioning stages. Design considerations and benefits of reconfigurable micro-positioning stages are introduced. Section III solves how to design function modules. Modules definition and some typical function modules are presented in this section. Section IV mainly focuses on how to design reconfigurable micro-positioning stages. A framework for designing reconfigurable micro-positioning stages is proposed. Referring to the proposed framework, reconfigurable micro-positioning stages are designed for case studies. In addition, simulations are conducted to validate their performance flexibilities in section V. Finally, conclusions and future works are made in section VI.

II. RESEARCH MOTIVATIONS

Modularisation is the method of dividing a product into some necessary and useful number of parts or sub-parts, which can provide the ability to offer different products easily by using different combinations of these modules [19], [20]. In recent years, modular robots have increasingly been proposed as a means to develop reconfigurable and self-repairable robotic system. A modular product can be reconfigured in a limited time, without much more complexity and without buying or manufacturing new modules. So the response in change of user demands or other changes in the system will be faster than monolithic structure positioning stage. To clarify this point, performances specification of the flexure-based micro-positioning stages and benefits of reconfigurable micro-positioning stages are introduced in this section firstly.

A. PERFORMANCES SPECIFICATION

Performance requirements for a compliant micro-positioning stage can be divided into two aspects: functional (resolution, stoke, bandwidth and load capacity) and non-functional (weight and dimensional scale) requirements.

The definition of resolution (R_r) is that the smallest incremental change can be achieved in the desired output of the system. Achieving a fine resolution level is a critical requirement for most precision applications. For a closed-loop micro-positioning system, R_r is mainly limited by resolution of actuators. Generally, PEAs are chose to actuate micro-positioning stages due to their high resolution, large output force and fast response [21]–[23].

Stroke (S) of a micro-positioning stage is defined as the largest motion range that can be achieved in the desired output. It is an important index to measure the performance of micro-positioning stage which determines the workspace of the positioning system. The stroke of the micro-positioning system can be improved by using amplification mechanisms or large stroke actuators. For practical applications, amplification mechanisms such as lever amplification mechanism, bridge type amplification mechanism and Scott-Russell mechanism with amplification ratio K are commonly adopted to enlarge the stroke of the PEA [24]–[28]. However, for piezo-actuated micro-positioning stages, R_r and S are two contradict performances. For example, the output displacement of the end-effector is amplified to $K{\cdot}S$ with amplification mechanism, but the resolution of the system is decreased to $K{\cdot}R_r$.

The bandwidth indicates the overall response time of the micro-positioning stage to an input signal. In scanning probe microscope application, a high bandwidth is required due to it can provide fast scanning rate [29], [30]. An appropriate controller can be designed to improve the achievable bandwidth of a system, but it is ultimately limited by the natural frequency of the physical plant. Generally, a material with high Young's modulus of elasticity(E) to density ratio(ρ) is preferred because a high E and low ρ will improve the dynamic performance of the positioning stage [31].

The load capacity is defined as the maximum force that the flexure-based mechanism can sustain without undergoing failure. The stress (S_s) subject to a given loading needs to satisfy the following condition:

$$S_s < S_{max} = \frac{S_y}{S_f} \tag{1}$$

where S_y is the yield strength of the material, S_f is the safety factor and S_{max} is the maximum sustainable stress of mechanism.

B. BENEFITS OF RECONFIGURABLE MICRO-POSITIONING STAGES

Monolithic micro-positioning stages, which mainly are fabricated in a piece of alloy metal with wire electrical discharging machining(WEDM) method, are tailored to specific tasks with fixed performances and dimensional scale [32]. If a certain flexure hinge failed to serve or working requirements are changed, a new one is need to be machined again which causing waste of unnecessary resources. However, reconfigurable micro-positioning stages can solves these problems effectively. Compared with monolithic micro-positioning stages, there are mainly three potential benefits for modular micro-positioning stages.

- Facilitated micro-positioning stages design. Using of modules means that a large number of micro-positioning stages can be created by using conceptual modules easily. Monolithic micro-positioning stages fabricated by WEDM or 3D printing method cannot reconfigure their structure to meet other performance requirements unless making a new one. However, reconfigurable micro-positioning stages can response the changing of working environment and task requirements in a limited time, by modifying modules to change their stiffness, dynamic performance, stroke, resolution or dimensional size accordingly.

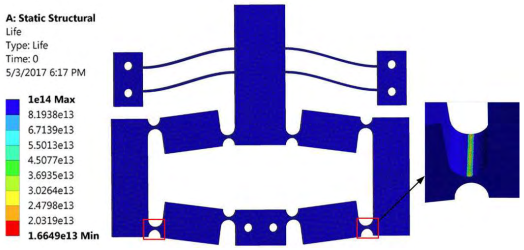


FIGURE 1. Fatigue simulation of a monolithic component.

- Eased upgrading and repairing process. Since a micro-positioning stage can be decomposed into several function modules, only certain modules need to be replaced or updated when upgrading is required. From practical experience, flexure hinges at different locations have different fatigue life [33]. A fatigue simulation of the monolithic structure is depicted in Fig.1 based on the S-N curve of aluminum alloy (**A.A**) $7075 - T6$ material [34]. Referring to the simulation result, flexure hinges located in bridge type amplification mechanism will break first under the 15 μm input displacement. In this case, the loading ratio R is set as 0 for the reason of output characteristics of the PEA. It means that some flexure hinges will break first and result in the failure of whole system when an input displacement was applied to the monolithic micro-positioning stage. However, reconfigurable micro positioning stages can solve this problem effectively, due to their self-repair ability can be realized by replacing the broken module with a new one.
- Reduced manufacturing process time. Since monolithic micro-positioning stages are mainly fabricated by WEDM which is a time-costed process. However, for reconfigurable micro-positioning stages, each module can be manufactured simultaneously, it can reduce the manufacturing process time dramatically. In addition, the volume production of standardized modules also decreases the cost.

III. MODULES DEFINITION

The reconfigurable micro-positioning stage can be regarded as an end-effector connected with several kinematic chains. Each chain is composed by function modules integrated with standardization interfaces. The next step is how to design function modules integrated with interfaces. In this paper, interfaces are elements whose function is to link the output of the module to the end-effector, which are integrated into each modules.

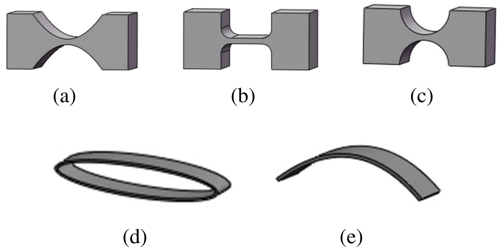


FIGURE 2. Primitive flexures of lumped and distributed compliance: (a) parabolic, (b) corner filet, (c) circular, (d) ellipse, (e) bending-beam.

The minimum flexure element of complaint mechanisms is a flexure region which transfer force and motion through elastic deformation, thus canceled friction, noise and backlash. Normally the motion type and range of flexure hinges are determined by geometrical characteristics of the notch type. Basic lumped compliance and distributed compliance flexures are shown in Fig.2(a)-(c) and Fig.2(d)-(e) respectively. While we do not choose these flexure hinges as basic modules to construct the reconfigurable mechanism for the reason of limited motion range and generated assembling errors. Therefore, compound flexures which composed by two or more primitive flexures are presented for the ability of providing large translational or rotational motion, as shown in Fig.3. However, these flexures are too complex to standardization.

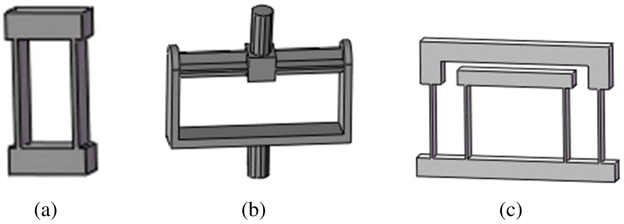


FIGURE 3. Complex flexural joints: (a) four-bar translational joint, (b) rotational joint, (c) compound translational joint.

A. THEORETICAL ASPECTS

During the literature review, the structure of micro-positioning stages introduced in previous literatures have some common characteristics [35]–[39]. Namely, different parts in micro-positioning stages have a specific function. Here, the totally decoupled two-DoF (Degree of Freedom) micro-positioning stage depicted in Fig.4 is taken as an example to illustrate these characteristics. This symmetrical micro-positioning stage is composed of four identical chains. Each chain can be divided into four main components (A, B, C and D) for their different functions.

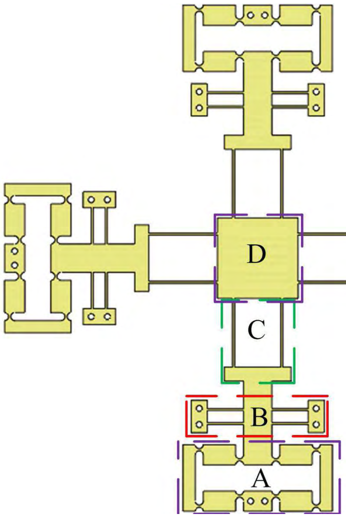


FIGURE 4. A totally decoupled two-DoF monolithic micro-positioning stage.

A: amplifier mechanism - to amplify the limited stroke of PEA; *B*: self-guiding mechanism - to avoid the parasitic motion; *C*: parallelogram beam flexure - to provide large translational motion; *D*: end-effector - to support/manipulate the object. From this point, the micro-positioning stage can be regarded as that assembled by different function modules.

Function modules implement technical functions independently or in combination with other modules, which are the basic elements to assemble reconfigurable micro-positioning stages. Therefore, to design standardized modules is a key problem should be addressed in designing reconfigurable micro-positioning stages. In this paper, function modules such as amplification module, self-guiding module, parallelogram beam flexure module and end-effector module are introduced in detail. Theoretically, these modules should be independent, standardized and interchangeable, hence it can interact and co-operate with one another to change from one configuration to another manually. As a result, the development process of a reconfigurable micro-positioning stage is significantly shortened compared with traditional design process.

B. AMPLIFICATION MODULES

For the purpose of compensating the limited stroke of PEA, amplification mechanisms are often utilized in micro-positioning stages. The typical secondary lever amplification mechanism and bridge type amplification mechanism are shown in Fig.5. Due to advantages of easy for calculation and compactness structure, these amplification mechanisms have been widely adopted in applications where large stroke are required [40], [41]. The amplification ratio of the secondary lever amplification mechanism and bridge type amplification mechanism can be derived by equation (2) and (3), respectively. The structural parameters in the equations can be referred in Fig.5 and ΔL_1 is the displacement of link *AB* along the driven direction.

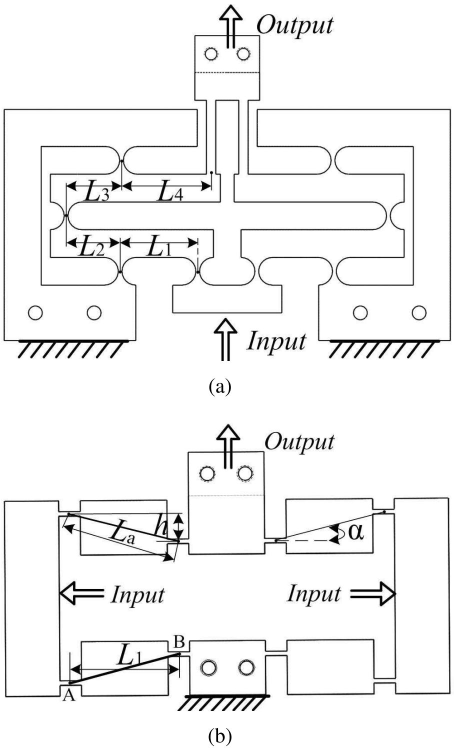


FIGURE 5. Typical amplification mechanisms: (a) secondary lever amplification mechanism, (b) bridge type amplification mechanism.

$$R_{amp} = \frac{L_4.L_2}{L_3.L_1} \tag{2}$$

$$R_{amp} = \frac{\sqrt{L_a^2.\sin^2\alpha - 2L_a.\Delta L_1.\cos\alpha - \Delta L_1^2} + L_a.\sin\alpha}{\Delta L_1} \tag{3}$$

C. SELF-GUIDING MODULES

One of the most significant performance attributes of a micro-positioning stage is the ability to move the end-effector with only the specified direction, *i.e.*, all parasitic motions were fully eliminated. Utilizing self-guiding mechanism on parallel or serial micro-positioning stage is an effective method for this issue [42]. As shown in Fig.6(a), it is a typical double-blade self-guiding mechanism, the stiffness K_1 along the driven direction can be calculated by following equation:

$$K_1 = \frac{4Ebt^3}{L_b^3} \tag{4}$$

While the high stiffness of the self-guiding mechanism cause the decrease of effective output displacement of the micro-positioning stage. Referring to the equation (4), lower stiffness can be obtained by using a narrower and longer beam flexure. However, the compactness requirement constraint the length of the flexure beam and the thickness of the flexure hinge is restricted by the manufacturing tolerance [43]. Hence, the compound double parallelogram

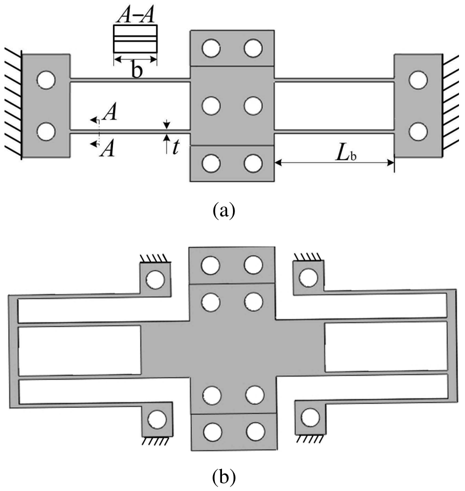


FIGURE 6. Self-guiding mechanisms: (a) double-blade self-guiding mechanism, (b) compound double parallelogram.

self-guiding module with relative low stiffness and compact structure is adopted to replace double-blade mechanism as shown in Fig.6(b). The stiffness of this module can be calculated by:

$$K_2 = \frac{2Ebt^3}{L_b^3} \tag{5}$$

where E denotes the modulus of the material, b is width of the beam flexure, L_b and t is the length and thickness of beam flexure respectively.

D. BEAM MODULES

The beam flexure can be regarded as a prismatic joint or two translational joints which plays a role of transferring motion in micro-positioning stages. The distributed compliance beam modules, as shown in Fig.7(a), possess the benefits of higher flexibility, less vulnerable to stress concentrations. However, variation of position of the rotation center could imply loss of precision in case apply kinematic synthesis to the pseudo-rigid-body (PRB) model. For the lumped compliance beam modules, as shown in Fig.7(b), the position of rotation center can be found analytically, but the motion relies on the deflections of the flexures are considerable small [44].

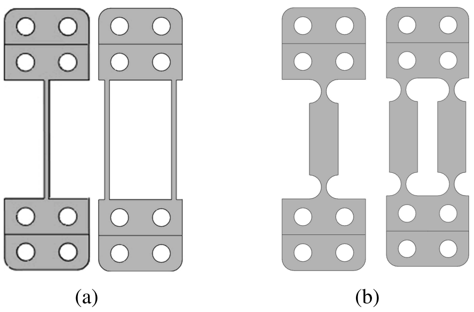


FIGURE 7. Beam flexures: (a) distributed compliance beam flexures, (b) lumped compliance beam flexures.

E. END-EFFECTOR MODULES

End-effector plays a role of supporting loads or implementing tasks in micro-positioning stages. As shown in Fig.8, the end-effector can realize six-DoF motion under unconstraint conditions in theory. Six kinematics chains can be linked to the end-effector independently via interfaces. In addition, the geometrical shape of end-effector determines the configuration of the positioning stage. Two typical end-effector modules utilizing for planar micro-positioning stages are presented in Fig.9. Referring to presented figures, the end-effector linked by four or six kinematic chains can obtain different motion types.

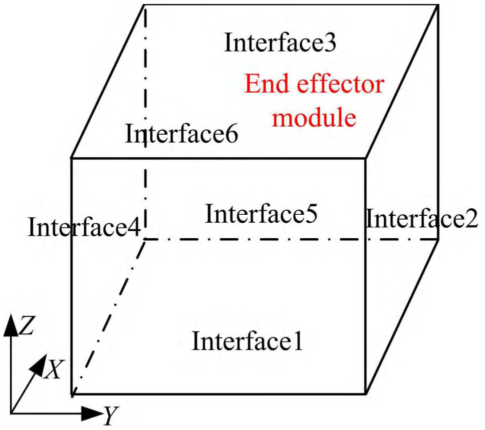


FIGURE 8. Concept of modules connection.

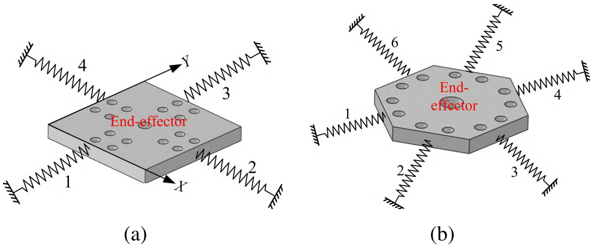


FIGURE 9. End-effector modules: (a) square shape end-effector, (b) hexagon shape end-effector.

IV. FRAMEWORK FOR DESIGNING RECONFIGURABLE MICRO-POSITIONING STAGES

The design of a reconfigurable micro-positioning stage has some common characteristics of design general mechanism. As shown in Fig.10, it is an iterative design cycle which can be decomposed into two stages and four steps. At stage level, the conceptual design phase provides solutions considering only the functional aspects. While the detailed design phase refines the concept to comply with requirements that are non-functional related. The purpose of each design steps are listed as following: performance requirements - to define

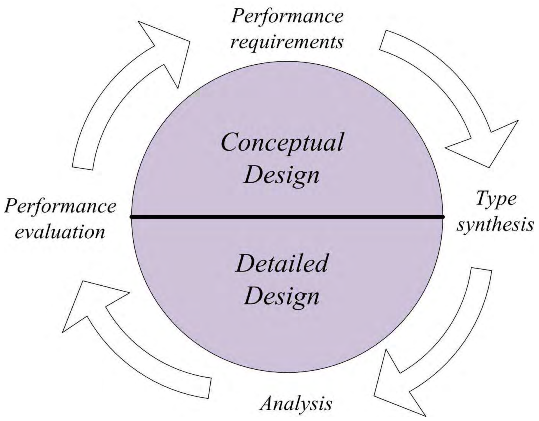


FIGURE 10. **Iterative design framework for designing general mechanism.**

functional and non-functional requirements referring to a specific application; type synthesis - to find all types of mechanism with a specific behavior; analysis - to compare the simulation behavior with the desired behavior defined by the requirements; performance evaluation - to evaluate results and revise the requirements if needed.

Referring to the iterative design framework and characteristics of modular design methodology, the complete design process framework for reconfigurable micro-positioning stage is depicted in Fig.11. As a summary for this whole framework, reconfigurable micro positioning stages can be created by asking following questions:

- What are the design objectives?
- What are the functional and non-functional requirements for the design objective?
- How to arrange the structure of the objective?
- Did the evaluation results can meet the expected requirements?

By this way, modular products (micro-positioning stages and micro-grippers) can be generated quickly with low cost.

V. CASE STUDIES

In this section, case studies are presented to validate benefits of reconfigurable micro-positioning stages. The research on totally decoupled two-DoF micro-positioning stages is a hot issue, therefore some modules with specific functions to construct two-DoF micro-positioning stages were designed, including two end-effectors, an amplification mechanism, two self-guiding mechanisms, two beam flexures and a ground block which are listed in Fig.12. Ideally, these modules have standardization interfaces which can connect or co-operate with one another to assemble the desired micro-positioning stage.

The use of function modules increased the variety of micro-positioning stages can be validated by following two aspects: products variety and performances variety.

- Products variety. Products variety means that many kinds of modular products can be generated by using presented modules. As shown in Fig.13, some selected micro-positioning stages (one-DoF, two-DoF, three-DoF) and a micro-gripper are assembled with designed modules.
- Performances variety. For a certain micro-positioning stage or micro-gripper, the performance (stroke, motion range and natural frequency) can be changed by reconfiguring structure or using different modules fabricated by different materials.

Referring to the designed function modules, some selected two-DoF decoupled micro-positioning stages are listed in Fig.14. A modular micro-positioning stage can reconfigure its structure to another form by adding or replacing the function modules. For example, V_{i1} can be reconfigured to V_{i2} by partially stacked modules for the purpose of decreasing the dimensional scale; V_{i1} also can be reconfigured to V_{i3} for the purpose of obtaining a large travel range by adding a bridge type amplification module. Furthermore, V_{1i} can be transformed into V_{2i} or V_{3i} by replacing the parallelogram flexure module or flexure-guiding module for different purposes. Here $i = 1, 2, 3$.

To further validate benefits of the reconfigurable micro-positioning stage, a comparative study is conducted in this section. The monolithic two-DoF decoupled micro-positioning stage and its directional stiffness simulation are presented in Fig.15. This micro-positioning stage has the same key dimensional parameters with reconfigurable positioning stage. In this case, **A.A** 7075-T6 is adopted to fabricate these modules and the material properties are listed in Tab. 1. By the way, other low density material like Acrylonitrile Butadiene Styrene(**ABS**) can be utilized to fabricate the ground block module for the purpose of reducing the weight of the positioning stage. During the simulation process, all stages are subjected to the same constraint conditions and the solid type Quad.4 with 182 node was chosen element to mesh the positioning stage.

TABLE 1. **Material properties.**

Material parameters of **A.A** 7075-T6.			
E	σ	υ	ρ
72GPa	570MPa	0.33	$2.81\times10^3 Kg/m^3$

To further validate the performance varieties including, directional stiffness, dimensional size, motion range and natural frequency of reconfigurable micro positioning stages, simulations based on FEA method are conducted in detail.

Firstly, the stiffness and dynamic performances of a monolithic micro-positioning stage is a constant value when prototype fabrication was finished. As shown in Fig.15, the directional stiffness of this monolithic stage is $KV = 0.4437\text{N}/\mu\text{m}$. If stiffness changing is required, we need to machine a new micro-positioning stage. However, for reconfigurable micro-positioning stages, the stiffness can be modified by replacing a certain module. For example, the V_{11} can be reconfigured to V_{21} or V_{31} for the purpose of decreasing the directional stiffness of the micro-positioning stage. The stiffness comparison is listed in Fig.16, where the directional

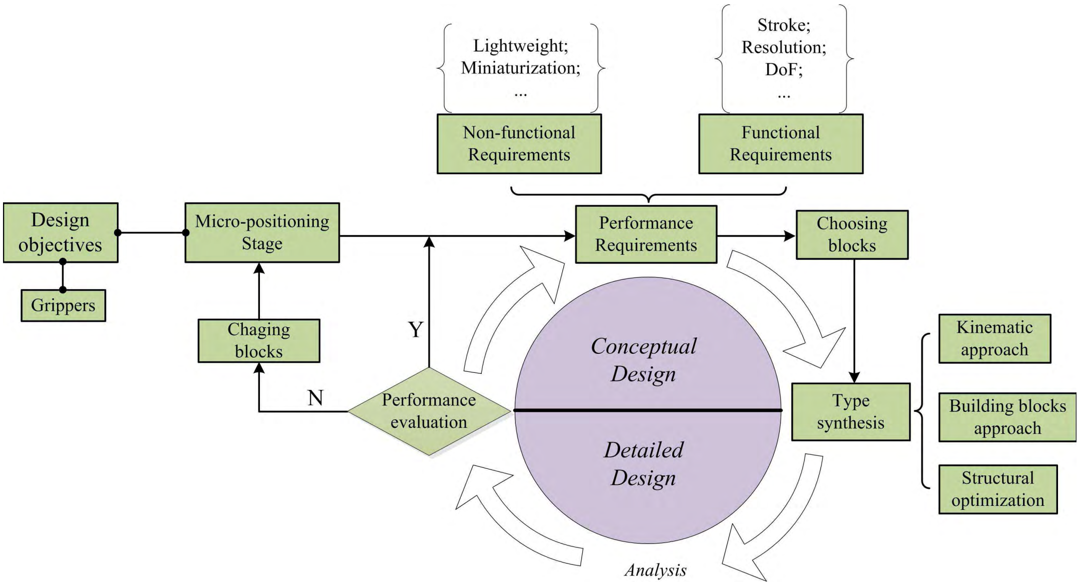


FIGURE 11. Complete design process framework.

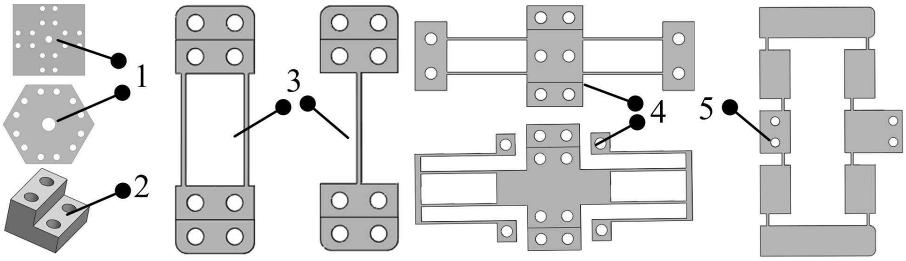


FIGURE 12. Typical modules: 1, end-effectors; 2, ground block; 3, beam flexures; 4, guiding mechanisms; 5, amplification mechanism.

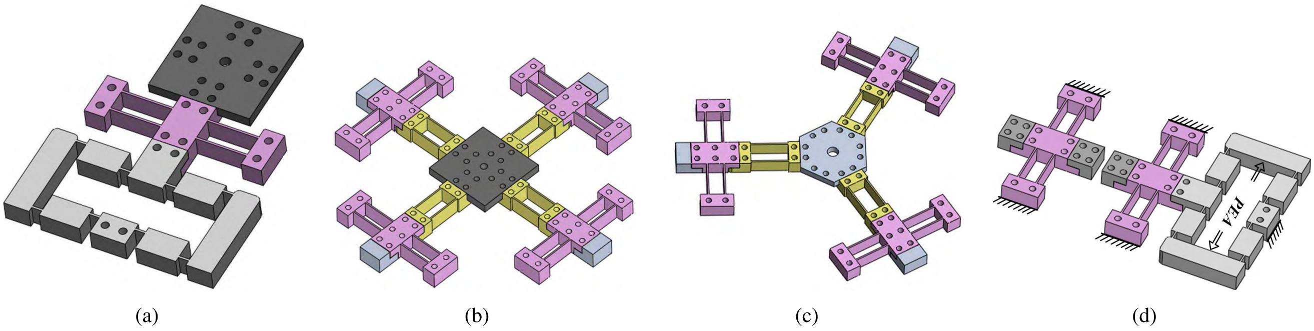


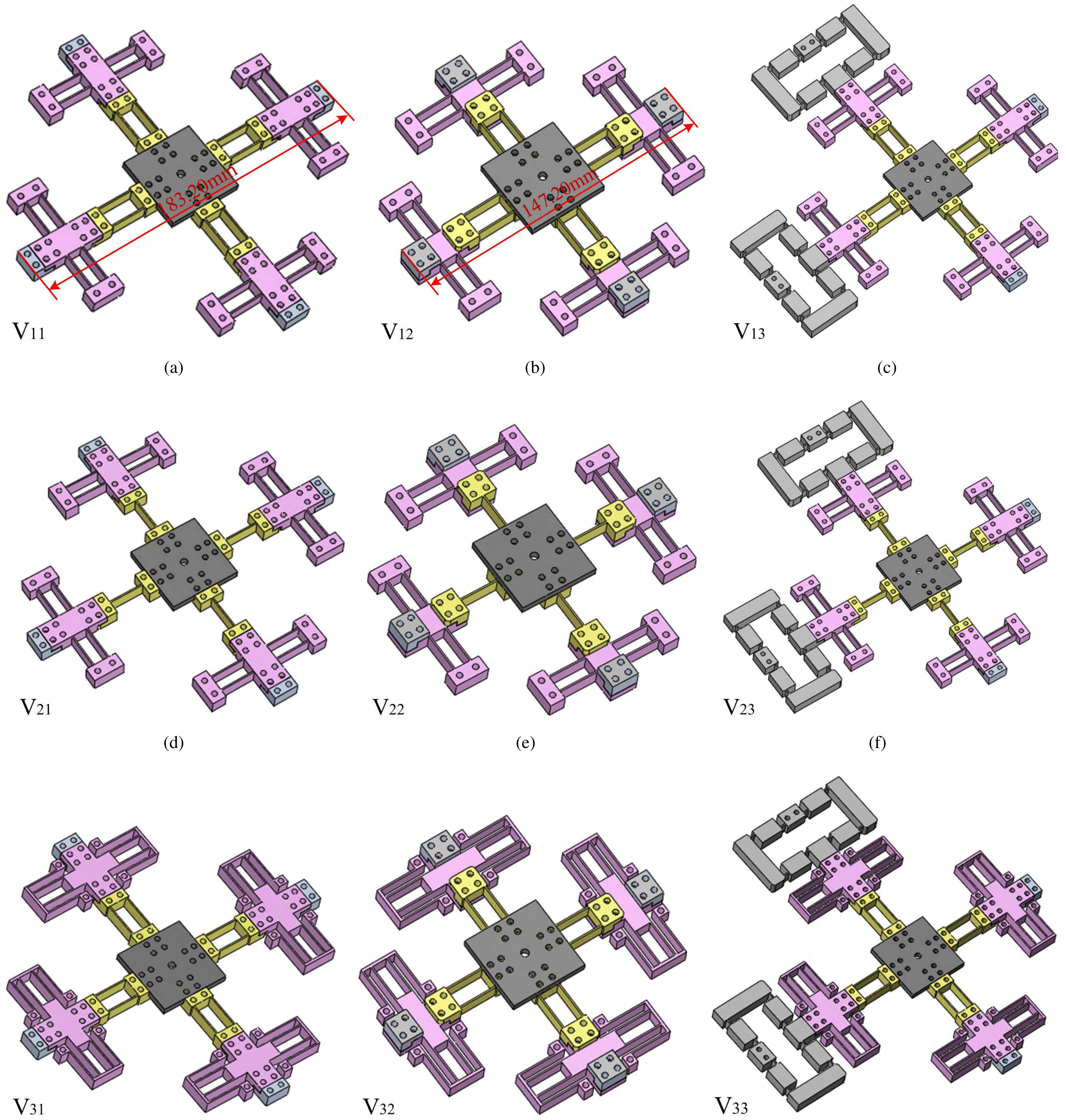
FIGURE 13. Selected modular products to validate products variety: (a) one-DoF micro-positioning stage, (b) two-DoF micro-positioning stage, (c) three-DoF micro-positioning stage, (d) micro gripper.

stiffness of V_{21}, V_{21} and V_{31} is $KV_{11} = 0.4805\text{N}/\mu\text{m}$, $KV_{21} = 0.4072\text{N}/\mu\text{m}$ and $KV_{31} = 0.3191\text{N}/\mu\text{m}$ respectively. Compared with the stiffness of positioning stage V_{11}, the stiffness of V_{21} and V_{31} decreased 15.25% and 33.59% respectively.

Secondly, dimensional size of reconfigurable micro-positioning stages can be adjusted accordingly. As shown in Fig.14, the micro-positioning stage V_{11} can be reconfigured to V_{12} for the purpose of working in a limited space. Here, we use *DA* as an index to measure the ratio of decreased size, so it can be calculated by:

$$DA = \frac{S_{V_{i1}} - S_{V_{i2}}}{S_{V_{i1}}} \tag{6}$$

Taking V_{11} and V_{12} as an example, where $S_{V_{11}} = 183.20 \times 183.20$, $S_{V_{12}} = 147.20 \times 147.20$. The *DA* is calculated as 35.44%, which means that way can decrease the dimensional size dramatically.



(a) (b) (c) (d) (e) (f) (g) (h) (i)

FIGURE 14. **Selected two-DoF modular micro-positioning stages.**

Thirdly, motion range and resolution of reconfigurable micro-positioning stages can be adjusted for different situations. For piezo-actuated micro-positioning stages, the resolution and motion range are two contradict indexes. The limited stroke of PEAs are generally compensated by amplification mechanisms, which causing the degrade of positioning stage resolution. However, reconfigurable micro-positioning stages can solve this issue effectively. For example, the V_{11} can be reconfigured to V_{13} by adding an amplifier module to enlarge motion range, vice versa V_{13} can be reconfigured to V_{11} by removing the amplifier module to enhance the resolution.

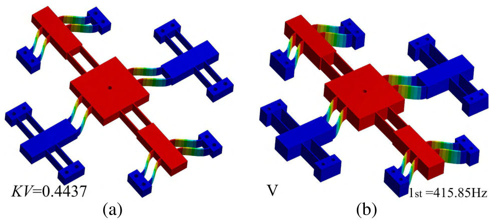


FIGURE 15. Simulations of decoupled monolithic micro-positioning stage: (a)Directional stiffness simulation, (b)First mode simulation.

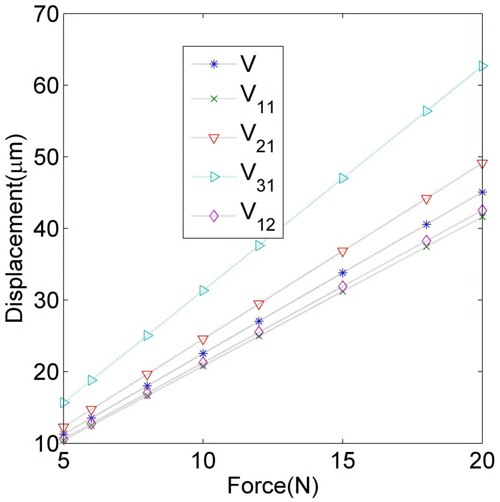


FIGURE 16. Stiffness comparison between V, V_{11}, V_{21}, V_{31} and V_{12}.

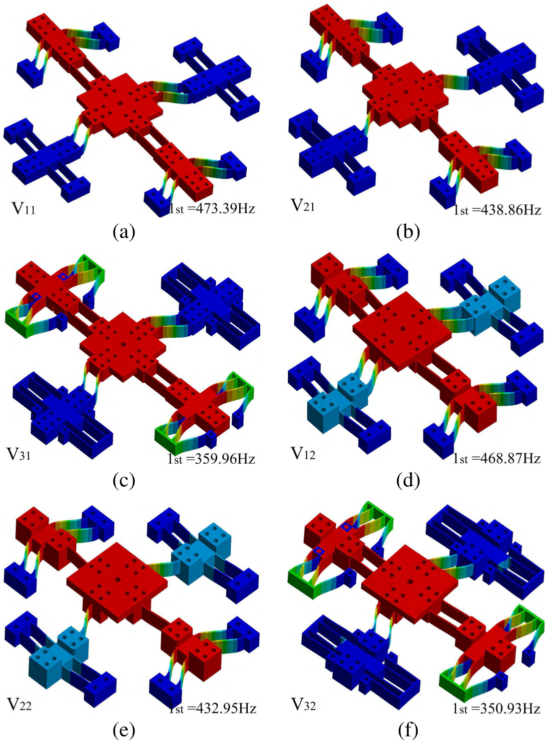


FIGURE 17. First modal shapes of reconfigurable planar micro-positioning stages: (a) The first mode of V_{11}, (b) The first mode of V_{21}, (c) The first mode of V_{31}, (d) The first mode of V_{12}, (e) The first mode of V_{22}, (f) The first mode of V_{32}.

Finally, dynamic performances of reconfigurable micro-positioning stages are validated by simulation results as shown in Fig.17. The natural frequency of micro-positioning stage can be derived by following equation:

$$f = \frac{1}{2\pi}\sqrt{\frac{K_{ds}}{M_{eff}}} \tag{7}$$

where K_{ds} and M_{eff} represent directional stiffness and effective mass of positioning stage respectively. Referring to Equ.(7), the high bandwidth can be achieved by increasing the directional stiffness or decreasing effective mass of positioning stage. Therefore, high stiffness parallelogram modules, light ground block and end-effector modules can be utilized for high frequency purpose.

VI. CONCLUSIONS AND FUTURE WORKS

A new concept and platform of reconfigurable planar micro-positioning stages is proposed in this study which allows to generate a series of tailored micro-positioning stages via adjustment of a finite number of function modules. The viability of the proposed conceptual stages are proved, as well as their capability of dramatically shortening the time to market of design new high precision positioning stage. Compared with conventional monolithic micro-positioning stages, benefits of reconfigurable micro-positioning stages are in three folders: increased varieties of positioning stages; eased upgrading and repairing process; reduced manufacturing process time. The experimental case study on a set of reconfigurable micro-positioning stages are built using the proposed design process framework to validate their flexibility and functionality. The proposed reconfigurable design solution provides a convenient way to adjust the function, effective range, and capacity of the micro-positioning stages during or after development process. Therefore, it eases the adaption to the varieties of requirements and could avoid unnecessary fabrication of stages fitting for minor changes.

The future work on this kind of reconfigurable micro-positioning stages includes designing and optimizing standardized modules so as to enhance the interchangeability of modules. In addition, the development of a library of function modules is also under our plan, which can provide the opportunity to choose the most appropriate modules adaptive to design requirements. Further more, how to avoid the misalignment, disorder mode shapes and increasing the motion accuracy are also challenges and can be regarded as future research direction. Finally, some prototype modules will be fabricated to validate the precision of proposed positioning stages.

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