Design of Flexure-based Modular Architecture Micro-positioning Stage

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Abstract As the current trend in numerous industrial domains is to miniaturise products, micro-positioning stage(MPS) capable of performing micro-manipulation and micro-assembly tasks with sub-micrometer or nanometer precision is playing an increasing important role in these fields. In addition, well performances and low cost are two emergency issues need to be addressed for widely using flexure-based MPSs. However, the design and fabrication process for MPSs at present are costly both in time and money. Especially, the designed configurations are tailored to a specific application without flexibility. Thus, the purpose of this paper is to introduce a design of precision flexure-based reconfigurable MPSs which provide better flexibility and functionality and allows to reduce the time to market significantly. To begin with, performance requirements and benefits for reconfigurable MPSs are introduced. Then, some typical modules and their functions are introduced in detail. Finally, some selective stages assembled with function modules are proposed as case studies, for the purpose of validating the benefits of reconfigurable MPSs.

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1 Introduction

Flexure-based MPSs featured with high precision and fast response received widely attention in applications ranging from cell manipulation, fiber alignment to non-circular precision manufacturing due to their remarkable performances (Liang et al. 2018 - Ding et al. 2017). To realize a sub-micrometer resolution, the use of flexure hinges is compulsory. This type of joints is usually machined monolithically by electric discharging machining(EDM) method, and takes the advantages of being without wear, lubrication and backlash (Chen et al. 2017; Du et al. 2016). Flexure-based mechanisms have been developed rapidly due to their significant benefits and the applications become increasingly prevalent in medical instruments and precise mechanical devices (Beck et al. 2018 - kota et al. 2005).

At present, flexure-based monolithic MPSs capable of implementing micro-manipulation and micro-assembly tasks are widely required as current development trend of products is miniaturization and integration. However, currently process to design and manufacture a flexure-based MPS is still costly both in time and money. Meanwhile, monolithic MPSs are tailored to specific tasks with constant performances and dimensional scale. If a certain flexure hinge is broken to serve or requirements of MPS are modified, the whole design process has to be restarted from the starting point, which consists in non-negligible waste of resources. Therefore, one should not only focus on designing a positioning stage, but should also be able to reconfigure and reuse the stage quickly according to the changed conditions. Compliant MPSs are traditionally manufactured in a monolithic piece using EDM method, which are not suitable for different materials construction, ease of fabrication and cost savings. During the literature review, only a few researchers used modular method to design flexure-based mechanism and dealt with problems faced. C.C. Ng reported a parallel kinematic manipulator assembled by same modular units in modular configurations (Ng et al. 2006). D. Gendreau developed a modular architecture of micro-manufacturing systems for micro-assembly (Gendreau et al. 2010). J.J. Yu reported the compliant building blocks method to design large-stroke compliant joints and micro/nano positioner (Yu et al. 2009). G.B. Hao reported a position-space based approach to design reconfigurable symmetric compliant mechanisms (Li and Hao 2018). In addition, P. Gandhi reported guidelines for assembling high performance compliant mechanisms (Gandhi et al. 2012).

The main purpose of this paper is to present a new concept of MPS with modular architecture. This kind of stage takes advantages of optimized design with multiple materials, flexibility and low cost compared with monolithic stages (Richard and Clavel 2011). This approach can be compared to Lego robotics, which are both choosing finite number of bricks to create the desired machine. For Lego robotics, all provided bricks are required to assemble the desired machine. However, for reconfigurable MPSs, some of the pre-given modules are optional, which depends on the design requirements. Overall, the configuration of reconfigurable MPSs can be adjusted to meet different functional and non-functional requirements, 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 (Ng et al. 2006). The remainder of the paper is arranged as follows: Section 2 answers why we need reconfigurable MPSs. Design considerations and benefits of reconfigurable MPSs are introduced. Section 3 solves how to design function modules. In addition, Section 4 describes modules definition and some typical function modules. Some reconfigurable MPSs are designed based on proposed framework to validate their performance flexibility for case studies in Section 5. Finally, conclusions are made in Section 6.

2 Research Motivations

For commercialization, it is necessary to take into account parameters like flexibility, productivity, time and cost criteria. Modular approach promises the benefits of high volume production, the ability to produce a wide variety of products that are customized for individual customers (Kong et al. 2009; Ding et al. 2019). In addition, modular stages allow to uses of multiple materials for optimized design. 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 MPS for different scenarios. To clarify this point, performances specification of the flexure-based MPSs and potential benefits of modular MPSs are introduced in this section firstly.

2.1 Performance Requirements

The function of MPS is to move an object or a tool to a specific location or along a desired path. Thus, it is desirable to possess a high resolution, high precision motion, large workspace, high speed and high bandwidth (Reddy et al. 2018; Qin et al. 2018). As depicted in Fig.1, performance requirements for designing MPS can be classified into two categories-functional requirements and non-functional requirements. Functional requirement is also called behaviour requirement, which describes the function must be realized by the product, like DoFs, resolution *etc*. Non-functional requirements refer to the characteristics of the product must have for the purpose of decreasing cost or easing of maintenance.

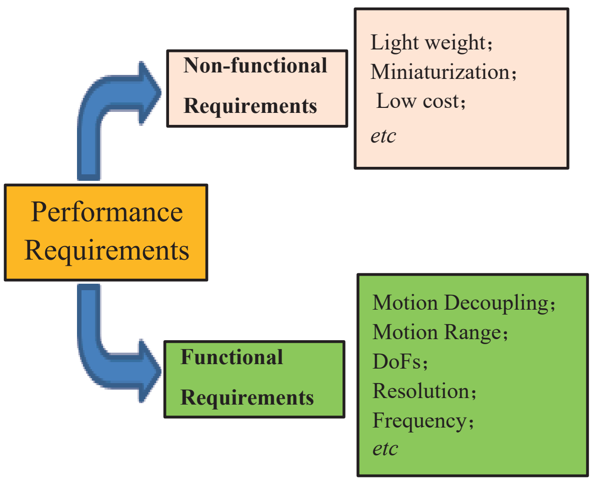

Fig. 1 Performance requirements for a MPS.

Resolution (R_e) refers to the smallest incremental change that can be achieved in the desired output of the system. Achieving a fine resolution is a critical requirement for a MPS. To realize this purpose, actuators like PEA (Piezoelectric Actuator)and GMA (Giant Magnetostrictive Actuator) featured with high positioning resolution are widely adopted to drive the stages. In addition, high resolution sensors, such as laser sensor and capacitive sensor are also utilized to improve the closed-loop system resolution. Generally speaking, PEAs are chosen to drive the MPSs for benefits of high resolution, large output force and fast response.

Workspace of a MPS is determined by the travel range of each driven direction. To get a large workspace, on one hand, actuators like EMA (Electromagnetic Actuator) and VCM (Voice Coil Motor) with large output force or large stroke can be adopted. On the other hand, amplification mechanisms such as lever amplification mechanism, bridge type amplification mechanism and Scott-Russell mechanism are extensively adopted to enlarge the stroke of the PEA. For flexure-based MPS, the workspace is also limited by the motion range of flexible joints, which is determined by its notch type and material properties.

The bandwidth indicates the overall response time of the MPS to an input signal. 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 structure. 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. In addition, optimizing the mass distribution, using high bandwidth actuators and adopting parallel structure can improve their dynamic performance.

The motion decoupling characteristics of a MPS ensures the motion quality of the stage. Parasitic motion must be avoided using the designed symmetry structures, since it is very hard to be cancelled by control method (Lai et al. 2012). Meanwhile, the symmetrical structure makes the MPS overly constrained and adding the redundant axial stiffness. It further decreases the effective output displacement of actuators (Kim et al. 2012; Cai et al. 2018).

2.2 Benefits of Modularisation

Monolithic fabrication of flexure-based MPSs are manufactured by EDM, which limits the use of multiple materials. In addition, these stages are tailored to specific tasks with constant performances and dimensional scale (Lates et al. 2017). If a certain flexure joints failed to serve or working requirements changed, a new positioning stage need to be machined again. Thus, it increases the cost and causes waste of unnecessary resources. Therefore, the designed stages should have ability to reconfigure and reuse the system quickly and easily according to the new demands and changed conditions. Modular architecture MPSs can solve these problems effectively. It provide a better way to improve the variety of MPS with low cost. Overall, there are mainly three potential benefits for modular architecture MPSs compared with monolithic fabrication stages.

- Ease of upgrading and repairing process: Modularity is identified as an important aspect for product maintenance because it allows separated diagnoses of product components and isolation of wear parts. In other words, only certain modules need to be replaced or updated when upgrading or repairing is required. From practical experiences, flexure joints at different locations have different fatigue life. It means that some flexure hinges will break first and result in the failure of the whole system. Thus it needs to design and fabricate a new one. However, the repairing process is easy for modular MPSs which can be realized by replacing the broken module with a new one. In addition, modular architecture positioning stage can make response the changing of task requirements in a limited time by modifying modules to change their stiffness, dynamic performances, stroke, resolution or dimensional scale accordingly.
- Reduce of the time-to-market: Monolithic fabrication MPSs are mainly manufactured by EDM which is a time-costed process. While for modular architecture MPSs, each module can be machined simultaneously. In addition, the standardized modules are suitable for mass production, therefore it also can decrease the cost. Furthermore, using modules means that a large number of positioning stages can be created by using conceptual modules easily. Finally, the possibility to upgrade, adapt or modify the module for extending the service life of the positioning stage is another potential benefit of modularity.
- Allow using multiple materials: As mentioned above, flexure-based MPSs are mainly manufactured in a piece of aluminum alloy with EDM. In practical applications, using stiff materials means increase the force loading on the positioning stage. Therefore, the high output force PEAs are needed and not beneficial for positioning stage miniaturization. Modular architecture MPS allows using multiple materials which is better for optimizing the structure of the stage.

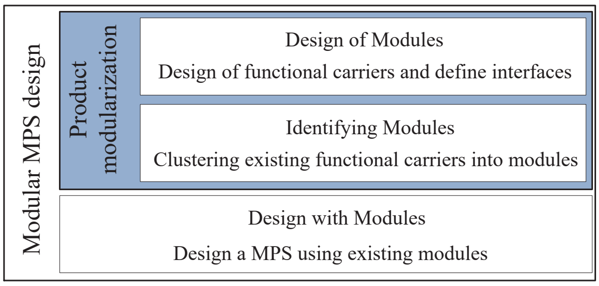

Fig. 2 Modular MPS design method.

3 Methods to build modular MPS

Considering that modularisation is a design activity and the definition of modular products are made up of modules, we define modular MPS design as an activity of designing a product that is made up of functional modules (Gershenson et al. 2003). Generally speaking, the modular design can be divided into three steps: design of modules, identifying modules and design with modules, as shown in Fig.2. Design of modules is a process to design a group of functional carriers into modules and designing their corresponding interfaces. Identifying modules entails considering an existing product, evaluating the relevance of a component grouping, clustering those components accordingly, eventually, redesigning and integrating the defined modules and corresponding interfaces. Design with modules is a process of designing a product using existing modules. A typical example is the design of a computer as an assembly of existing modules with standard interfaces, such as a motherboard, a card slots and USB interfaces.

3.1 Design of modules

The available definition of the concept of a module is that it is a group of functional carriers. Therefore, to design modular MPSs, the first step is to break down a monolithic stage into possible function modules. This process is defined as modularisation. During conducting modularisation process, the following factors need to be taken into consideration - time to market, multiple uses of functional carrier, product variety, assembly/configuration, core competency, use intensity, service, and modification/adaptation.

For a MPS, the minimum flexible element is a flexured region which transfers force and motion through elastic deformation, thus cancels friction, noise and backlash. However, these flexure elements are not suitable to be regarded as basic modules to construct the modular MPS for the reason of time-consuming assembling process and increased assembling errors. In addition, compound flexures which are composed by two or more primitive flexures possess benefits of large translational or rotational motion, they are also not suitable to be regarded as basic module for the reason of their too complex structure to standardization.

3.2 Identifying modules

The next step of MPS development is to group already defined functional carriers into relevant modules. Expressed in mathematical terms, considering a MPS P as a set of n functional carriers $P = \{1, 2, ..., n\}$, defining a modular architecture A as a set of m modules $A = \{M_1, M_2, ..., M_m\}$ and a module M_j as a subset of P ($M_j \subset P, \forall j \in [1, m]$). A is a partition of P, that is $P = \bigcup_{i=1}^{m} M_j$ and $M_j \bigcap M_k = \Phi$ for each $(j, k) \in [1, m]^2, j \neq k$. In other words, the approached identification of modules consists of finding the optimal partition of functional carriers into modules (Bonvoisin et al. 2016).

4 Modules Definition

The modular architecture MPS can be regarded as an end-effector connected with several kinematic chains, as shown in Fig.3. Each chain is composed by function modules integrated with standardisation interfaces. So 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 module. Ideally, the modules introduced in this research have standardization interfaces, which can join or connect with one another to assemble the desired products.

From practical experiences, the MPS can be regarded as that assembled by different function modules. Function modules implement technical functions independently or in combination with other modules, which are basic elements to construct modular architecture MPSs. Referring to this, function modules are classified as basic modules, including beam module, connection module and actuation module; auxiliary modules, including ground module; adaptive modules, including amplification module.

4.1 Beam Module

The beam module is one of basic modules, which plays a role of transferring force or motion in positioning stages. As depicted in Fig.4(a), the double beam

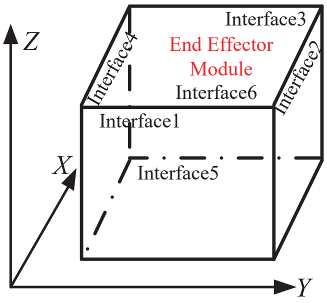

Fig. 3 Concept of modules connection.

flexure can be regarded as a prismatic joint or four rotational joints, which plays a role of transferring motion. The two typical beam modules - distributed compliance and lumped compliance beam modules are presented in Fig.4(b) and (c) respectively. For distributed compliance beam modules, it possesses the benefits of higher flexibility, less vulnerable to stress concentrations. However, variation of the rotation center position could imply loss of precision in case of applying kinematic synthesis to the pseudo-rigid-body (PRB) model. For lumped compliance beam modules, the position of rotation center can be found analytically, but the motion relies on the deflections of the flexures, which are considerable small.

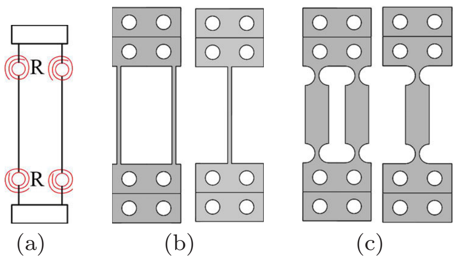

Fig. 4 Beam modules (a) kinematic model of beam module, (b) distributed compliance beams, (c) lumped compliance beams.

In addition, beam modules are also the basic elements to construct the guiding mechanisms. The two typical guiding mechanisms are composed by basic beam modules featured different stiffness as shown in Fig.5. Guiding mechanisms are defined as mechanisms that can provide motion only in a specific direction. To improve the motion performance, the structure of flexure-based MPSs are often designed as symmetry to avoid parasitic motion. Compared with non-symmetric structure, the symmetric MPS takes the advantages of avoiding parasitic motion, reducing cross-axis coupling and decreasing thermal sensitivity. However, the symmetric structure increases the stiffness of MPSs, leads to large displacement loss. In a modular architecture MPS, there are two methods to solve this problem. One is using soft material to fabricate beam modules, another is changing double-beam module into single-beam module, as shown in Fig.5.

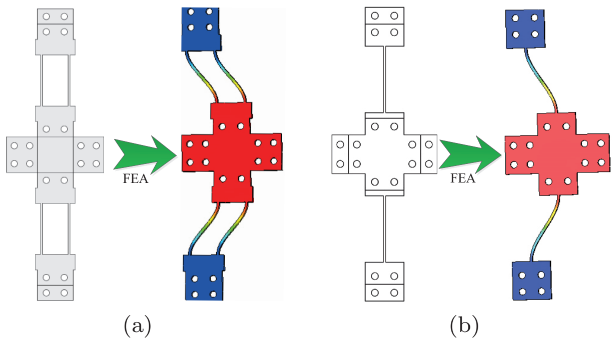

Fig. 5 Guiding mechanims: (a) double-beam guiding module, (b) single-beam guiding module.

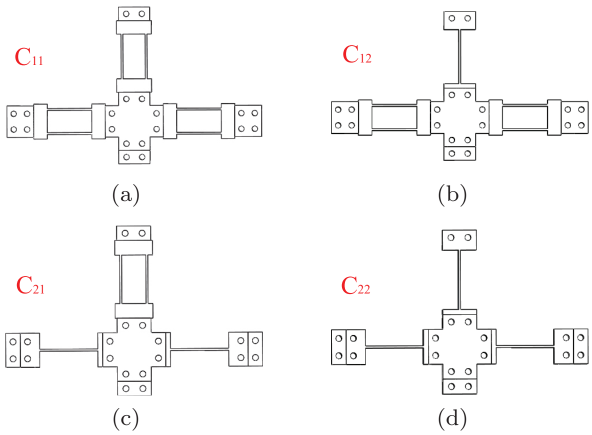

Fig. 6 Kinematic chains composed of different beam modules. (a) C_{11}, (b) C_{12}, (c) C_{21}, (d) C_{22}.

Moreover, the beam modules are also the basic elements to construct kinematic chains. As aforementioned, a MPS can be regarded as an end-effector combining with kinematics chains in serial or parallel. Referring to that, some kinematic chains C_{11}, C_{12}, C_{21} and C_{22} are created using the distributed compliance beam modules as presented in Figure.6. Each kinematic chain can be utilized as subchain to compose of a MPS.

4.2 Connection Module

Connection module is defined to assemble the basic module, auxiliary module or adaptive module together to realize a certain function. For example, two beam modules and one connection module can be assembled as a guiding mechanism to provide a precise motion as shown in Fig.5. The end-effector in this research is another connection module which plays a role of supporting loads or implementing tasks in a MPS. In addition, the geometrical shape of an end-effector determines the number of chains in a MPS. In other words, the motion dexterity is partially determined by shape of end-effector. For a planar mechanism, three motions can be achieved at most, namely two translational motions along and one rotation motion. Referring to the previous publications, three typical end-effector modules utilizing for constructing planar MPSs are presented in Fig.7. Based on geometrical shape of presented central platform(CP), the end-effector linked by three, four or six kinematic chains can obtain different motion types.

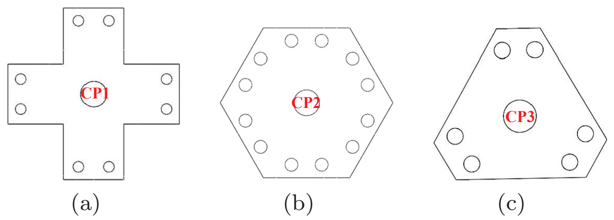

Fig. 7 Typical end-effector modules: (a) Square, (b) Hexagon, (c) Triangle.

4.3 Ground Module

Generally speaking, monolithic MPSs are made of a mono-material, such as Aluminum Alloy(AA) and Acrylonitrile Butadiene Styrene(ABS). As is known to us, the dynamic performance of a MPS is determined by the effective stiffness and mass of the mechanism. Therefore, to obtain a well performance, mass optimization is necessary for the mechanism. Considering this, the ground module fabricated with much light material in modular MPS is better for improving the dynamic performance of the stage.

4.4 Amplification Module

Amplification modules are designed for enlarging the stroke of actuators, especially for MPSs which are driven by PEAs. Although amplifiers like bridge type amplification mechanism and lever based amplification mechanism are utilized to enlarge the workspace of the stage, the adopted amplification mechanisms decrease

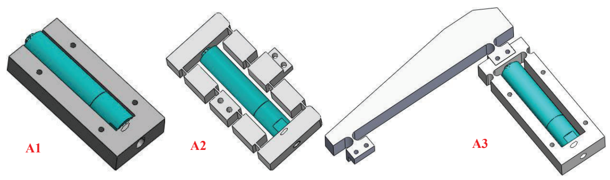

Fig. 8 Actuation modules for different requirements.

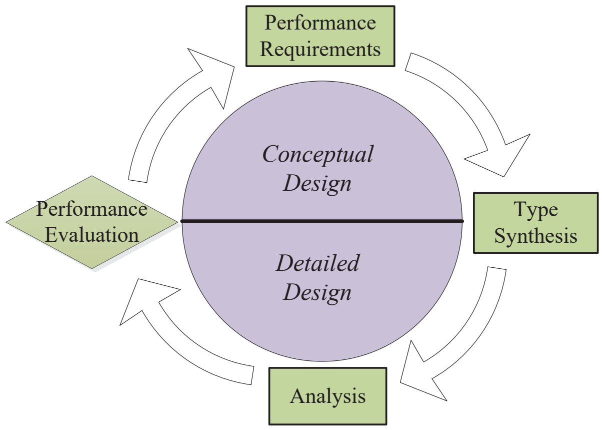

Fig. 9 A framework to guide reconfigurable MPS design.

the resolution of the MPS. For modular MPS, the amplification module is defined as an auxiliary module, the amplification function is optional which depends on user requirements. In this paper, three types actuation modules are designed for requirements as depicted in Fig.8. Due to some advantages, bridge type amplification and lever amplification mechanism are integrated into $A2$ and $A3$ modules respectively.

5 Cases of Reconfigurable MPS Design

The design of a reconfigurable MPS has some common characteristics of design general mechanism. As shown in Fig.9, 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 step is listed as following: performance requirements - to define functional and non-functional requirements referring to a specific application; type synthesis - to find all types of mechanism with a specific behaviour; analysis - to compare the simulation behaviour with the desired behaviour 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, reconfigurable MPSs 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?
– Can the evaluation results meet the expected requirements?

Referring to the previous publications, the research on decoupled two-DoF MPSs is a hot issue. Some modules are presented to create the decoupled stages to validate benefits of modular MPSs in this section. Overall, the using of modular architecture increasing the products variety can be validated by products variety and performances variety.

Product variety means that many kinds of products can be generated by using designed modules. As shown in Fig.10, some decoupled two-DoF basic stages(BS) are presented which composed by different kinematic chains. Apart from these decoupled two-DoF positioning stages, other kinds of modular products also can be generated. For example, one-DoF, three-DoF positioning stages can be assembled with different central platforms and micro-grippers can be generated with two guiding modules, as depicted in Fig.11. In addition, the motion range can be adjusted by changing different actuation modules.

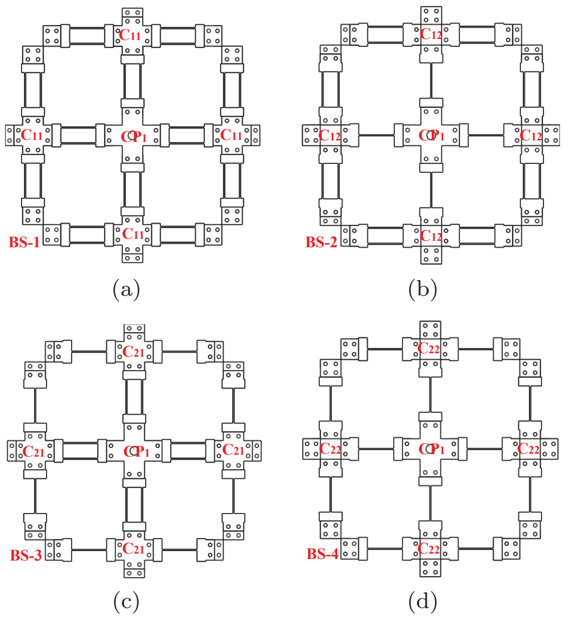

Fig. 10 Basic stages composed of different chains: (a) BS-1, (b) BS-2, (c) BS-3, (d) BS-4.

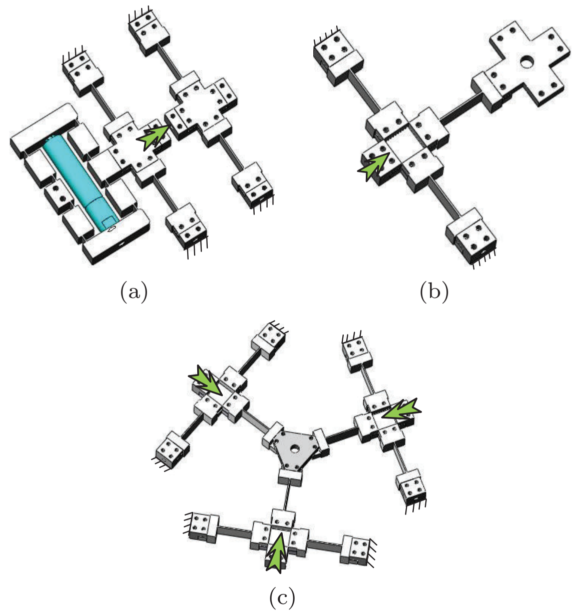

Fig. 11 Variety of modular products: (a) Micro-gripper, (b) Single DoF stage, (c) Three DoF stage.

Performance variety means that motion range, resolution and natural frequency of a certain MPS or gripper can be changed by using different modules. For example, the dynamic performance of MPS can be enhanced by using the modular architecture. As is well known, the natural frequency of MPS can be derived by following equation:

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

where K_{ds} and M_{eff} represent directional stiffness and effective mass of positioning stage respectively. Referring to Eq.(1), the high bandwidth can be achieved by increasing the directional stiffness or decreasing effective mass of the MPS. For modular MPS, the directional stiffness can be increased by using parallelogram beam modules. In addition, using light weight ground modules and end-effector modules can decrease the effective mass of MPS. Moreover, a comparison is conducted to validate dynamic performance of modular MPSs in Fig.12. In this case, the ground module is made by ABS materials and the rest of components is fabricated by AA 7075-T6. Properties of the aforementioned two materials are listed in Tab.1.

In addition, motion range and resolution of modular MPSs can also be adjusted in different situations. Generally speaking, the resolution and motion range are two contradict indexes for piezo-driving MPS. The limited stroke of PEAs are generally compensated by amplification mechanisms which deteriorate the resolution of

Table 1 Material properties.

Material parameters of A.A 7075-T6 and ABS.			
E	σ	υ	ρ
72GPa	570MPa	0.33	$2.81\times10^3 Kg/m^3$
2GPa	318.9MPa	0.394	$1.02\times10^3 Kg/m^3$

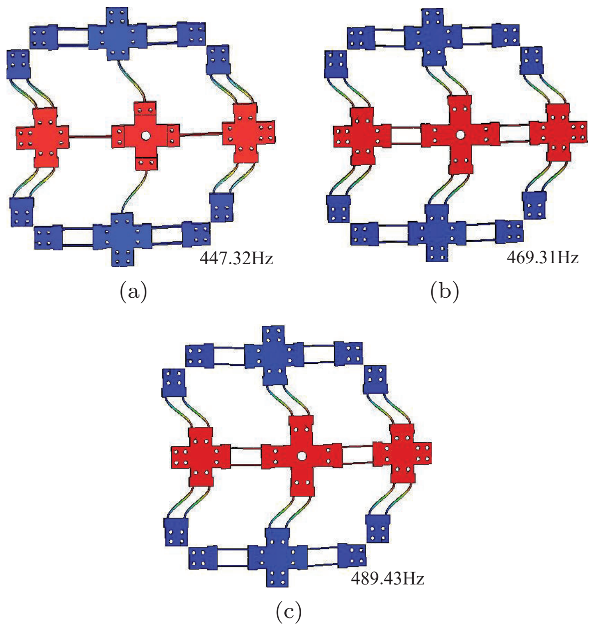

Fig. 12 Dynamic performances comparison. (a) BS-2 stage, (b) BS-1 stage, (c) BS-1 stage with ground module made by ABS material.

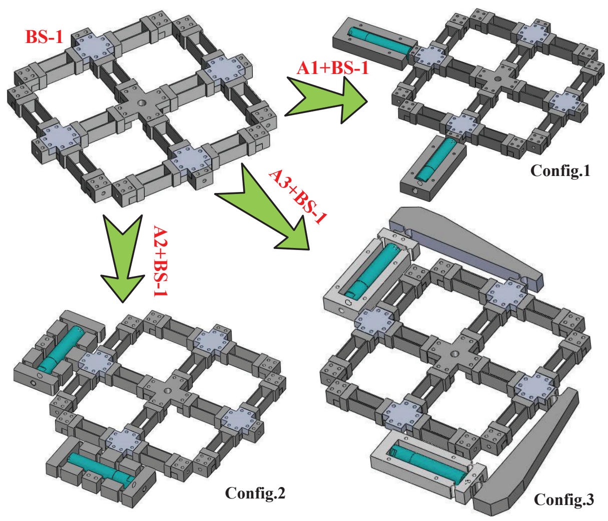

Fig. 13 The principle to change the motion range of modular MPS.

MPS. However, modular architecture MPSs can solve this issue effectively. For example, the $BS-1$ can be reconfigured to $Config$.2 or $Config$.3 by adding actuation module module $A2$ or $A3$ to enlarge motion range, vice versa $Config$.2 or $Config$.3 can be reconfigured to $Config$.1 by changing the amplification module into actuation module $A1$ to enhance the resolution, as presented in Fig.13.

6 Conclusions

A concept of modular MPS is proposed in this study which allows to generate a series of tailored MPSs via adjustment of a finite number of modules. Compared with conventional monolithic MPSs, benefits of modular MPS are listed as following: ease of upgrading and repairing process; reducing of the time-to-market; allowing using multiple materials. The simulation case study on a set of modular MPSs are built to validate their flexibility and functionality. The proposed modular architecture design provides a convenient way to adjust the function and capacity of the MPSs 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 modular MPSs includes finding the minimized modules to compose the basic stages so as to enhance the interchangeability of modules. In addition, the development of a library of modules is also our plan, which provides the opportunity to choose the most appropriate modules to adaptive design requirements.

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