



(51) International Patent Classification:

B25J 9/10 (2006.01) *G05D 3/12* (2006.01)
G03F 7/20 (2006.01) *G02B 7/198* (2021.01)

(21) International Application Number:

PCT/US2023/033486

(22) International Filing Date:

22 September 2023 (22.09.2023)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

63/376,657 22 September 2022 (22.09.2022) US
63/510,991 29 June 2023 (29.06.2023) US

(71) Applicant: **BOARD OF REGENTS, THE UNIVERSITY OF TEXAS SYSTEM** [US/US]; 210 West 7th Street, Austin, Texas 78701 (US).

(72) Inventors: **ZHOU, Lei**; 4105 Mckinley Fields Drive, Austin, Texas 78731 (US). **WU, Jingjie**; 2100 Rio Grande St, Austin, Texas 78705 (US).

(74) Agent: **HAMILTON, Lee G.** et al.; Meunier Carlin & Curfman LLC, 999 Peachtree Street NE, Suite 1300, Atlanta, Georgia 30309 (US).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CV, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IQ, IR, IS, IT, JM, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, MG, MK, MN, MU, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, CV, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SC, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT,

(54) Title: SYSTEMS AND METHODS FOR OVER-ACTUATED CONTROL

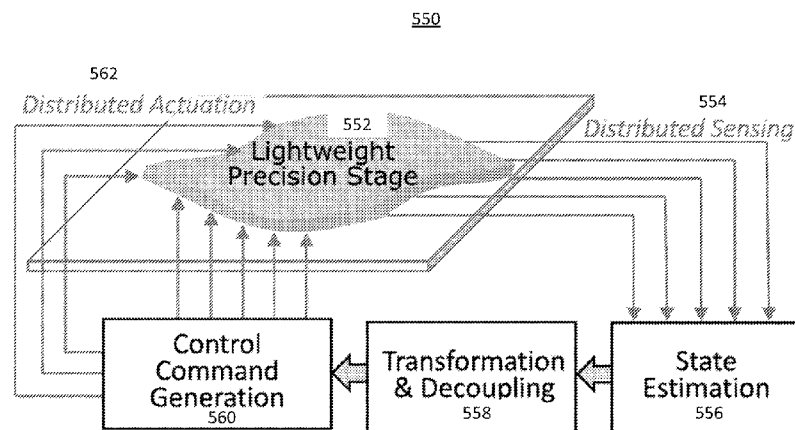


FIG. 5

(57) Abstract: According to one aspect, the present disclosure relates to a system. The system includes a part, a plurality of actuators configured to over-actuate the part; and a controller configured to control the part using the plurality of actuators. According to another aspect, the present disclosure relates to a method of designing and over-actuated system. The method includes positioning a plurality of actuators to over-actuate a part of the over-actuated system; and configuring a controller to control the part using the plurality of actuators.

LU, LV, MC, ME, MK, MT, NL, NO, PL, PT, RO, RS, SE,
SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN,
GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

SYSTEMS AND METHODS FOR OVER-ACTUATED CONTROL**CROSS-REFERENCE TO RELATED APPLICATIONS**

[0001] This application claims the benefit of U.S. provisional patent application No. 63/510,991, filed on June 29, 2023, and titled "SYSTEMS AND METHODS FOR OVER -ACTUATED CONTROL," and U.S. provisional patent application No. 63/376,657, filed on September 22, 2022, and titled "METHOD OF LIGHTWEIGHT HIGH-ACCELERATION PRECISION POSITIONING STAGE," the disclosures of which are expressly incorporated herein by reference in their entireties.

BACKGROUND

[0002] Control systems are a common component of mechanical systems. Control systems can use actuators to move parts of a mechanical system to specific positions and/or orientations in space. The bandwidth of a control system is the amount of time it takes for the control system to respond to an input to that control system. Control systems can be limited by physical properties of the system. For example, the weight of the part being controlled, the power of the actuators, and the accuracy of the sensors. Improvements in the bandwidth of control systems can improve the functioning of mechanical systems and devices controlled by those control systems.

SUMMARY

[0003] In some aspects, the techniques described herein relate to a system including: a part; a plurality of actuators configured to over-actuate the part; and a computing device in operable communication with the plurality of actuators, wherein the computing device includes a processor and a memory, the memory having computer-executable instructions stored

thereon that, when executed by the processor, cause the processor to: control the part using the plurality of actuators.

[0004] In some aspects, the techniques described herein relate to a system, wherein the part is a selectively compliant part.

[0005] In some aspects, the techniques described herein relate to a system, wherein the selectively compliant part is configured to have a first flexible mode.

[0006] In some aspects, the techniques described herein relate to a system, wherein the memory has further computer-executable instructions stored thereon that, when executed by the processor, cause the processor to control the first flexible mode of the selectively compliant part.

[0007] In some aspects, the techniques described herein relate to a system, wherein controlling the first flexible mode of the selectively compliant part includes actively controlling a flexible dynamic of the selectively compliant part.

[0008] In some aspects, the techniques described herein relate to a system, wherein the plurality of are configured so that a control bandwidth of the system is greater than the first flexible mode.

[0009] In some aspects, the techniques described herein relate to a system, wherein the part has a second flexible mode greater than the first flexible mode.

[0010] In some aspects, the techniques described herein relate to a system, wherein the second flexible mode is greater than a control bandwidth of the system.

[0011] In some aspects, the techniques described herein relate to a system, wherein the part is a precision stage.

[0012] In some aspects, the techniques described herein relate to a system, wherein the part is a laser-cutting mirror.

[0013] In some aspects, the techniques described herein relate to a system, wherein the first flexible mode is a bending mode.

[0014] In some aspects, the techniques described herein relate to a method of designing an over-actuated system, including: positioning a plurality of actuators to over-actuate a part of the over-actuated system; and configuring a controller to control the part using the plurality of actuators.

[0015] In some aspects, the techniques described herein relate to a method, further including configuring the part in in the over-actuated system to be selectively compliant.

[0016] In some aspects, the techniques described herein relate to a method, wherein the part is configured to have a first flexible mode.

[0017] In some aspects, the techniques described herein relate to a method, wherein configuring the controller to control the part using the plurality of actuators includes configuring the controller to control the first flexible mode of the part.

[0018] In some aspects, the techniques described herein relate to a method, wherein the controller has a control bandwidth less than a second flexible mode of the part.

[0019] In some aspects, the techniques described herein relate to a method, wherein the controller is configured so that a control bandwidth of the system is greater than the first flexible mode.

[0020] In some aspects, the techniques described herein relate to a method, wherein the first flexible mode is a bending mode.

[0021] In some aspects, the techniques described herein relate to a method, wherein the part is a precision stage and the over-actuated system is a photolithography machine.

[0022] In some aspects, the techniques described herein relate to a method wherein the part is a laser-cutting mirror and the over-actuated system is a laser cutter.

[0023] Other systems, methods, features and/or advantages will be or may become apparent to one with skill in the art upon examination of the following drawings and detailed description. It is intended that all such additional systems, methods, features and/or advantages be included within this description and be protected by the accompanying claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] The components in the drawings are not necessarily to scale relative to each other. Like reference numerals designate corresponding parts throughout the several views.

[0025] FIG. 1A illustrates a flowchart of an example method of designing an over-actuated system, according to implementations of the present disclosure.

[0026] FIG. 1B illustrates a flowchart of an example method of designing an over-actuated system, according to implementations of the present disclosure.

[0027] FIG. 2 illustrates a system block diagram of a system for over-actuated control, according to implementations of the present disclosure.

[0028] FIG. 3 illustrates an example computing device.

[0029] FIG. 4A illustrates an example gain/frequency plot showing an actively controlled flexible dynamic and uncontrolled flexible dynamics.

[0030] FIG. 4B illustrates a plot of stage acceleration vs. closed-loop stiffness/control bandwidth, illustrating the benefits of an example implementation of the present disclosure.

[0031] FIG. 5 illustrates a control loop for a lightweight precision stage, according to an example implementation of the present disclosure.

[0032] FIG. 6 illustrates a table of example controller parameters, according to a study of an example implementation of the present disclosure.

[0033] FIG. 7A illustrates an example of stage design with a visualization of vibration modes, according to an example implementation of the present disclosure.

[0034] FIG. 7B illustrates an example of loop gain of a vertical-directional position control for two example modes, according to an example implementation of the present disclosure.

[0035] FIG. 8A illustrates acceleration and bandwidth for an example implementation of the present disclosure for an example lightweight stage with flexible mode control.

[0036] FIG. 8B illustrates an example of control bandwidth and loop gain for an example implementation of the present disclosure.

[0037] FIG. 9 illustrates a control block diagram for an example lightweight precision positioning stage with model decoupling, according to an example implementation of the present disclosure.

[0038] FIG. 10 illustrates example controller parameters for an example implementation of the present disclosure.

[0039] FIG. 11A illustrates an example implementation of the present disclosure with four flexible modes.

[0040] FIG. 11B illustrates a stage without flexible mode control with four flexible modes according to implementations of the present disclosure.

[0041] FIG. 12A illustrates loop gains for (a) y-DOF (translation in the horizontal direction).

[0042] FIG. 12B illustrates z-DOF (translation in the vertical direction).

[0043] FIG. 13 illustrates an planar motor hardware CAD model for experimental evaluation according to implementations of the present disclosure.

[0044] FIG. 14 illustrates a fabricated stage according to implementations of the present disclosure.

[0045] FIG. 15A illustrates an example of a planar motor stator according to implementations of the present disclosure.

[0046] FIG. 15B illustrates an example of a coil winding according to implementations of the present disclosure.

[0047] FIG. 16 illustrates example optimal parameters used in a study of an example implementation.

DETAILED DESCRIPTION

[0048] Described herein are systems and related methods for controlling mechanical systems, including controlling over-actuated systems. As used herein, the term “over actuate” or “over actuated” refer to a system that has more actuators than degrees of freedom in the system. For example, a system with 5 degrees of freedom can be over actuated if it has 6 actuators. It should be understood that, while implementations of the present disclosure are illustrated with different numbers of actuators (e.g., 3, 6, etc.) any number of actuators can be

configured to over actuate a system, so long as that system has fewer actuators than degrees of freedom.

[0049] Implementations of the present disclosure include methods for designing a mechanical system. An example method 100 is illustrated in FIG. 1A.

[0050] At step 110 the method includes positioning a plurality of actuators (e.g., actuators 204a, 204b, 204c of FIG. 2) to over-actuate a part (e.g., part 202 of FIG. 2) of a system (e.g., system 200 shown in FIG. 2).

[0051] At step 120, the method includes configuring a controller (e.g., the computing device 206 shown in FIG. 2) to control the part using the plurality of actuators. This disclosure contemplates that the controller includes at least one processor and a memory (e.g., at least the basic configuration illustrated in FIG. 3). The controller can be coupled to the actuators through one or more communication links. This disclosure contemplates the communication links are any suitable communication link. For example, a communication link may be implemented by any medium that facilitates data exchange including, but not limited to, wired, wireless and optical links.

[0052] Optionally, the method further includes configuring the part in the over-actuated system to be selectively compliant. An example part is a precision positioning stage for a photolithography system. Examples 1, 2, and 3 below describe implementations of the present disclosure where an example precision positioning stage is configured to be selectively compliant in an over-actuated system. As used herein, the term “selectively compliant” refers to a part that is designed to be flexible at a predetermined resonance frequency. Optionally, the selectively compliant part can be characterized by a first flexible mode.

[0053] The controller can be configured at step 120 to control the first flexible mode of the part using the plurality of actuators. Examples 1, 2, and 3 below describe implementations of the present disclosure where a precision positioning stage includes a first flexible mode that is controlled using the plurality of actuators.

[0054] Optionally, the part has additional flexible modes that are at higher frequencies than the first flexible mode. Implementations of the present disclosure can include systems that have control bandwidths greater than the first flexible mode. However, in some implementations the control bandwidth is less than the second flexible mode. Optionally, the method 100 includes designing the part (e.g., a selectively compliant part) so that the first flexible mode is at a frequency below the control bandwidth of the system, but the second flexible mode (and subsequent flexible modes) is at a higher frequency than the control bandwidth of the system. The method 100 can further include designing the part so that the difference in frequency between the first flexible mode and second flexible mode is maximized.

[0055] It should be understood that the flexible modes described herein can optionally include flexing any direction and/or along any axis. For example, in some implementations the first flexible mode is a bending mode.

[0056] The method 100 described herein can be used to design a mechanical part. Some non-limiting example parts include precision stages for photolithography and laser cutting mirrors for laser cutters.

[0057] With reference to FIG. 1B, a method 150 of designing an over actuated system according to an example embodiment of the present disclosure is illustrated. At step 160 the method includes hardware parameter design. The hardware parameter design at step 160

includes designing the part (e.g., the part 202 shown in FIG. 2). The hardware parameter design can be performed so that the hardware (e.g., a part being controlled) has an actively controlled mode 162 within the control bandwidth 164.

[0058] At step 170, the method includes placing actuators and/or sensors (e.g., the sensors 210 shown in FIG. 2) on the hardware (e.g., sensors and actuators that are configured to move a part and measure the part's position, orientation, speed, etc.).

[0059] At step 180, the method includes designing a controller to control the hardware designed at step 160 using the actuators and sensors placed at step 170. The controller can include a control loop, as described further herein with reference to FIG. 5 and examples 1 and 2.

[0060] With reference to FIG. 2, an example system 200 is shown according to an example implementation of the present disclosure. The example system 200 includes a part 202 that is configured to be controlled by a plurality of actuators 204a, 204b, 204c. It should be understood that the number of actuators shown in FIG. 2 is provided only as an example. This disclosure contemplates that the system may include more or less actuators than shown in FIG. 2. As described with reference to Example 1, Example 2, and Example 3 herein, an example part 202 is a precision positioning stage, and example actuators 204a, 204b, 204c can include planar motors and permanent magnet arrays.

[0061] The part 202 can optionally be a selectively compliant part. An example of a selectively compliant part is a part 202 that has a first flexible mode at a resonant frequency.

[0062] The actuators 204a, 204b, 204c are configured to over-actuate the part 202. In some implementations, the actuators 204a, 204b, 204c are configured so that the control

bandwidth of the system is greater than a flexible mode of the part 202 (e.g., the first flexible mode). The control bandwidth is a parameter that characterizes the frequency range over which the system can control the part 202.

[0063] The system can also include a computing device 206. The computing device 206 can include any or all of the components described with reference to the computing device 500 illustrated in FIG. 3. As shown in FIG. 2, the computing device 206 can be coupled to the actuators 204a, 204b, 204c through one or more communication links. This disclosure contemplates the communication links are any suitable communication link. For example, a communication link may be implemented by any medium that facilitates data exchange including, but not limited to, wired, wireless and optical links. The computing device 206 can be a controller configured to control the part 202 using the actuators. For example, the computing device 206 can be configured to control the part 202 when operating at the first flexible mode. Optionally, controlling a selectively compliant part at the first flexible mode includes actively controlling the selectively compliant part using the actuators 204a, 204b, 204c to control a flexible dynamic of the selectively compliant part.

[0064] The computing device 206 can further be operably connected to any number of sensors 210 configured to measure any properties of the part 202, for example using one or more communication links. As described herein, a communication link may be implemented by any medium that facilitates data exchange including, but not limited to, wired, wireless and optical links. Non-limiting examples of sensors 210 include sensors configured to measure the position, orientation, and/or speed of the part 202. Such sensors include, but are not limited to, accelerometers, gyroscopes, magnetometers, or combinations thereof. Optionally, the sensors

210 can be configured to measure the properties of any or all of the actuators, including the positions, orientations, and speeds of the actuators.

[0065] Optionally, the computing device 206 can be configured to implement a control loop. An example control loop 550 can include one or more of the operations illustrated in FIG. 5. The control loop 550 can include a part 552 that is controlled (illustrated as a lightweight precision stage in FIG. 5). The control loop 550 can include distributed sensing 554 for state estimation 556. Transformation and decoupling 558 can be performed based on the state estimation 556 and control commands can be generated at block 560. Additionally, distributed actuation 562 of the part 552 can be performed (e.g., using the actuators 204a, 204b, 204c, and based on the control command(s) generated at block 560).

[0066] It should be understood that the flexible modes described herein can refer to different types of deformation in the part 202. In some implementations, the flexible modes described herein can be bending modes.

[0067] Implementations of the present disclosure can include systems 200 that are designed so that the part 202 has a second flexible mode that is greater than the first flexible mode. The second flexible mode can optionally be greater than the control bandwidth of the system 200.

[0068] The system 200 can be any system where a part 202 is actuated. Implementations of the present disclosure can be used for high speed instruments and manufacturing machines where the part 202 can be a cutting head, laser, wafer stage, or any other component. Implementations of the present disclosure can be used for any part that move rapidly (e.g., during a high speed manufacturing process). High speed instruments and

manufacturing machines can have their throughput limited by the resonance of different parts. Implementations of the present disclosure allow for parts to be designed so that their resonance frequencies can be controlled by the system (i.e., so that they are selectively compliant) allows increased throughput and/or efficiency. Some non-limiting examples of parts 202 that can be designed according to implementations of the present disclosure include precision stages for photolithography and laser-cutting mirrors.

[0069] Example 1:

[0070] An example implementation of the present disclosure includes a precision positioning stage for a photolithography system and a method for designing the same.

[0071] The dynamics of a precision positioning stage considering its flexible structural behaviors can be described by where x is a vector of state variables of both rigid-body displacements and flexible displacements in the modal coordinate, M , D , K are the mass, damping and stiffness matrices, respectively, u is the vector of control signals, y is a vector of measurement signals, B is the input matrix which maps the control input u to corresponding states, C is the output matrix which maps state variables to measurements, θp is a vector of stage's geometric design parameters, and θa , θs are the vectors of actuator and sensor locations, respectively.

[0072] The design optimization problem for a lightweight precision stage described by (1) can be used to find a set of hardware design parameters θp , θa , and θs and a controller design that can minimize the stage's weight while maximizing while maximizing the control bandwidth, meanwhile satisfying certain robustness criteria.

[0073] Implementations of the present disclosure include an optimization framework. The optimization framework can include a sequential framework of designing the hardware and controller for lightweight stages with their low-frequency flexible modes actively controlled. In one step, an optimization problem that determines the stage's geometric parameter is formulated to facilitate the active control for the stage's low-frequency flexible modes. In another step, an optimization can be performed to determine the location of actuators and sensors. In yet another step, feedback controllers are synthesized for the designed stage to control the stage's motion as well as the low-frequency flexible modes. Three example steps are introduced in detail with reference to the present example.

[0074] In a lightweight precision stage with active control for low-frequency flexible modes, the stage's geometry design optimization can be formulated as

$$\begin{aligned}
 & \min_{\theta_p} J_m(\theta_p), \\
 & \text{s.t. } \omega_i \leq \omega_{low}, \quad i = 1, \dots, n \\
 & \quad \omega_j \geq \omega_{high}, \quad j = n+1, \dots, m \\
 & \quad \theta_{p,min} \leq \theta_p \leq \theta_{p,max}.
 \end{aligned} \tag{2}$$

[0075] Here, the objective function J_m represents the stage's weight, θ_p is a vector for the stage's geometric parameters, ω_i is the i -th modal frequency with its corresponding vibration mode actively controlled, and ω_j is the j -th resonance frequency where the corresponding mode shape is not controlled. ω_{low} is the upper bound for the actively-controlled resonance frequencies, and ω_{high} is the lower bound for the uncontrolled resonance frequencies. $\theta_{p,min}$ and $\theta_{p,max}$ are the lower and upper bounds for the stage's geometric parameter, respectively.

[0076] With the stage structure design optimization formulation (2), the stage's flexible modes under active control are having resonance frequencies below ω_{low} , and that of the uncontrolled modes are beyond ω_{high} . Such an optimization process can enforce material removal in the stage's structure to allow for compliance in trolled flexible modes, and add material to stiffen trolled modes.

[0077] The actuator and sensor placement optimization problem for the proposed lightweight stage with active flexible mode controlled can be formulated as:

$$\max_{\theta_a \in D_a} J_a(\theta_a) = \sum_{i=1, \dots, n} W_{pi}(\theta_a) - \gamma \sum_{i=n+1, \dots, m} W_{pi}(\theta_a), \quad (3)$$

$$\max_{\theta_s \in D_s} J_s(\theta_s) = \sum_{i=1, \dots, n} W_{oi}(\theta_s) - \gamma \sum_{i=n+1, \dots, m} W_{oi}(\theta_s), \quad (4)$$

[0078] Where θ_s are vectors of actuator and sensor placement parameters, respectively; D_a and D_s are the design domains for actuator/sensor locations, and γ is a positive user-defined weighting constant. W_{pi} and W_{oi} are the controllability and observability grammians of i -th flexible mode, respectively, which can be calculated as:

$$W_{pi} = \frac{\|\phi_i(\theta_a)^\top B_a(\theta_a)\|_2^2}{4\zeta_i\omega_i}, \quad W_{oi} = \frac{\|C_s(\theta_s)^\top \phi_i(\theta_s)\|_2^2}{4\zeta_i\omega_i}, \quad (5)$$

[0079] where ϕ_i is the mass-normalized mode shape of i -th flexible mode, B_a and C_s are the force and measurement assembling matrices, ζ_i is the modal damping ratio, and ω_i is the i -th resonance natural frequency. The controllability/observability grammians W_{pi} and W_{oi} quantitatively evaluate the controllability/observability of the corresponding flexible mode in

the control system, which will reflect on the peak resonance magnitude in the system's frequency response.

[0080] With actuator/sensor placement optimization formulation in (3A) and (4A), a goal can be to maximize the controllability/observability for the actively-controlled modes to reduce the required controller gain, and to minimize those of the uncontrolled modes to reduce their coupling with the control systems. The value of γ provides a trade-off between the two design goals: a low value in γ emphasizes reducing the needed controller gain for actively-controlled modes, and a high value in γ emphasizes the cross-talk between uncontrolled modes and controlled modes.

[0081] With the stage's structure and actuator/sensor locations determined, the plant dynamics of the stage can be found. Feedback controllers can be designed for each degree of freedom (DOF) to enable precision positioning and disturbance rejection. Here, the lightweight stage plant dynamics $P : u \rightarrow y$ can be obtained from solving (2), (3), and (4). The sensor measurements y are transformed to individual DOFs via a measurement decoupling transformation. Four single-input, single-output (SISO) feedback controllers can then be designed for four decoupled channels assuming the cross-coupling between different DOFs is negligible. For each DOF, a fixed structure SISO controller is selected following reference [11A] as:

$$C_k(s) = K_p \left(\frac{s + \omega_l}{s} \right) \left(\frac{s}{\omega_d} + 1 \right) \left(\frac{\omega_{lp}^2}{s^2 + 2z_{lp}\omega_{lp}s + \omega_{lp}^2} \right), \quad (6)$$

[0082] where the controller parameters illustrated in FIG. 6. Optionally, all the controller parameters except the controller gain can be determined by a target control

bandwidth ω_{bw} . [1A, 12A]. This approach effectively simplifies the parameter tuning process.

The proportional gain K_p and the target bandwidth are determined such that the control bandwidth is maximized while satisfying a robustness criteria [13A] of:

$$\|S_k(s)\|_{\infty} \leq 2, k = 1, \dots, n, \quad (7)$$

[0083] where $S_k(s)$ is the closed-loop sensitivity function of the k -th channel as $S_k = (I - G_k C_k)^{-1}$. With the control effort signals u_k for each channel computed, an actuation recoupling transformation is used to map the control signals to individual actuators.

[0084] **Example 2:**

[0085] Another example implementation includes a study where a design and control paradigm for lightweight precision motion stages including over-actuation and compliant stage structures were developed. The example implementation can break the acceleration bandwidth trade-off, as a means to tackle key technical barriers toward the development of future IC manufacturing equipment with enhanced throughput. Combining (a) over-actuation (i.e., high-bandwidth feedback control of the stage's flexible dynamics with distributed actuation and sensing) and (b) intentionally-introduced compliance in the stage structure can enable new precision stages with excellent (closed-loop) stiffness-to-weight ratio that passive stage structures cannot achieve, thereby delivering substantially-improved acceleration without sacrificing control performances. In an example implementation, designing the stage's physical structure and actively controlling the stage's low-frequency vibration modes via over-actuation can reduce the weight of a precision stage by 55% compared to a baseline stage while enhancing its control bandwidth. Implementations of the present disclosure include over-

actuation for precision stages, and systematic and synergistic design-control framework for over-actuated lightweight stages to fully exploit the new capability afforded by the introduction of distributed actuation, sensing, and control.

[0086] Implementations of the present disclosure include lightweight stages for future high-throughput and/or sustainable machines.

[0087] Precision motion stages can be used in manufacturing machines or scientific instruments to perform positioning tasks with micro- or nano-meter accuracy. One example is the photolithography machines for IC manufacturing [2], where the wafer and photomask (or reticle) scanning stages have sub-nanometer positioning accuracy with extreme speed and acceleration to guarantee the required manufacturing accuracy and throughput. Other example applications of precision stages include precision machine tools (e.g. laser-based machines [4] and micro-machining systems [5]), additive manufacturing tools [6], IC packaging systems [7], metrology (e.g. CMMs [8] and IC inspection systems [9]), in-cleanroom wafer handlers [10], scientific instruments (e.g. X-ray microscopes [11] and scanning probe microscopes [12]), and many others. A precision motion stage can therefore be said to be a core component of a wide range of manufacturing equipment and instruments. In view of their purpose of positioning tools and parts in machines and instruments, the stage's positioning accuracy and dynamic performance (i.e., bandwidth and robustness) can be primary concerns [13]. In addition, their acceleration and power efficiency can be critical specifications that directly determine the productivity and sustainability of the overall machine or instrument as discussed below.

[0088] In modern photolithography systems, the wafer and reticle stages are both under high-speed motion during the patterning process. The exposure, or patterning, happens

during the stages' constant velocity motion phase, and the acceleration/deceleration phase is the "dead time" and should be minimized [14, 15]. The acceleration capability of wafer and reticle stages can be one of the key limiting factors of today's photolithography scanner's throughput [16]. As a non-limiting example, a state-of-the-art EUV lithography scanner (ASML NXE3400C [2]) produces 170 wafers per hour (WPH), and the cost of a fully processed wafer is around \$17,000 [17]. Based on these figures, a mere 1% improvement in throughput would result in a productivity increase of 744 wafer/year (\$12.6 million/year) for every machine (assuming 20-layer ICs). The same applies to many other processes such as laser-based machining [4] and IC inspection [9]. This huge potential calls for an urgent need to create new precision positioning stages with higher acceleration, which requires the systems to have either increased thrust force or reduced moving weight. Although sizing up actuators or increasing excitation current can improve the stage's force generation, they also incur increases in cost and thermal losses and thus are challenging to be deployed. In contrast, reducing the stage's weight not only enhances its acceleration but also reduces the system's volume, which is highly desirable for future manufacturing machines.

[0089] Another aspect of precision motion stages is their energy efficiency. IC manufacturing can be a critical component of any effort to reduce global energy consumption and greenhouse gas emissions. According to the 2018 Manufacturing Energy Consumption Survey [18], semiconductor-related device manufacturing accounted for 15.8 billion kWh of the annual US electricity consumption and approximately 112,000 ton/year in CO₂ emission [19]. Although motion and handling systems directly contribute to about only 1% power consumption of IC manufacturing tools [20], their heat generation must be compensated to

avoid positioning errors induced by thermal growth, which requires up to 10% of the system's cooling power [21]. Lightweighting precision stages can effectively reduce the power required for motion tasks and enable more sustainable IC manufacturing machines. Moreover, an increasing number of processes require precision positioning for wafers in an ultra-clean vacuum environment. In these systems, magnetic levitation is often employed to avoid contamination generation [13], where the stage's weight is compensated by actuation forces. Reducing the stage's weight is critical to lower the power required for thermal management. From this discussion above, the following statement can be deduced:

[0090] Although control algorithms [22-35] can improve the motion system's tracking accuracy, the stage's hardware design is not modified in synergy with the controllers, which can limit the achievable lightweight and thus acceleration.

[0091] Other systems [41-47] illustrate a fundamental trade-off between the stage's acceleration capability and control bandwidth illustrated in FIG. 4A: a rigid stage design can achieve high control bandwidth but leads to a heavy stage construction which limits acceleration; on the other extreme, a lightweight stage design can have high acceleration but low stage resonance frequencies which limit control bandwidth.

[0092] Implementations of the present disclosure include over-actuated lightweight stages with flexible dynamics control.

[0093] High-bandwidth feedback control can be used to offer mechanical stiffness in the closed-loop system. High-bandwidth feedback control can be used to control flexible structures through over-actuation, i.e., actively controlling the stage's flexible dynamics with

distributed actuators and sensors, which offers an opportunity to remove the limitation on position control bandwidth imposed by the stage's structural resonances.

[0094] Implementations of the present disclosure include introducing compliance in the stage's structure through minimizing the resonance frequencies of the stage's flexible modes being controlled while maximizing the resonance frequencies of the uncontrolled modes. The stage's target control bandwidth is between the two groups of resonance frequencies, as shown in FIG. 4A. This design methodology can enable material removal in the stage's structure to provide compliance in the actively-controlled modes, and will enable high closed-loop control bandwidth by having high resonance frequencies in the uncontrolled modes. Example implementations of the present disclosure provide break the acceleration-bandwidth trade-off and create new stages with unprecedented acceleration without sacrificing positioning bandwidth, as illustrated by the new feasible range 452 shown in FIG. 4B.

[0095] FIG. 7A shows a diagram for a lightweight magnetically levitated planar stage of 320mm×320 mm. The stage's magnetic design follows Kim et al. [50], where four Halbach permanent magnet (PM) arrays are located at the corners of the stage to provide both vertical-directional levitation forces and lateral-directional thrust forces. The lightweight stage structure uses ribs to reinforce a thin stage top. In this example design, the stage's first flexible mode is intentionally designed to be compliant (resonance 50 Hz, well within the target control bandwidth), and the rest of the flexible modes are stiffened to have resonance frequencies above 500 Hz as shown in FIG. 7A. FIG. 7B shows the loop frequency response of the vertical-directional position control of the proposed over-actuated stage and that of a baseline lightweight stage (only rigid-body motion controlled; first resonance frequency 250 Hz). Data

show that the proposed stage can achieve a high control bandwidth of 120 Hz with excellent robustness, while the control bandwidth of the baseline is limited at 25 Hz due to the stage's uncontrolled structural resonance. In addition, the weight of the proposed stage is 1.2 kg while that of the baseline stage is 2.7 kg. The significant weight reduction (55%) and bandwidth increase (4×) show the excellent potential of the example method studied.

[0096] Optionally, the example systems and methods can include designing the part being controlled (e.g., the stages illustrated in FIG. 7A- FIG. 7B) designed to achieve a large separation in structural resonance frequencies (e.g., the separation shown in FIG. 4A). A systematic stage topology design exploration method can be used to apply implementations of the present disclosure to any mechanical system. In addition, while the example implementation included sequential methods for the stage's hardware and controller design, implementations of the present disclosure can also include synergy between hardware design and control must be leveraged to better exploit the potential of the proposed method.

[0097] Example 3:

[0098] An implementation of the present disclosure was developed and tested for high-precision positioning stages.

[0099] High-precision positioning stages can be important in a wide range of manufacturing machines and instruments such as wafer/reticle stage in photolithography scanners and MEMS inspection systems, and their motion performance can be critical to the quality and throughput of the systems. Implementations of the present disclosure include a lightweight precision motion system with unprecedented acceleration capability while maintaining exceptional positioning accuracy and high control bandwidth that solves problems

with existing motion systems [1C]. The example implementation can overcome problems with existing lightweight stages. For example, when the weight of an existing lightweight stage is reduced, the reduction of stages' weight tends to decrease its structural resonance frequency to near or within the control bandwidth, which limits the closed-loop control bandwidth and can even cause stability issues [2C].

[00100] The example implementation can overcome a limitation of existing lightweight stages, where the achievable control bandwidth can be limited by the first structural resonance frequency. Thus, existing stages are limited by a fundamental trade-off between the stage's control bandwidth and acceleration capability, as is shown in FIG. 8A. The example implementation of the present disclosure can break this fundamental trade off.

[00101] The example implementation of the present disclosure includes a lightweight precision stage with high acceleration capability and high closed-loop stiffness simultaneously. The present disclosure further includes a sequential structure and control design framework for lightweight stages with low frequency flexible modes of the stage being actively controlled. Consequently, the example target closed-loop control bandwidth lies in between the resonance frequencies as shown in the plot illustrated in FIG. 8B. The sequential structure and control design framework described herein can allow material removal in controlled resonance mode shapes to reduce the stage's weight while enabling high control bandwidth which is limited by the uncontrolled resonance frequencies.

[00102] Additionally, the present disclosure includes an optimization problem to compute the best actuator/sensor placement. In some implementations, maximizing the controllability/observability of the actively-controlled flexible modes while minimizing that of

the uncontrolled modes can deliver the best positioning performance with reasonable control effort magnitude. The present example implementation further includes a case study simulated to evaluate the effectiveness of the example approach, where a stage weight reduction is demonstrated compared to a baseline case. These results demonstrate the potential of the proposed lightweight precision stage design framework. Experimental evaluation of the designed stage's motion performance is performed on a magnetically levitated linear motor platform.

[00103] The study included control co-design methods using implementations of the present disclosure. The sequential control codesign framework can optionally be used to design the hardware and controller for lightweight motion stages with their low-frequency flexible modes actively controlled. The study included an optimization problem that determines the stage's geometric parameters and is formulated to facilitate the active control for low-frequency flexible modes. The study further included another optimization that determines the actuator and sensor locations is performed to enhance the control bandwidth. The study also included feedback controllers that are synthesized for the decoupled plant dynamics to control the stage's motion and low-frequency flexible dynamics.

[00104] The example implementation in the study further included methods of stage geometry design. In the study, the stage structure design was configured so that low frequency flexible modes could be controlled. The example stage's geometry optimization can be formulated as the following optimization problem:

$$\begin{aligned}
& \min_{\theta_p} J_m(\theta_p), \\
\text{[00105]} \quad & \text{s.t.} \quad \omega_i \leq \omega_{\text{low}}, \quad i = 1, \dots, n \\
& \quad \quad \omega_j \geq \omega_{\text{high}}, \quad j = n + 1, \dots, m \\
& \quad \quad \theta_{p, \min} \leq \theta_p \leq \theta_{p, \max}.
\end{aligned} \tag{1}$$

[00106] Here, the objective function J_m represents the stage's weight, θ_p is a vector for the stage's geometric parameters, ω_i is the i -th modal frequency with its corresponding vibration mode actively controlled, and ω_j is the j -th resonance frequency where the corresponding mode shape is not controlled. ω_{low} is the upper bound for the actively controlled resonance frequencies, and ω_{high} is the lower bound for the uncontrolled resonance frequencies. $\theta_{p, \min}$ and $\theta_{p, \max}$ are the lower and upper bounds for the stage's geometric parameter, respectively. Such an optimization process can enforce material removal in the stage's structure to allow for compliance in the actively controlled flexible modes, and add material to stiffen the uncontrolled modes.

[00107] The selection of ω_{low} and ω_{high} can be used to determine the designed stage's dynamic behavior. The system's target control bandwidth can be between ω_{low} and ω_{high} , and ω_{high} sets the new upper bound for the achievable control bandwidth for the lightweight precision stage with actively controlled flexible modes, as illustrated in Fig. 8A.

[00108] To facilitate controller design while maintaining design feasibility, the values of ω_{low} and ω_{high} can be selected according to the target control bandwidth, for example $\omega_{\text{low}} \sim \frac{1}{2} \times \omega_{bw}$ and $\omega_{\text{high}} \sim 5 \times \omega_{bw}$, where ω_{bw} is the target bandwidth. This method, although robust, may lead to a relatively conservative stage design. To fully evaluate the feasible design range in FIG. 8A, the value of ω_{high} can be swept while considering the actuator/sensor placement.

[00109] The example implementation further included methods of actuator and sensor placement. With the stage's structure fixed, the actuator and sensor placement optimization problem for the proposed lightweight motion stage can be formulated as

$$[00110] \quad \max_{\theta_a \in D_a} J_a(\theta_a) = \sum_{i=1, \dots, n} W_{pi}(\theta_a) - \gamma \sum_{i=n+1, \dots, m} W_{pi}(\theta_a), \quad (2)$$

$$[00111] \quad \max_{\theta_s \in D_s} J_o(\theta_s) = \sum_{i=1, \dots, n} W_{oi}(\theta_s) - \gamma \sum_{i=n+1, \dots, m} W_{oi}(\theta_s), \quad (3)$$

[00112] where θ_a and θ_s are vectors of actuator and sensor placement parameters, respectively; D_a and D_s are the design domains for actuator/sensor locations, and γ is a positive user-defined weighting constant. W_{pi} and W_{oi} are the controllability and observability grammians of i -th flexible mode, respectively, which can be calculated as

$$[00113] \quad W_{pi} = \frac{\|\phi_i(\theta_a)^T B_a(\theta_a)\|_2^2}{4\zeta_i\omega_i}, \quad W_{oi} = \frac{\|C_s(\theta_s)^T \phi_i(\theta_s)\|_2^2}{4\zeta_i\omega_i}, \quad (4)$$

[00114] where ϕ_i is the mass-normalized mode shape of i -th flexible mode, B_a and C_s are the force and measurement assembling matrices, ζ_i is the modal damping ratio, and ω_i is the i -th resonance natural frequency. The controllability/observability grammians W_{pi} and W_{oi} quantitatively evaluate the controllability/observability of the corresponding flexible mode in the control system, which can reflect on the peak resonance magnitude in the system's frequency response.

[00115] With actuator/sensor placement optimization formulation in (2) and (3), the study of the example implementation was configured to maximize the controllability/observability for the actively-controlled modes to reduce the required controller gain, and to minimize those of the uncontrolled modes to reduce their coupling with the control systems and thus facilitate the controller design. The value of weighting parameter γ can provide a trade-off between the two design goals: a low value in γ emphasizes reducing the

needed controller gain for actively-controlled modes, and a high value in γ emphasizes reducing the cross-talk between uncontrolled modes and controlled modes.

[00116] The example implementation included feedback controllers and methods of feedback controller design. With the stage's hardware design (including both stage's structure and actuator/sensor placement) fixed, the plant dynamic can be found. Feedback controllers are designed for each motion degree of freedom to attain the target control performance. FIG. 9 shows a block diagram 900 including a control loop for a lightweight stage with all six rigid-body DOFs and one flexible mode under active control. Here, the lightweight stage plant dynamics $P: u \rightarrow y$ can be obtained from solving (1), (2), and (3). The sensor measurements y are transformed to individual DOFs via a measurement decoupling transformation. Seven single-input, single-output (SISO) feedback controllers can then be designed for seven decoupled channels assuming the cross-coupling between different DOFs is negligible near the target control bandwidth. For each DOF, a fixed-structure SISO controller is selected following reference [8C] as:

$$\mathbf{[00117]} \quad C_k(s) = K_p \left(\frac{s+\omega_i}{s} \right) \left(\frac{s}{\omega_d} + 1 \right) \left(\frac{\omega_{lp}^2}{s^2 + 2z_{lp}\omega_{lp}s + \omega_{lp}^2} \right), \quad (5)$$

[00118] where the controller parameters are illustrated in FIG. 10. This controller design follows [7C] where all the controller parameters except the controller gain can be determined by a target control bandwidth ω_{bw} . This approach can simplify the parameter tuning process. The proportional gain K_p and the target bandwidth are determined such that the control bandwidth is maximized while satisfying a robustness criteria of:

$$\mathbf{[00119]} \quad \|S_k(s)\|_{\infty} \leq 2, k = 1, \dots, n, \quad (6)$$

[00120] where $S_k(s)$ is the closed-loop sensitivity function of the k -th channel as $S_k = (I - G_k C_k)^{-1}$. With the control effort signals u_k for each channel computed, an actuation recoupling transformation is used to map the control signals to individual actuators.

[00121] The study included a case study of an example stage. The example stage was a practical lightweight maglev planar positioning stage with the actuator's weight and location considered simulated and compared to a baseline design where the stage's flexible modes are not actively controlled. The example implementation of a stage design was fabricated and the experimental setup for the maglev motor was built to verify the stage's actual closed-loop motion performance.

[00122] The study considered an evaluation of a simulation. Fig. 11A shows the magnetically levitated motion stage designed in the study of the example implementation. The magnetically levitated motion stage is a rib-reinforced structure made of 7075-T6 aluminum alloy of 300 mm × 300 mm in size. There are four neodymium permanent magnet arrays of 69.85 mm × 69.85 mm × 6.35 mm arranged at the corners of the stage to provide both the thrust forces for planar motion and the levitation forces. Therefore, in this case, the actuator positions are fixed so that the sensors are placed. The first four vibration mode shapes and corresponding resonance frequencies are also shown in FIG. 11A. Herein, the rigid-body motion of the stage in six DOFs are actively controlled. In addition, the example implementation of the present disclosure design controls the first flexible mode while the baseline has no control on flexible modes. The placement of the sensors is optimized in the example stage but not in the baseline case. With a target bandwidth of 50 Hz, the baseline stage's geometric parameters are designed to constrain the first resonance frequency above 250 Hz. The geometric parameters

$\theta_p \in \mathbb{R}^5$ and the actuator/sensor location parameters $\theta_a = [x_a, y_a]^\top$ and $\theta_s = [x_s, y_s]^\top$ are also shown in Fig. 11A. FIG. 16 illustrates a comparison of the simulation of the example implementation that was studied with a baseline design.

[00123] Due to the geometric complexity of the ribbed stage structure with permanent magnets, analytical models may not be sufficient to capture its structural dynamics accurately. In the example implementation, finite element (FE) simulation (with COMSOL Multiphysics) is used to simulate the stage's spatial-temporal behavior. In the stage geometry optimization problem (1) formulation for the example implementation of a stage shown in FIG. 11A, to facilitate controller design with a target control bandwidth of ~ 100 Hz, the values of ω_{low} and ω_{high} are selected as 50 Hz and 600 Hz, respectively. In addition, the rib width and base height can optionally be constrained to be larger than 1 mm and 0.635 mm respectively for the sake of manufacturability. With the stage geometry optimization problem (1) fully formulated, the Optimization Module in COMSOL Multiphysics can be selected to solve the problem, where an iterative method for derivative-free constrained optimization COBYLA [9C] is employed. The resultant stage resonance frequencies and mode shapes are illustrated in FIG. 11A and FIG. 11B. The sensor positioning optimization problem (3) is solved with $\gamma=50$. FIG. 11B illustrates a precision stage without flexible mode control and illustrates the corresponding flexible modes. FIG. 11A and FIG. 11B both consider a permanent magnet array with 69.85 mm $\times$ 69.85 mm $\times$ 6.35 mm for planar motor force generation, however the permanent magnet array and its size are only non-limiting examples, and other actuators and/or actuator sizes can be used in various implementations of the present disclosure.

[00124] FIG. 12A and FIG. 12B illustrate the loop gains of both proposed and baseline designs in y - and z-DOF. FIG. 12A illustrates that with sufficient stability margins in both cases, the control bandwidth in proposed design is significantly larger than baseline design in y-DOF since the 259 Hz resonance is limiting the bandwidth. In FIG. 12B, both cases can achieve 100 Hz bandwidth. However, the 259 Hz resonance is still coupled in this channel but with a small peak magnitude and imperfect actuator/sensor placement or decoupling can increase the peak and thus cause stability issues. The lightly-damped 259 Hz resonance mode can be excited by external disturbance and thus impair the stage's positioning precision. The weight of the proposed stage design (1.68 kg) is reduced by 24% compared to baseline design (2.21 kg). The comparisons indicate the potential of the proposed framework to improve stage's acceleration while maintaining high bandwidth and accuracy.

[00125] To verify the improvement and effectiveness of the example implementation that was studied, the designed stage of the case study was fabricated as shown in FIG. 14. The ribbed aluminum structure and base sheet are both done by precise waterjet cutting with taper compensation. The magnet arrays at corners provide thrust and levitation force. The magnet arrays are patterned as 4-segment-per-spatial- period Halbach arrays, which can generate higher magnetic field. They are made of N52 NdFeB permanent magnets with spatial period to be 25.4 mm and assembled by Loctite structural adhesive.

[00126] The overall planar motor design for actuation and sensing of the stage is shown in FIG. 13. Four inductive sensors are placed at the location computed from (3) to measure the vertical displacement. Optionally, the inductive sensors are DWAS-509-M8-390 sold under the trademark DW Series. Three laser displacement sensors sold under the

trademark Keyence LK-H152 were used to measure the full x and y axis motions. It should be understood that any sensors can be used, and that these are only non-limiting examples of inductive sensors and laser displacement sensors that were used in an example implementation of the present disclosure. The planar motor stators are made of Aluminum 6061 as shown in FIG. 15A. In the example implementation, the planar motor stator thickness is chosen to be 25.4 mm so that the magnet arrays are sufficiently far from the bottom half of the coil and the optical table while the winding resistance is not too large. To maximize the instantaneous force capability and therefore the acceleration capability, the thickness of the winding coils is chosen to be 15 mm according to parameter sweeping in the electromagnetic simulations, which were performed in the study using Ansys Maxwell. The example power op-amp used in the study was a PA12 sold under the trademark APEX, with a typical voltage swing of ± 34 V and peak current of 10 A. The study choose AWG#19 for the example coil winding with sufficiently small total winding resistance to generate the desired peak current. One single coil winding can include 100 turns with MWS AWG#19 resistance-bondable magnet wire as shown in FIG. 15B. Again, it should be understood that the dimensions and materials chosen for the planar motor design are intended only as non-limiting examples, and that other configurations of stages can be used in alternative implementations of the present disclosure.

[00127] The study of the example implementation evaluated a sequential hardware-control co-design framework for lightweight precision positioning stages with high acceleration capability and high control bandwidth simultaneously. The performance and effectiveness of the framework is first evaluated by numerical simulations using a maglev stage as case study. The significant weight reduction and improvement in control bandwidth of proposed design

compared to a baseline case demonstrate the huge potential. A planar motor is designed and built to experimentally evaluate the proposed stage design's motion performance and the results will be presented in the oral presentation.

[00128] In some implementations of the present disclosure an integrated hardware-control design approach can be used. A non-limiting example of an integrated hardware-control design approach is a nested control co-design framework to further exploit the synergy between the stage's structural design phase and controller design phase. Topology optimization formulation rather than shape parameterization can also be an effective computational tool to further optimize the stage's structure and reduce the stage's weight.

[00129] It should be appreciated that the logical operations described herein with respect to the various figures may be implemented (1) as a sequence of computer-implemented acts or program modules (i.e., software) running on a computing device (e.g., the computing device described in FIG. 3), (2) as interconnected machine logic circuits or circuit modules (i.e., hardware) within the computing device and/or (3) a combination of software and hardware of the computing device. Thus, the logical operations discussed herein are not limited to any specific combination of hardware and software. The implementation is a matter of choice dependent on the performance and other requirements of the computing device. Accordingly, the logical operations described herein are referred to variously as operations, structural devices, acts, or modules. These operations, structural devices, acts and modules may be implemented in software, in firmware, in special-purpose digital logic, and any combination thereof. It should also be appreciated that more or fewer operations may be

performed than shown in the figures and described herein. These operations may also be performed in a different order than those described herein.

[00130] Referring to FIG. 3, an example computing device 500 upon which the methods described herein may be implemented is illustrated. It should be understood that the example computing device 500 is only one example of a suitable computing environment upon which the methods described herein may be implemented. Optionally, the computing device 500 can be a well-known computing system including, but not limited to, personal computers, servers, handheld or laptop devices, multiprocessor systems, microprocessor-based systems, network personal computers (PCs), minicomputers, mainframe computers, embedded systems, and/or distributed computing environments including a plurality of any of the above systems or devices. Distributed computing environments enable remote computing devices, which are connected to a communication network or other data transmission medium, to perform various tasks. In the distributed computing environment, the program modules, applications, and other data may be stored on local and/or remote computer storage media.

[00131] In its most basic configuration, computing device 500 typically includes at least one processing unit 506 and system memory 504. Depending on the exact configuration and type of computing device, system memory 504 may be volatile (such as random access memory (RAM)), non-volatile (such as read-only memory (ROM), flash memory, etc.), or some combination of the two. This most basic configuration is illustrated in FIG. 3 by dashed line 502. The processing unit 506 may be a standard programmable processor that performs arithmetic and logic operations necessary for operation of the computing device 500. The computing

device 500 may also include a bus or other communication mechanism for communicating information among various components of the computing device 500.

[00132] Computing device 500 may have additional features/functionality. For example, computing device 500 may include additional storage such as removable storage 508 and non-removable storage 510 including, but not limited to, magnetic or optical disks or tapes. Computing device 500 may also contain network connection(s) 516 that allow the device to communicate with other devices. Computing device 500 may also have input device(s) 514 such as a keyboard, mouse, touch screen, etc. Output device(s) 512 such as a display, speakers, printer, etc. may also be included. The additional devices may be connected to the bus in order to facilitate communication of data among the components of the computing device 500. All these devices are well-known in the art and need not be discussed at length here.

[00133] The processing unit 506 may be configured to execute program code encoded in tangible, computer-readable media. Tangible, computer-readable media refers to any media that is capable of providing data that causes the computing device 500 (i.e., a machine) to operate in a particular fashion. Various computer-readable media may be utilized to provide instructions to the processing unit 506 for execution. Example tangible, computer-readable media may include, but is not limited to, volatile media, non-volatile media, removable media and non-removable media implemented in any method or technology for storage of information such as computer-readable instructions, data structures, program modules or other data. System memory 504, removable storage 508, and non-removable storage 510 are all examples of tangible, computer storage media. Example tangible, computer-readable recording media include, but are not limited to, an integrated circuit (e.g., field-programmable

gate array or application-specific IC), a hard disk, an optical disk, a magneto-optical disk, a floppy disk, a magnetic tape, a holographic storage medium, a solid-state device, RAM, ROM, electrically erasable program read-only memory (EEPROM), flash memory or other memory technology, CD-ROM, digital versatile disks (DVD) or other optical storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices.

[00134] In an example implementation, the processing unit 506 may execute program code stored in the system memory 504. For example, the bus may carry data to the system memory 504, from which the processing unit 506 receives and executes instructions. The data received by the system memory 504 may optionally be stored on the removable storage 508 or the non-removable storage 510 before or after execution by the processing unit 506.

[00135] It should be understood that the various techniques described herein may be implemented in connection with hardware or software or, where appropriate, with a combination thereof. Thus, the methods and apparatuses of the presently disclosed subject matter, or certain aspects or portions thereof, may take the form of program code (i.e., instructions) embodied in tangible media, such as floppy diskettes, CD-ROMs, hard drives, or any other machine-readable storage medium wherein, when the program code is loaded into and executed by a machine, such as a computing device, the machine becomes an apparatus for practicing the presently disclosed subject matter. In the case of program code execution on programmable computers, the computing device generally includes a processor, a storage medium readable by the processor (including volatile and non-volatile memory and/or storage elements), at least one input device, and at least one output device. One or more programs may implement or utilize the processes described in connection with the presently disclosed

subject matter, e.g., through the use of an application programming interface (API), reusable controls, or the like. Such programs may be implemented in a high-level procedural or object-oriented programming language to communicate with a computer system. However, the program(s) can be implemented in assembly or machine language, if desired. In any case, the language may be a compiled or interpreted language and it may be combined with hardware implementations.

[0001] References

[0002] Although the subject matter has been described in language specific to structural features and/or methodological acts, it is to be understood that the subject matter defined in the appended claims is not necessarily limited to the specific features or acts described above. Rather, the specific features and acts described above are disclosed as example forms of implementing the claims.

[0003] The following patents, applications, and publications, as listed below and throughout this document, describes various application and systems that could be used in combination the exemplary system and are hereby incorporated by reference in their entirety herein.

[0004] [1] Integrated circuits global market report 2021: Covid 19 impact and recovery to 2030. <https://www.globenewswire.com/news-release/2021/06/08/2243780/0/en/Integrated-Circuits-Global-Market-Report-2021-COVID-19-Impact-and-Recovery-to-2030.html>. Accessed: August 2021.

[0005] [2] ASML TwinScan NXE:3400C. <https://www.asml.com/en/products/euv-lithography-systems/twinscan-nxe3400c>. Accessed: September 2021.

[0006] [3] Jingjie Wu and Lei Zhou. Sequential structure and control co-design of lightweight precision stages with active control of flexible modes. In 2022 International Symposium on Flexible Automation (ISFA), to appear, 2022.

[0007] [4] Laser scan heads: Position your laser spot with unprecedented speed, precision and stability. <https://www.aerotech.com/motion-and-positioning/laser-scan-heads/>. Accessed: January 2022.

[0008] [5] Takahisa Masuzawa. State of the art of micromachining. *Cirp Annals*, 49(2):473–488, 2000.

[0009] [6] Paulo Jorge B´artolo and Ian Gibson. History of stereolithographic processes. In *Stereolithography*, pages 37–56. Springer, 2011.

[0010] [7] Kulicke & Soffa. <https://www.kns.com/>. Accessed: January 2022.

[0011] [8] J Śladek and A Gaska. Evaluation of coordinate measurement uncertainty with use of virtual machinemodel based on monte carlo method. *Measurement*, 45(6):1564–1575, 2012.

[0012] [9] KLA defect inspection and review. <https://www.kla.com/products/chip-manufacturing/defect-inspection-review>. Accessed: January 2022.

[0013] [10] Kensington labs wafer handling robot, precision motion control solutions. <https://www.kensingtonlabs.com/company-history/>. Accessed: January 2022.

[0014] [11] Junjing Deng, Curt Preissner, Jeffrey A Klug, Sheikh Mashrafi, Christian Roehrig, Yi Jiang, Yudong Yao, Michael Wojcik, Max D Wyman, David Vine, et al. The velociprobe: An ultrafast hard x-ray nanoprobe for high-resolution ptychographic imaging. *Review of Scientific Instruments*, 90(8):083701, 2019.

[0015] [12] Atomic force microscopes. <https://www.afmworkshop.com/>. Accessed: January 2022.

[0016] [13] Lei Zhou and JingjieWu. Magnetic levitation technology for precision motion systems: A review and future perspectives. *International Journal of Automation Technology*, 16(4):386–402, 2022.

[0017] [14] Hans Butler. Position control in lithographic equipment [applications of control]. *IEEE Control Systems Magazine*, 31(5):28–47, 2011.

[0018] [15] Jan van Schoot, Kars Troost, Frank Bornebroek, Rob van Ballegoij, Sjoerd Lok, Peter Krabbendam, Judon Stoeldraijer, Erik Loopstra, Jos P Benschop, Jo Finders, et al. High-na euv lithography enabling moore’s law in the next decade. In *International Conference on Extreme Ultraviolet Lithography 2017*, volume 10450, pages 109–128. SPIE, 2017.

[0019] [16] Precision mechatronics and asml technology enabling moore’s law. Invited Talk by Mark Schuster at UT Austin in ME 392Q Industry Lecture Series. November 2021.

[0020] [17] TSMC’s Estimated Wafer Prices Revealed: 300mm Wafer at 5nm Is Nearly \$17,000. <https://www.tomshardware.com/news/tsmcs-wafer-prices-revealed-300mm-wafer-at-5nm-is-nearly-dollar17000>. Accessed: August 2021.

[0021] [18] 2018 manufacturing energy consumption survey consumption results. <https://www.eia.gov/consumption/manufacturing>. Accessed: September 2021.

[0022] [19] Greenhouse gases equivalencies calculator - calculations and references. <https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references>. Accessed: August 2021.

[0023] [20] Energy saving in semiconductor manufacturing as design goal.

http://www.sasg.nl/SASG_68_EnergyConsumption_EUV_forSASG_CLui_05022020_handout.pdf

. Accessed: August 2021.

[0024] [21] Alberto Pirati, Jan van Schoot, Kars Troost, Rob van Ballegoij, Peter

Krabbendam, Judon Stoeldraijer, Erik Loopstra, Jos Benschop, Jo Finders, Hans Meiling, et al.

The future of euv lithography: enabling moore's law in the next decade. In Extreme Ultraviolet (EUV) Lithography VIII, volume 10143, pages 57–72. SPIE, 2017.

[0025] [22] Tom Oomen, Robbert van Herpen, Sander Quist, Marc van deWal, Okko

Bosgra, and Maarten Steinbuch. Connecting system identification and robust control for next-generation motion control of a wafer stage. *IEEE Transactions on Control Systems Technology*, 22(1):102–118, 2013.

[0026] [23] Tom Oomen. Advanced motion control for precision mechatronics:

Control, identification, and learning of complex systems. *IEEJ Journal of Industry Applications*, 7(2):127–140, 2018.

[0027] [24] Minghui Zheng, Shiyong Zhou, and Masayoshi Tomizuka. A design

methodology for disturbance observer with application to precision motion control: an h-infinity based approach. In *2017 American Control Conference (ACC)*, pages 3524–3529. IEEE, 2017.

[0028] [25] Peng Chao, Chongwei Han, Jianxiao Zou, and Guanghui Zhang. H-infinity

optimal inversion feedforward and robust feedback based 2-dof control approach for high speed-precision positioning systems. *Journal of Control Science and Engineering*, 2016, 2016.

[0029] [26] Sheikh T Mashrafi, Junjing Deng, Curt Preissner, and Srinivasa M Salapaka. Optimal control for x-ray microscopes. *IEEE/ASME Transactions on Mechatronics*, 25(2):627–637, 2020.

[0030] [27] Xu Chen and Masayoshi Tomizuka. Control methodologies for precision positioning systems. In *2013 American Control Conference*, pages 3704–3711. IEEE, 2013.

[0031] [28] Xu Chen and Masayoshi Tomizuka. An enhanced repetitive control algorithm using the structure of disturbance observer. In *2012 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, pages 490–495. IEEE, 2012.

[0032] [29] Xu Chen and Masayoshi Tomizuka. New repetitive control with improved steady-state performance and accelerated transient. *IEEE Transactions on Control Systems Technology*, 22(2):664–675, 2013.

[0033] [30] Nard Strijbosch, Lennart Blanken, Tom Oomen, et al. Frequency domain design of iterative learning control and repetitive control for complex motion systems. In *IEEE International Workshop on Sensing, Actuation, Motion Control, and Optimization*, pages 1–2, 2018.

[0034] [31] Sandipan Mishra, Joshua Coaplen, and Masavoshi Tomizuka. Precision positioning of wafer scanners segmented iterative learning control for nonrepetitive disturbances [applications of control]. *IEEE Control Systems Magazine*, 27(4):20–25, 2007.

[0035] [32] Iuliana Rotariu, Maarten Steinbuch, and Rogier Ellenbroek. Adaptive iterative learning control for high precision motion systems. *IEEE Transactions on Control Systems Technology*, 16(5):1075–1082, 2008.

[0036] [33] Dick De Roover and Okko H Bosgra. Synthesis of robust multivariable iterative learning controllers with application to a wafer stage motion system. *international Journal of Control*, 73(10):968–979, 2000.

[0037] [34] Berk Altın and Kira Barton. Robust iterative learning for high precision motion control through adaptive feedback. *Mechatronics*, 24(6):549–561, 2014.

[0038] [35] Joost Bolder and Tom Oomen. Rational basis functions in iterative learning control—with experimental verification on a motion system. *IEEE Transactions on Control Systems Technology*, 23(2):722–729, 2014.

[0039] [36] Dick Laro, Rein Boshuizen, Dennis Oom, Leo Sanders, and Jan van Eijk. Lightweight 450 mm wafer stages enabled by over-actuation. In *Proceedings of the 10th international conference of the EUSPEN*, volume 1, pages 433–436, 2010.

[0040] [37] Min Li, Kaiming Yang, Yu Zhu, Haihua Mu, and Chuxiong Hu. State/model-free variable-gain discrete sliding mode control for an ultraprecision wafer stage. *IEEE Transactions on Industrial Electronics*, 64(8):6695–6705, 2016.

[0041] [38] Robert-H Munnig Schmidt. Ultra-precision engineering in lithographic exposure equipment for the semiconductor industry. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 370(1973):3950–3972, 2012.

[0042] [39] Runze Ding, Chenyang Ding, Yunlang Xu, Weike Liu, and Xiaofeng Yang. An optimal actuator placement method for direct-drive stages to maximize control bandwidth. In *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*, pages 556–561. IEEE, 2020.

[0043] [40] Ran Zhou, Chuxiong Hu, Ze Wang, Suqing He, and Yu Zhu. Nonlinearity compensation and highfrequency flexibility suppression based ric method for precision motion control systems. IEEE Transactions on Industrial Informatics, 2022.

[0044] [41] KB Lim. Method for optimal actuator and sensor placement for large flexible structures. Journal of Guidance, Control, and Dynamics, 15(1):49–57, 1992.

[0045] [42] Ming-Chih Weng, Xiaodong Lu, and David L Trumper. Vibration control of flexible beams using sensor averaging and actuator averaging methods. IEEE Transactions on control systems technology, 10(4):568–577, 2002.

[0046] [43] Sharon L Padula and Rex K Kincaid. Optimization strategies for sensor and actuator placement. Technical report, 1999.

[0047] [44] Sylvaine Leleu, Hisham Abou-Kandil, and Yvan Bonnassieux. Piezoelectric actuators and sensors location for active control of flexible structures. In Proceedings of the 17th IEEE Instrumentation and Measurement Technology Conference [Cat. No. 00CH37066], volume 2, pages 818–823. IEEE, 2000.

[0048] [45] Gijs van der Veen, Matthijs Langelaar, Stan van der Meulen, Dick Laro, Wouter Aangenent, and Fred van Keulen. Integrating topology optimization in precision motion system design for optimal closed-loop control performance. Mechatronics, 47:1–13, 2017.

[0049] [46] JingWang, Ming Zhang, Yu Zhu, Kaiming Yang, Xin Li, LeijieWang, Jinchun Hu, and Chuxiong Hu. Integrated optimization of 3d structural topology and actuator configuration for vibration control in ultra-precision motion systems. Structural and Multidisciplinary Optimization, 60(3):909–925, 2019.

[0050] [47] Arnoud Delissen, Dick Laro, Harry Kleijnen, Fred van Keulen, and Matthijs Langelaar. High-precision motion system design by topology optimization considering additive manufacturing. In 20th International

[0051] Conference of the European Society for Precision Engineering and Nanotechnology, EUSPEN 2020, pages 257–258. EUSPEN, 2020.

[0052] [48] Robbert van Herpen, Tom Oomen, Edward Kikken, Marc van de Wal, Wouter Aangenent, and Maarten Steinbuch. Exploiting additional actuators and sensors for nano-positioning robust motion control. *Mechatronics*, 24(6):619–631, 2014.

[0053] [49] Ioannis Proimadis, Coen HHM Custers, Roland T’oth, JW Jansen, Hans Butler, Elena Lomonova, and Paul MJ Van den Hof. Active deformation control for a magnetically levitated planar motor mover. *IEEE Transactions on Industry Applications*, 58(1):242–249, 2021.

[0054] [50] Won-jong Kim and David L Trumper. High-precision magnetic levitation stage for photolithography. *Precision engineering*, 22(2):66–77, 1998.

[0055] [51] John L Junkins. Introduction to dynamics and control of flexible structures. Aiaa, 1993.

[0056] [52] Andre Preumont, Jean-Paul Dufour, and Christian Malekian. Active damping by a local force feedback with piezoelectric actuators. *Journal of guidance, control, and dynamics*, 15(2):390–395, 1992.

[0057] [53] Yan-Ru Hu and Alfred Ng. Active robust vibration control of flexible structures. *Journal of sound and vibration*, 288(1-2):43–56, 2005.

[0058] [54] Scott M Newman. Active damping control of a flexible space structure using piezoelectric sensors and actuators. Technical report, NAVAL POSTGRADUATE SCHOOL MONTEREY CA, 1992.

[0059] [55] Enrique J Lavernia and Tirumalai S Srivatsan. The rapid solidification processing of materials: science, principles, technology, advances, and applications. *Journal of Materials Science*, 45(2):287–325, 2010.

[0060] [1A] Butler, Hans. “Position control in lithographic equipment [applications of control].” *IEEE Control Sys. Mag.* Vol. 31 No. 5 (2011): pp. 28–47.

[0061] [2A] Albero, J, Bargiel, S, Passilly, N, Dannberg, P, Stumpf, M, Zeitner, UD, Rousselot, C, Gastinger, K and Gorecki, C. “Micromachined array-type Mirau interferometer for parallel inspection of MEMS.” *Journal of Micromechanics and Microengineering* Vol. 21 No. 6 (2011): p. 065005.

[0062] [3A] Oomen, Tom, van Herpen, Robbert, Quist, Sander, van de Wal, Marc, Bosgra, Okko and Steinbuch, Maarten. “Connecting system identification and robust control for nextgeneration motion control of a wafer stage.” *IEEE Trans. on Ctrl. Sys. Tech.* Vol. 22 No. 1 (2013): pp. 102–118.

[0063] [4A] Oomen, Tom. “Advanced motion control for precision mechatronics: Control, identification, and learning of complex systems.” *IEEJ Journal of Ind. Appl.* Vol. 7 No. 2 (2018): pp. 127–140.

[0064] [5A] Laro, Dick AH, Boshuisen, Rein and van Eijk, Jan. “Design and control of over-actuated lightweight 450 mm wafer chuck.” *2010 ASPE Spring Topical meeting, Cambridge, Massachusetts, USA*: pp. 141–144. 2010. ASPE.

- [0065] [6A] Garcia-Sanz, Mario. "Control Co-Design: an engineering game changer." *Advanced Control for Appl.: Eng. and Ind. Sys.* Vol. 1 No. 1 (2019): p. e18.
- [0066] [7A] van der Veen, Gijs, Langelaar, Matthijs, van der Meulen, Stan, Laro, Dick, Aangenent, Wouter and van Keulen, Fred. "Integrating topology optimization in precision motion system design for optimal closed-loop control performance." *Mechatronics* Vol. 47 (2017): pp. 1–13.
- [0067] [8A] Delissen, Arnoud, Laro, Dick, Kleijnen, Harry, van Keulen, Fred and Langelaar, Matthijs. "High-precision motion system design by topology optimization considering additive manufacturing." *20th Int. Conf. of the European Society for Precision Eng. and Nanotech., EUSPEN 2020*: pp. 257– 258. 2020. EUSPEN.
- [0068] [9A] Wu, Jingjie and Zhou, Lei. "Control Co-design of Actively Controlled Lightweight Structures for High-acceleration Precision Motion Systems." *American Control Conf., to appear*. 2022.
- [0069] [10A] van Herpen, Robbert, Oomen, Tom, Kikken, Edward, van de Wal, Marc, Aangenent, Wouter and Steinbuch, Maarten. "Exploiting additional actuators and sensors for nanopositioning robust motion control." *Mechatronics* Vol. 24 No. 6 (2014): pp. 619–631.
- [0070] [11A] Franklin, Gene F, Powell, J David, Emami-Naeini, Abbas and Powell, J David. *Feedback control of dynamic systems*. Vol. 4. Prentice hall Upper Saddle River (2002).
- [0071] [12A] Ding, Runze, Ding, Chenyang, Xu, Yunlang, Liu, Weike and Yang, Xiaofeng. "An optimal actuator placement method for direct-drive stages to maximize control bandwidth." *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*: pp. 556–561. 2020. IEEE.

[0072] [13A] Ortega, MG and Rubio, FR. "Systematic design of weighting matrices for the H mixed sensitivity problem." *Journal of Process Control* Vol. 14 No. 1 (2004): pp. 89–98.

[0073] [14A] Powell, Michael JD. "A direct search optimization method that models the objective and constraint functions by linear interpolation." *Adv. in opt. and num. analysis*. Springer (1994): pp. 51–67.

[0074] [15A] Rankers, Adrian Mathias. "Machine dynamics in mechatronic systems: An engineering approach."

[0075] [1B] Laro, Dick AH, Rein Boshuisen, and Jan van Eijk. "Design and control of over-actuated lightweight 450 mm wafer chuck." 2010 Spring Topical meeting, Cambridge, Massachusetts, USA. ASPE, 2010.

[0076] [2B] Oomen, Tom, et al. "Connecting system identification and robust control for next-generation motion control of a wafer stage." *IEEE Transactions on Control Systems Technology* 22.1 (2013): 102-118.

[0077] [3B] van Herpen, Robbert, et al. "Exploiting additional actuators and sensors for nano-positioning robust motion control." *Mechatronics* 24.6 (2014): 619-631.

[0078] [4B] Ronde, M. J. C., et al. "Model-based spatial feedforward for over-actuated motion systems." *Mechatronics* 24.4 (2014): 307-317.

[0079] [5B] Huang, Tao, et al. "Pole assignment control of MIMO motion systems with flexible structures and its application to an ultraprecision wafer stage." *IEEE/ASME Transactions on Mechatronics* 23.5 (2018): 2273-2284.

[0080] [6B] Proimadis, Ioannis, et al. "Active Deformation Control for a Magnetically Levitated Planar Motor Mover." IEEE Transactions on Industry Applications 58.1 (2021): 242-249.

[0081] [7B] Van De Wal, Marinus Maria Johannes, et al. "Lithographic apparatus, substrate support system, device manufacturing method and control program." U.S. Patent No. 9,715,182. 25 Jul. 2017.

[0082] [1C] Oomen T, van Herpen R, Quist S, van de Wal M, Bosgra O, Steinbuch M. Connecting system identification and robust control for next-generation motion control of a wafer stage. IEEE Transactions on Control Systems Technology. 2013;22(1):102-118.

[0083] [2C] Oomen T. Advanced motion control for precision mechatronics: Control, identification, and learning of complex systems. IEEJ Journal of Ind Appl. 2018;7(2):127-140.

[0084] [3C] Laro DA, Boshuisen R, van Eijk J. Design and control of over-actuated lightweight 450 mm wafer chuck. In: 2010 ASPE Spring Topical meeting, Cambridge, Massachusetts, USA. ASPE; 2010. p. 141-144.

[0085] [4C] van Herpen R, Oomen T, Kikken E, van de Wal M, Aangenent W, Steinbuch M. Exploiting additional actuators and sensors for nano-positioning robust motion control. Mechatronics. 2014;24(6):619-631.

[0086] [5C] Wang J, Zhang M, Zhu Y, Yang K, Li X, Wang L, et al. Integrated optimization of 3D structural topology and actuator configuration for vibration control in ultra-precision motion systems. Structural and Multidisciplinary Optimization. 2019;60(3):909-925.

[0087] [6C] Wu J, Zhou L. Control Co-design of Actively Controlled Lightweight Structures for High acceleration Precision Motion Systems. In: American Control Conf., to appear; 2022. .

[0088] [7C] Butler H. Position control in lithographic equipment [applications of control]. IEEE Control Sys Mag. 2011;31(5):28-47.

[0089] [8C] Franklin GF, Powell JD, Emami-Naeini A, Powell JD. Feedback control of dynamic systems. vol. 4. Prentice hall Upper Saddle River; 2002.

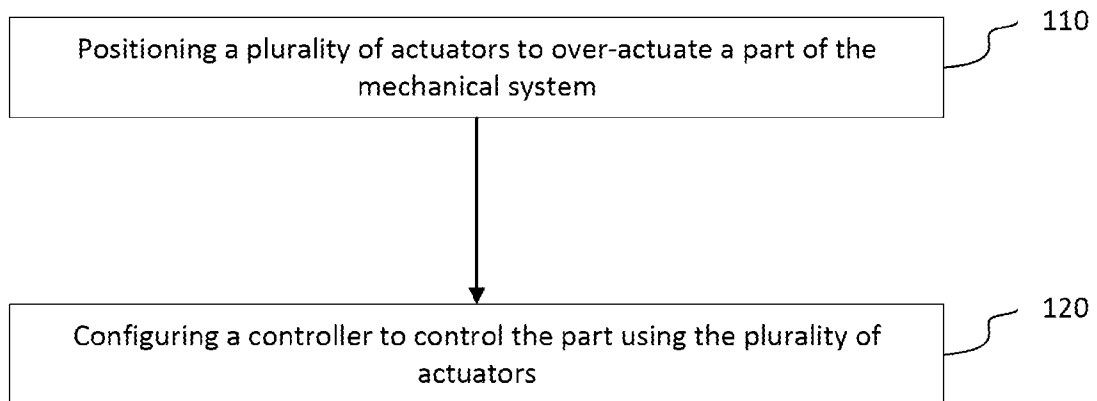
[0090] [9C] Powell MJ. A direct search optimization method that models the objective and constraint functions by linear interpolation. In: Adv. in opt. and num. analysis. Springer; 1994. p. 51-67.

WHAT IS CLAIMED:

1. A system comprising:
 - a part;
 - a plurality of actuators configured to over-actuate the part; and
 - a computing device in operable communication with the plurality of actuators, wherein the computing device comprises a processor and a memory, the memory having computer-executable instructions stored thereon that, when executed by the processor, cause the processor to: control the part using the plurality of actuators.
2. The system of claim 1, wherein the part is a selectively compliant part.
3. The system of claim 2, wherein the selectively compliant part is configured to have a first flexible mode.
4. The system of claim 3, wherein the memory has further computer-executable instructions stored thereon that, when executed by the processor, cause the processor to control the first flexible mode of the selectively compliant part.
5. The system of claim 4, wherein controlling the first flexible mode of the selectively compliant part comprises actively controlling a flexible dynamic of the selectively compliant part.

6. The system of claim 3, wherein the plurality of are configured so that a control bandwidth of the system is greater than the first flexible mode.
7. The system of claim 3, wherein the part has a second flexible mode greater than the first flexible mode.
8. The system of claim 7, wherein the second flexible mode is greater than a control bandwidth of the system.
9. The system of claim 1, wherein the part is a precision stage.
10. The system of claim 1, wherein the part is a laser-cutting mirror.
11. The system of claim 3, wherein the first flexible mode is a bending mode.
12. A method of designing an over-actuated system, comprising:
 - positioning a plurality of actuators to over-actuate a part of the over-actuated system; and
 - configuring a controller to control the part using the plurality of actuators.
13. The method of claim 12, further comprising configuring the part in the over-actuated system to be selectively compliant.

14. The method of claim 13, wherein the part is configured to have a first flexible mode.
15. The method of claim 14, wherein configuring the controller to control the part using the plurality of actuators comprises configuring the controller to control the first flexible mode of the part.
16. The method of claim 15, wherein the controller has a control bandwidth less than a second flexible mode of the part.
17. The method of claim 15, wherein the controller is configured so that a control bandwidth of the system is greater than the first flexible mode.
18. The method of claim 14, wherein the first flexible mode is a bending mode.
19. The method of claim 12, wherein the part is a precision stage and the over-actuated system is a photolithography machine.
20. The method of claim 12 wherein the part is a laser-cutting mirror and the over-actuated system is a laser cutter.

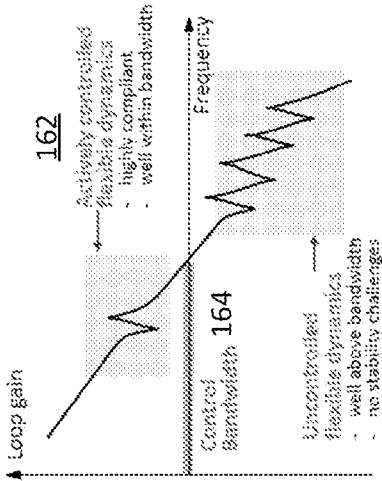
100**FIG. 1A**

150

160

1. Hardware Parameter Design

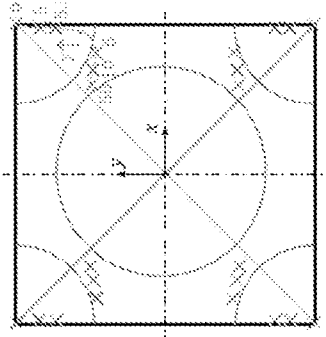
$$\begin{aligned} \min_{\theta_p} J_m(\theta_p), \\ \text{s.t. } \omega_i \leq \omega_{\text{low}}, \quad i = 1, \dots, n \\ \omega_j \geq \omega_{\text{high}}, \quad j = n+1, \dots, m \\ \theta_{p,\min} \leq \theta_p \leq \theta_{p,\max} \end{aligned}$$



170

2. Actuator/sensor placement

$$\begin{aligned} \max_{\theta_i \in \mathcal{O}_a} J_a(\theta_a) &= \sum_{i=1, \dots, a} W_{ai}(\theta_a) - \gamma \sum_{i=1, \dots, m} W_{bi}(\theta_b), \\ \max_{\theta_i \in \mathcal{O}_s} J_s(\theta_s) &= \sum_{i=1, \dots, a} W_{sa}(\theta_s) - \gamma \sum_{i=1, \dots, m} W_{si}(\theta_s), \\ W_{pi} &= \frac{\|z_i(\theta_i)^T B_a(\theta_a)\|^2}{4\zeta_i \omega_i}, \quad W_{si} = \frac{\|C_s(\theta_s)^T z_i(\theta_s)\|^2}{4\zeta_i \omega_i} \end{aligned}$$



180

3. Controller Design

$$\begin{aligned} M(\theta_p)\ddot{x} + D(\theta_p)\dot{x} + K(\theta_p)x &= B(\theta_p, \theta_a)u \\ \dot{y} &= C(\theta_p, \theta_s)x \end{aligned}$$

Loop shaping controller satisfying robustness requirement

$$C_k(s) = K_p \left(\frac{s + \omega_i}{s} \right) \left(\frac{s}{\omega_d} + 1 \right) \left(\frac{\omega_{fp}^2}{s^2 + 2\zeta_{fp}\omega_{fp}s + \omega_{fp}^2} \right)$$

$$\|S_k(s)\|_{\infty} \leq 2, \quad k = 1, \dots, n,$$

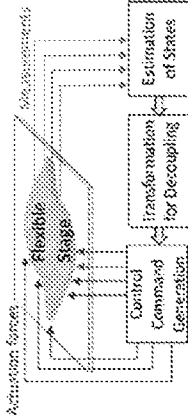


FIG. 1B

200

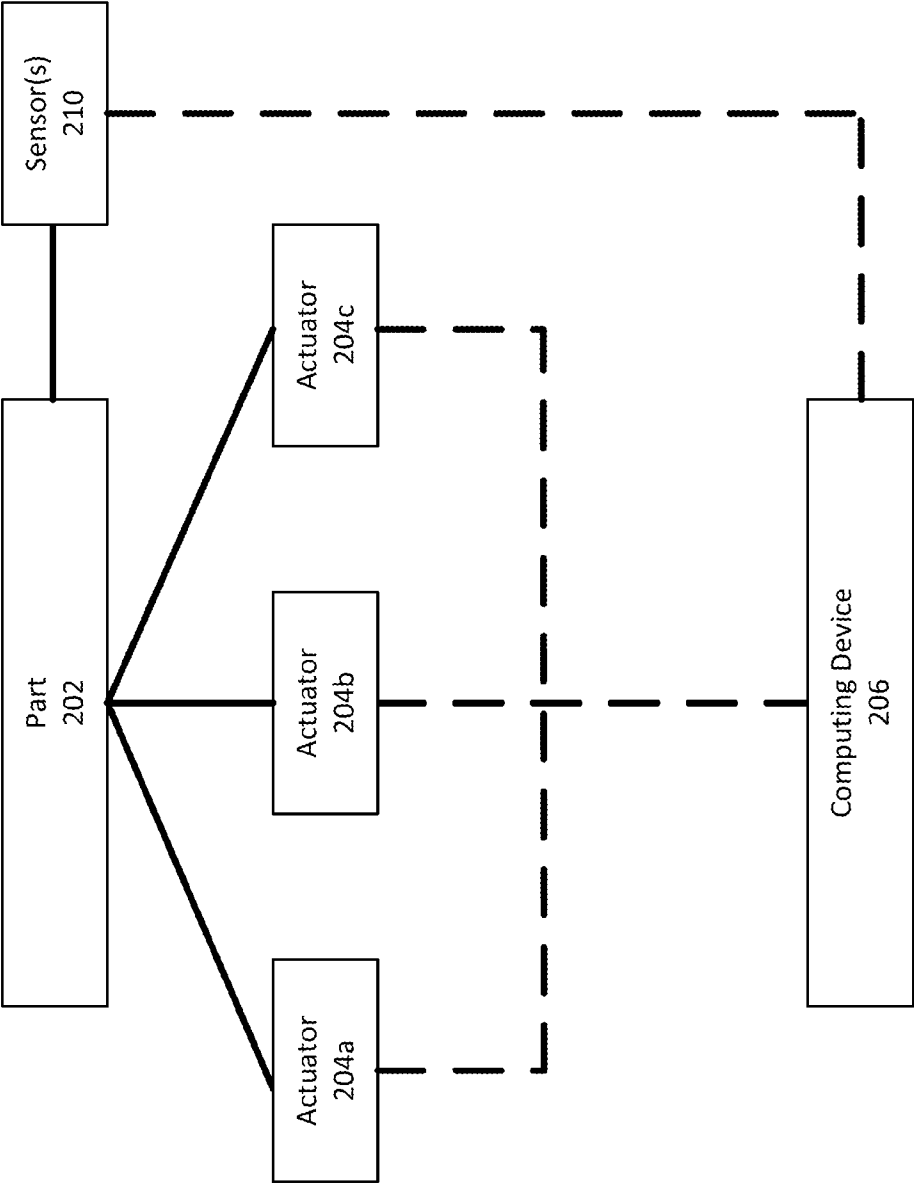


FIG. 2

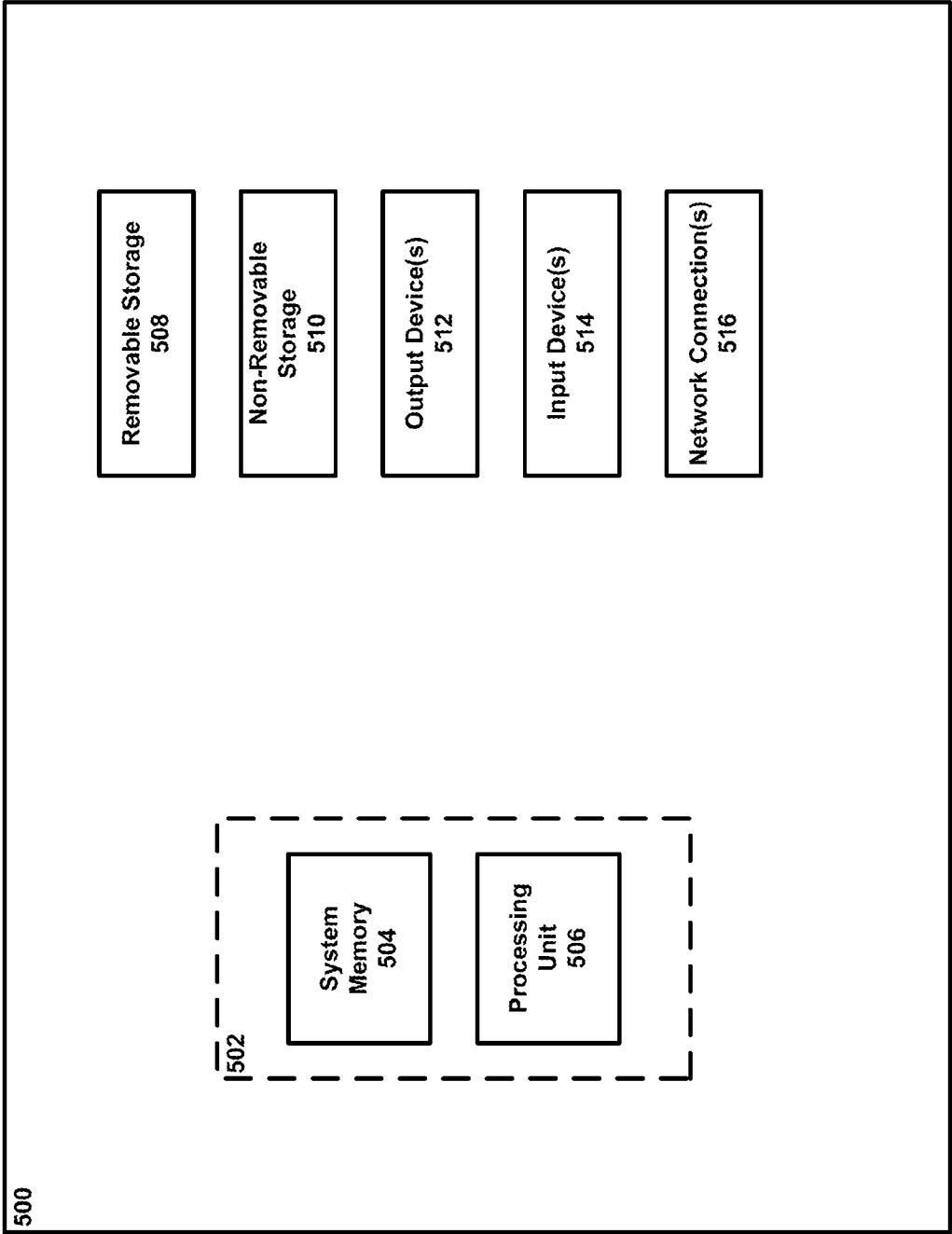
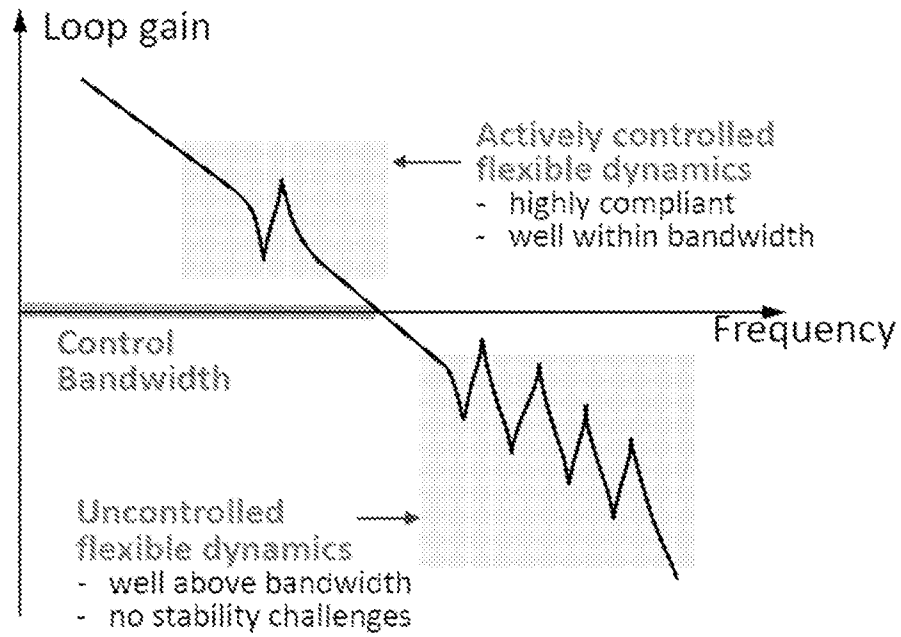
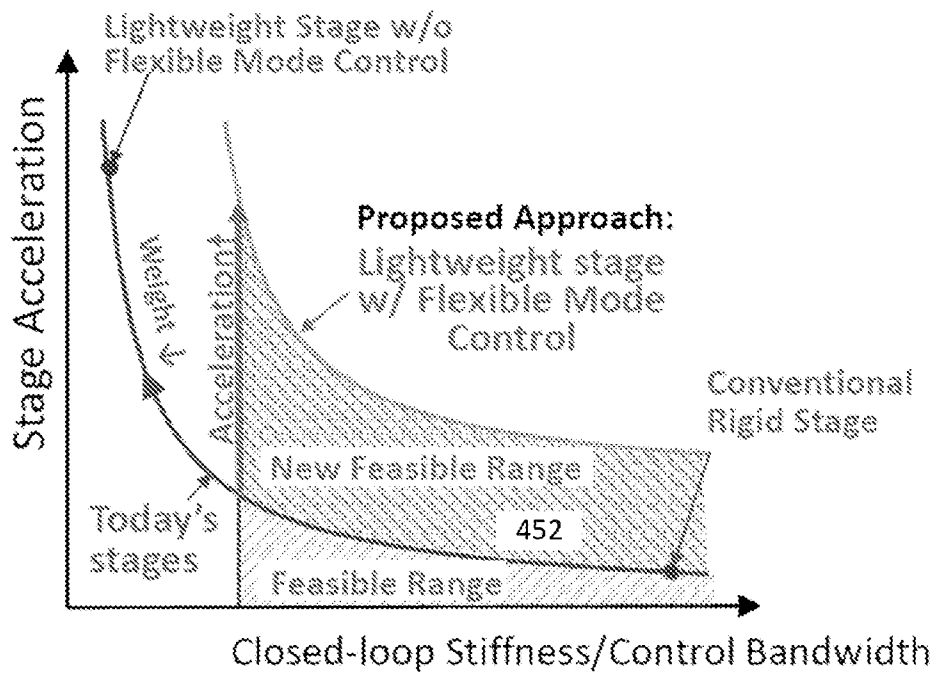


FIG. 3

**FIG. 4A****FIG. 4B**

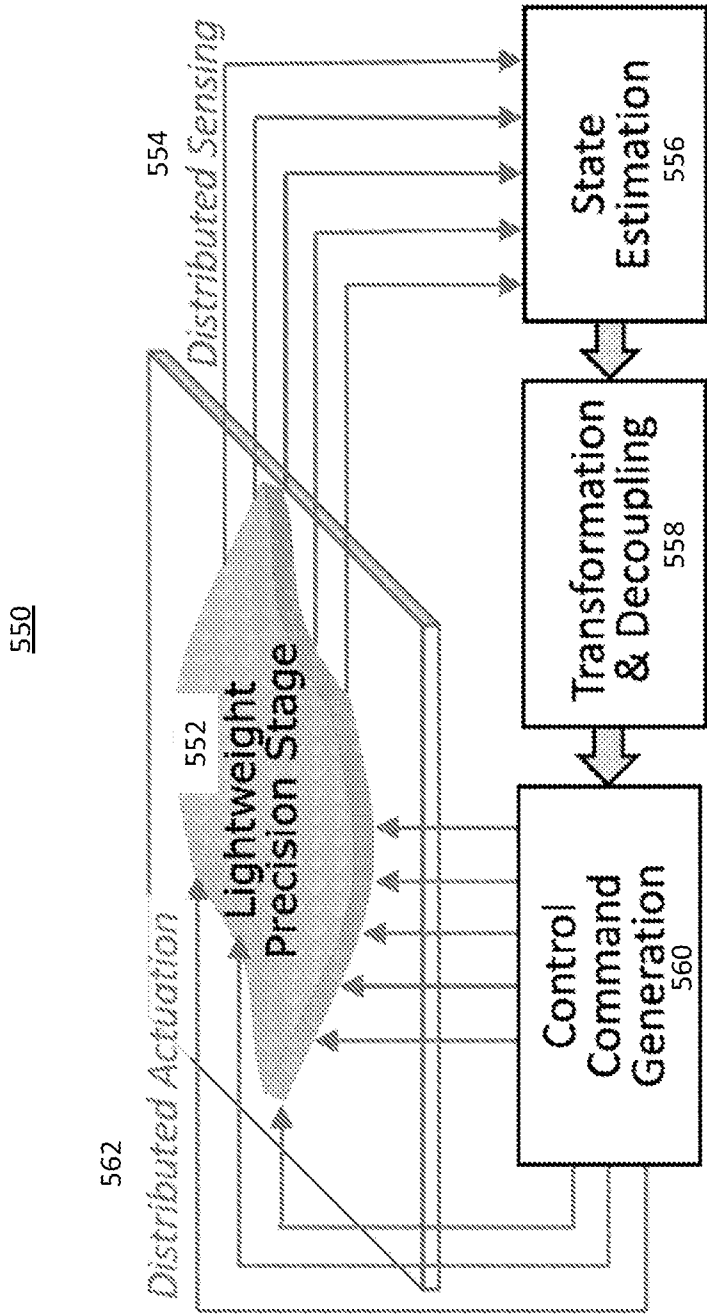


FIG. 5

TABLE 1: CONTROLLER PARAMETERS [1].

Parameter	Description	Typical Value
ω_{bw}	Desired bandwidth [rad/s]	–
α	PID frequency ratio	0.3
K_p	Proportional gain	–
ω_i	Integrator frequency	ω_{bw}/α^2
ω_d	Differentiator frequency	ω_{bw}/α
ω_{lp}	Lowpass filter frequency	$\alpha\omega_{bw}$
z_{lp}	Lowpass filter damping ratio	0.7

FIG. 6

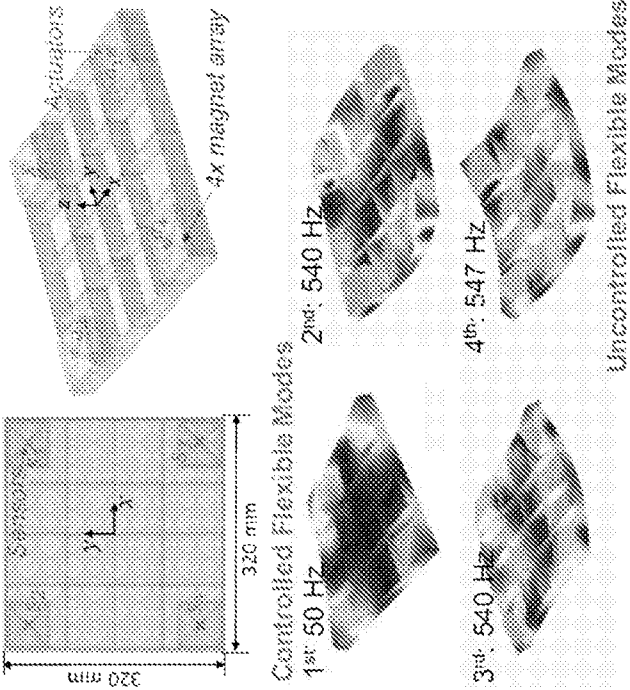


FIG. 7A

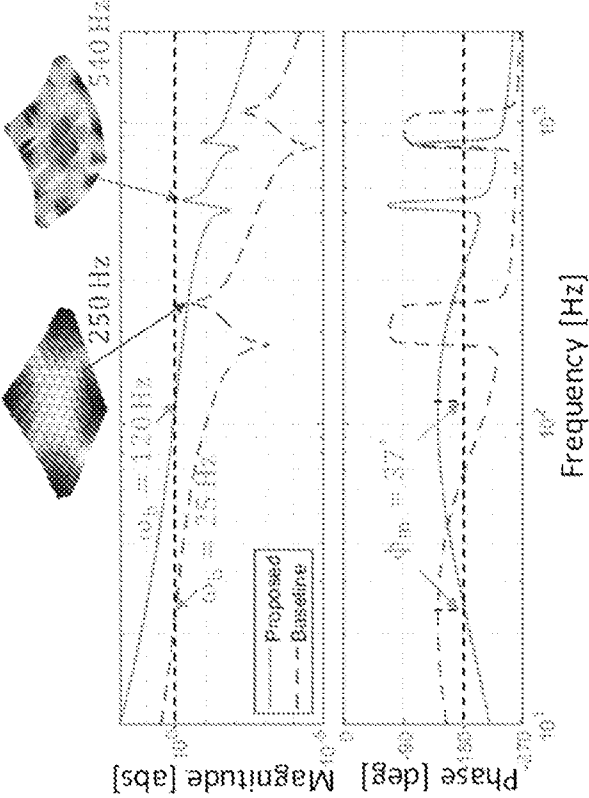
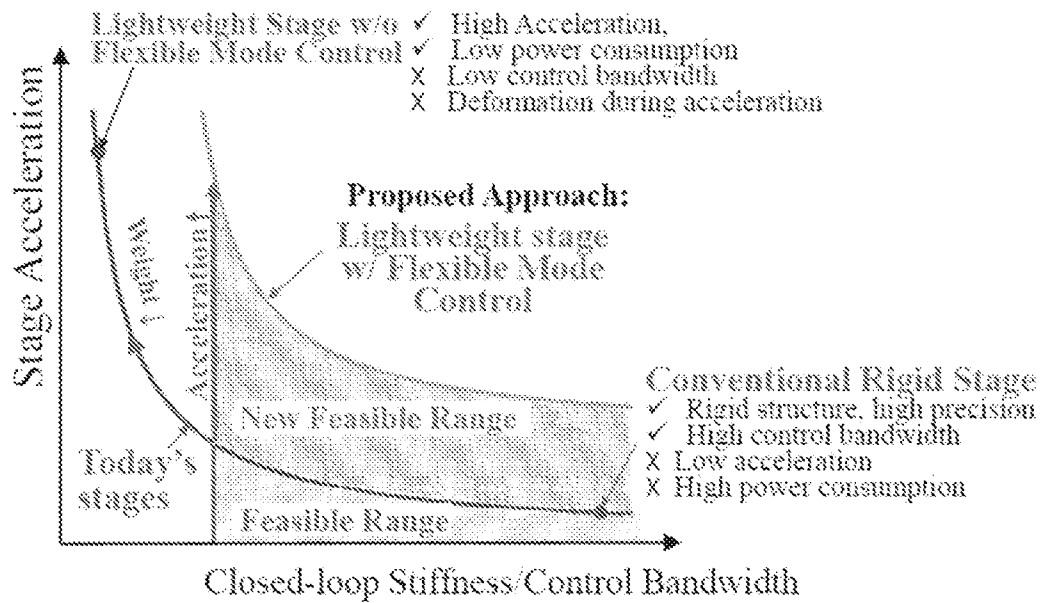
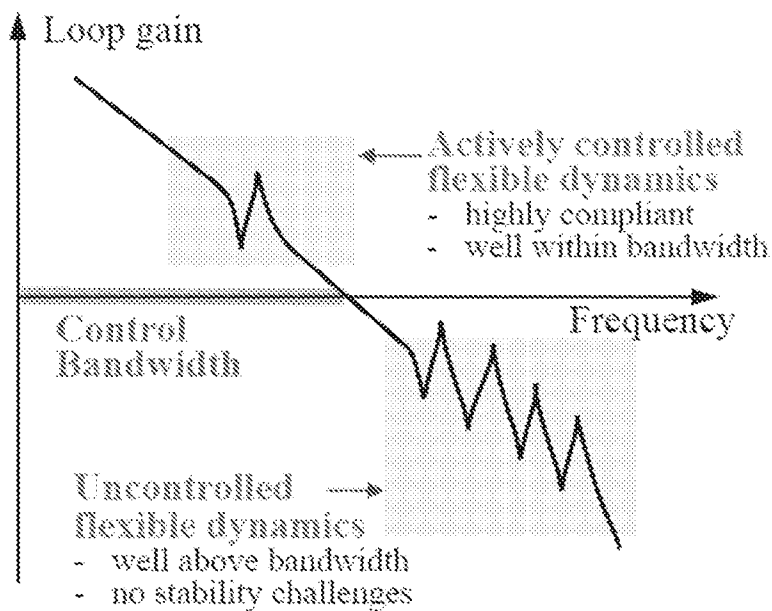


FIG. 7B

**FIG. 8A****FIG. 8B**

900

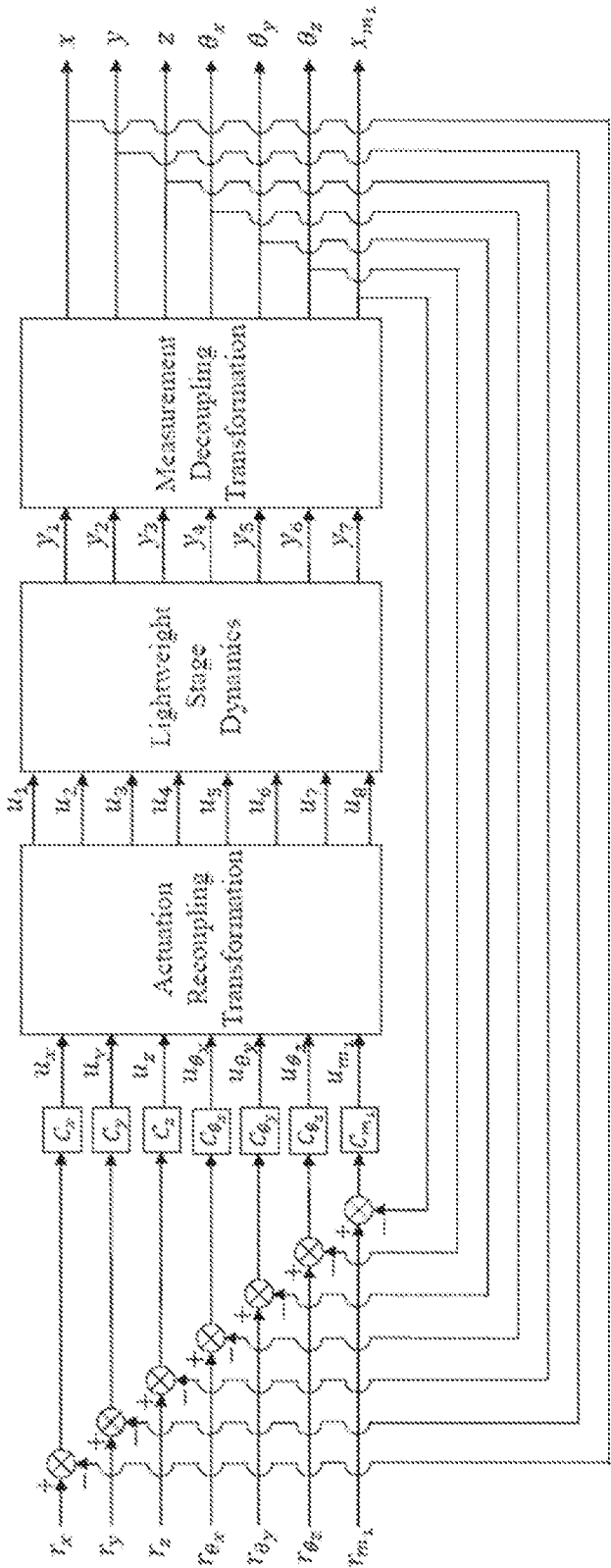


FIG. 9

Parameter	Description	Typical Value
ω_{bw}	Desired bandwidth [rad/s]	—
α	PID frequency ratio	3
K_p	Proportional gain	—
ω_i	Integrator frequency	ω_{bw}/α^2
ω_d	Differentiator frequency	ω_{bw}/α
ω_{lp}	Lowpass filter frequency	$\alpha\omega_{bw}$
z_{lp}	Lowpass filter damping ratio	0.7

FIG. 10

Proposed: Practical lightweight stage w/ 1st flexible mode controlled

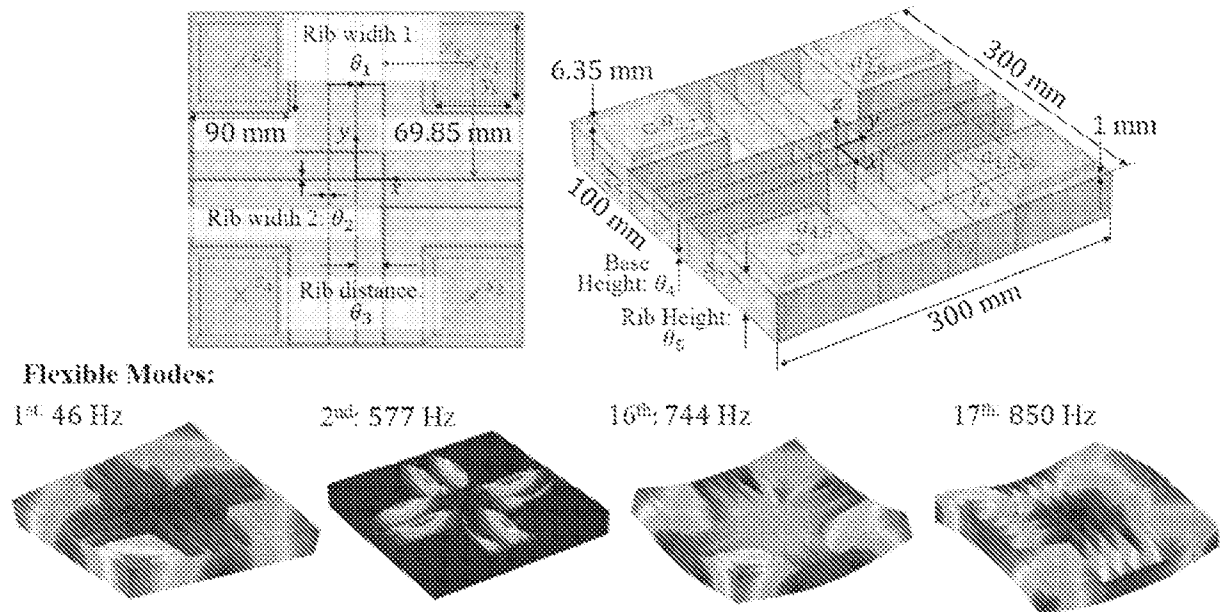


FIG. 11A

Baseline: Practical precision stage w/o flexible mode control

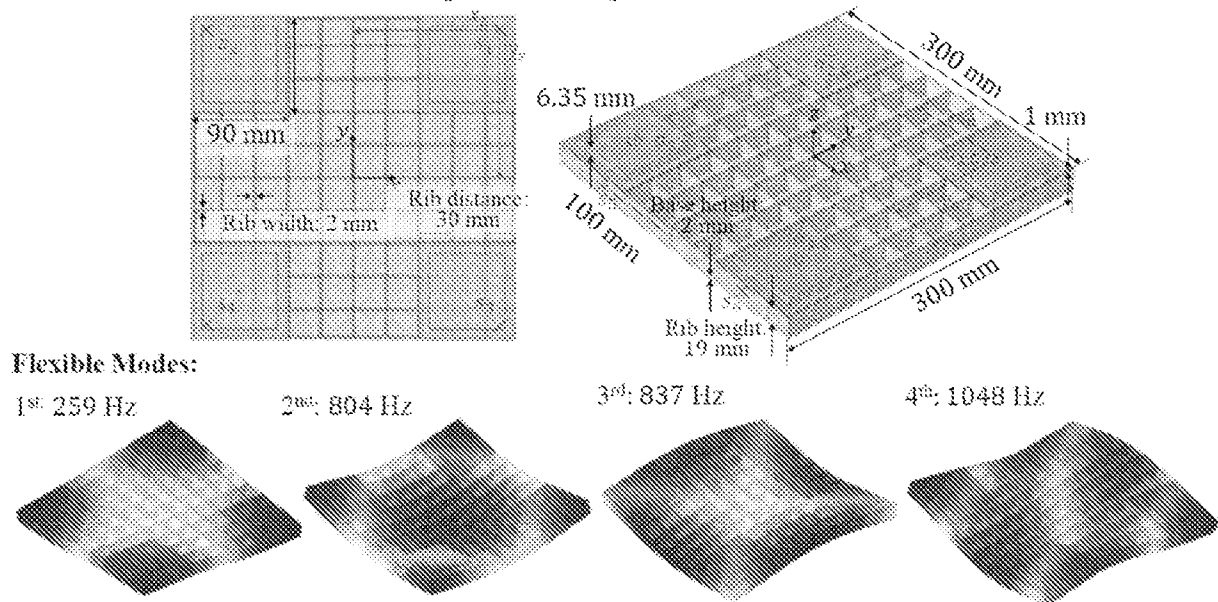


FIG. 11B

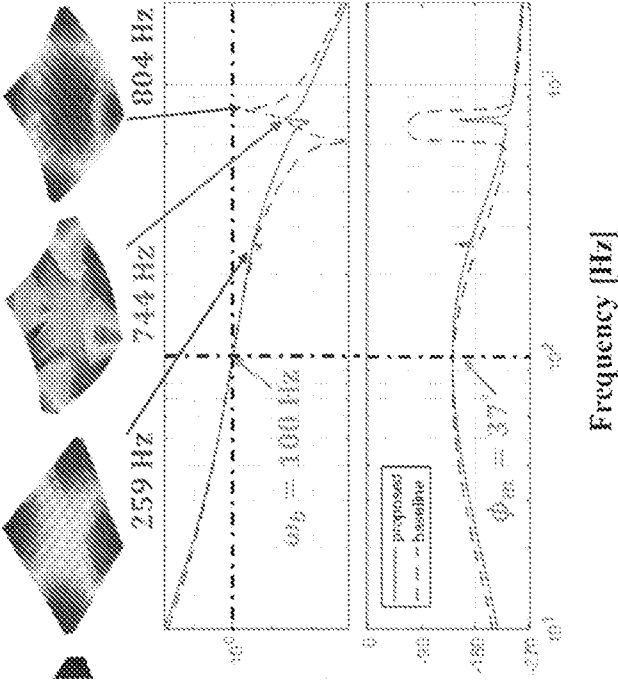


FIG. 12A

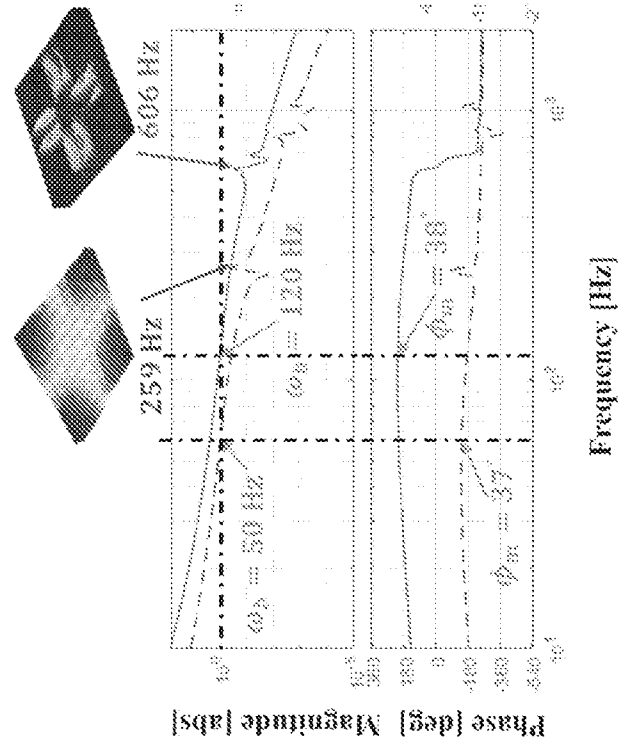


FIG. 12B

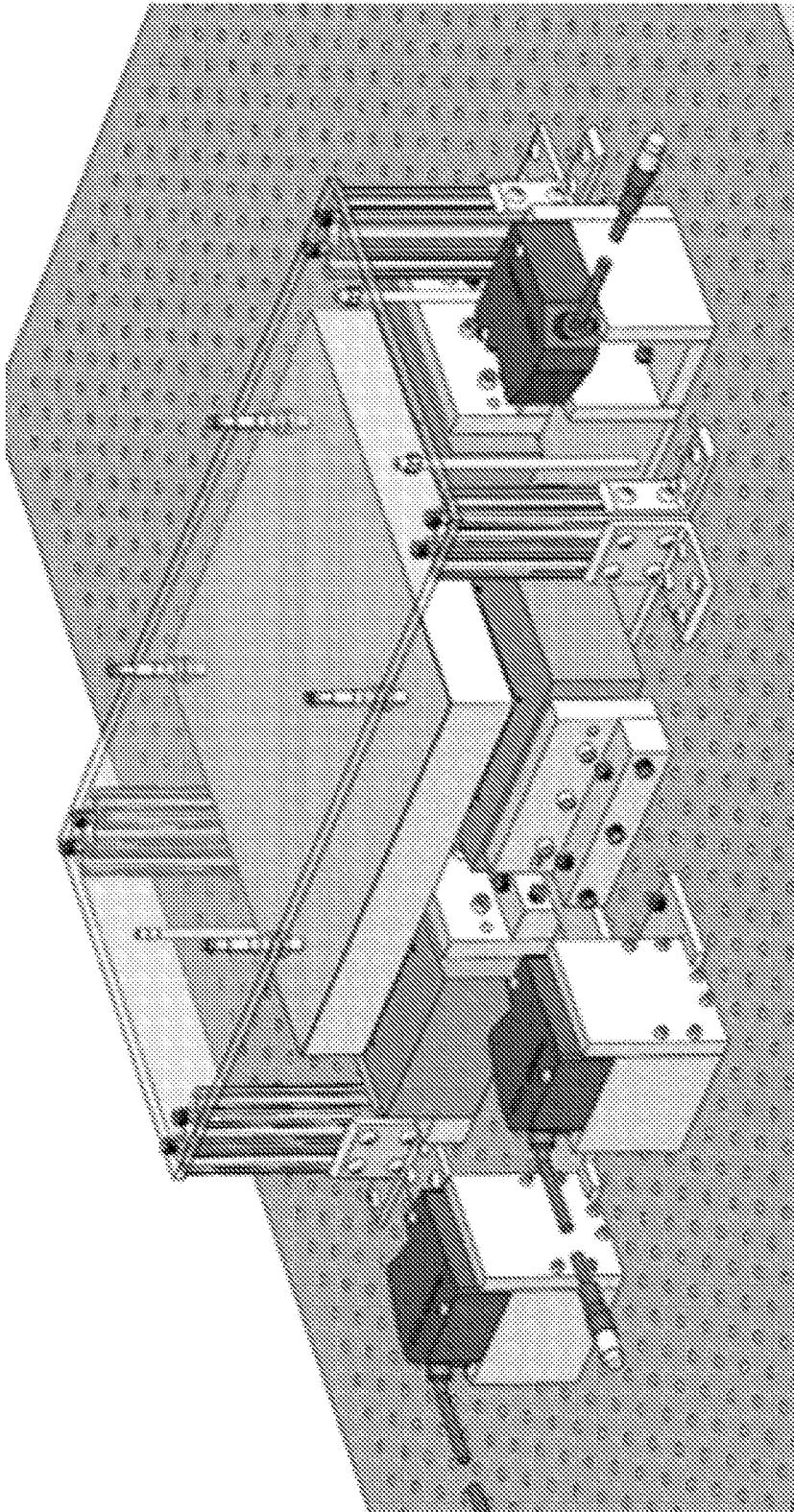


FIG. 13

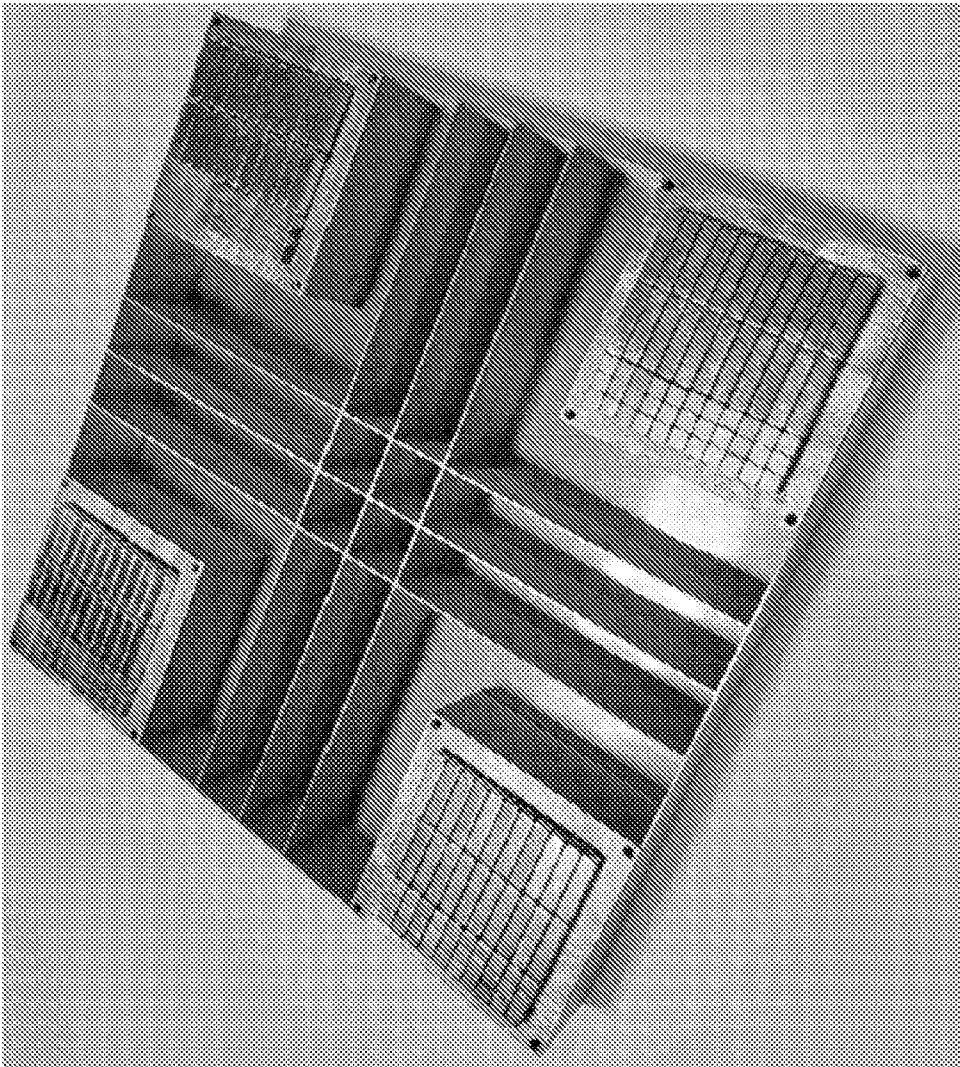


FIG. 14

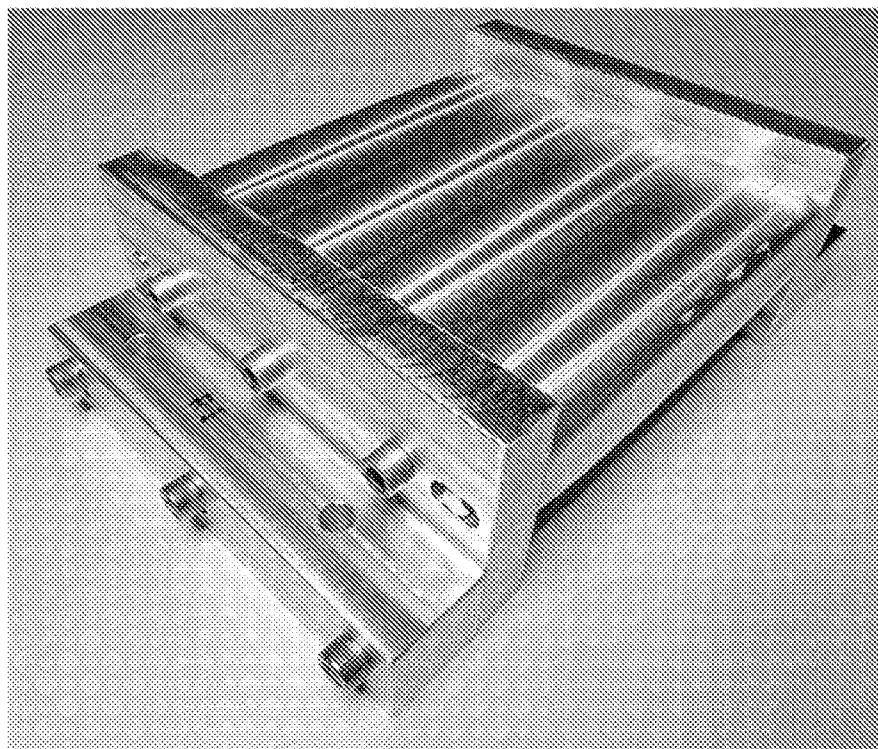


FIG. 15A

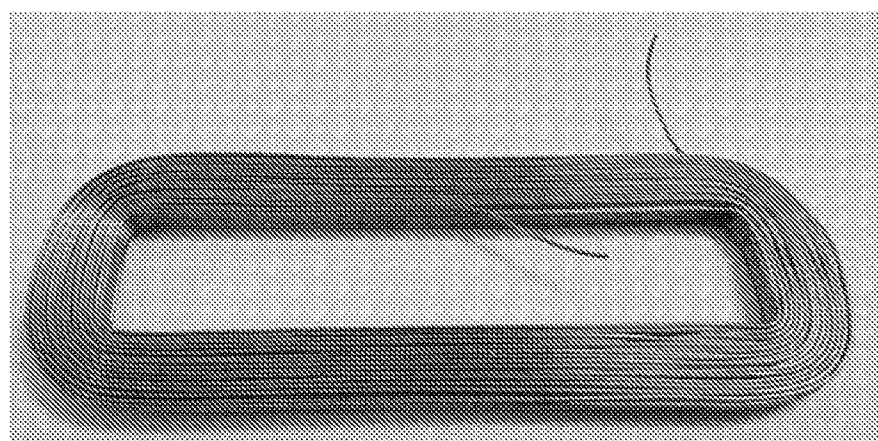


FIG. 15B

	Baseline Design	Proposed Design
Stage weight	2.21 kg	1.68 kg
First res. freq.	259 Hz	46 Hz
2nd res. freq.	804 Hz	577 Hz
<i>y</i> motion bandwidth	50 Hz	120 Hz
<i>z</i> motion bandwidth	100 Hz	100 Hz
Max sensitivity	1.94	1.92

FIG. 16

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2023/033486

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - INV. - B25J 9/10; G03F 7/20; G05D 3/12 (2023.01)

ADD. - G02B 7/198 (2023.01)

CPC - INV. - B25J 9/10; G03F 7/20; G05D 3/12 (2023.08)

ADD. - G02B 7/198 (2023.08)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

See Search History document

Electronic database consulted during the international search (name of database and, where practicable, search terms used)

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2015/0316860 A1 (ASML NETHERLANDS B.V.) 05 November 2015 (05.11.2015) entire document	1-5, 7, 9, 10, 12-15, 19, 20
---		---
Y		6, 8, 11, 16-18
Y	US 2017/0038693 A1 (ASML NETHERLANDS B.V.) 09 February 2017 (09.02.2017) entire document	6, 8, 11, 16-18
A	US 2014/0340666 A1 (ASML NETHERLANDS B.V.) 20 November 2014 (20.11.2014) entire document	1-20
A	US 2018/0181005 A1 (CARL ZEISS SMT GMBH) 28 June 2018 (28.06.2018) entire document	1-20
A	US 2017/0119347 A1 (NEURAL ANALYTICS INC.) 04 May 2017 (04.05.2017) entire document	1-20

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"D" document cited by the applicant in the international application

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

14 November 2023

Date of mailing of the international search report

DEC 11 2023

Name and mailing address of the ISA/

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, VA 22313-1450

Facsimile No. 571-273-8300

Authorized officer

Taina Matos

Telephone No. PCT Helpdesk: 571-272-4300