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Design and control of a cascaded piezoelectric actuated two-degrees-of-freedom positioning compliant stage

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ABSTRACT

A novel piezoelectric driven compliant stage and its associated PC-based X–Y axes control schemes have been developed as a potential carrier of automatic optical inspection (AOI) systems and other possible applications in precision positioning. The design is based on compliant structure with a mechanical amplifier mechanism. Two orthogonal stages are integrated into a final 2-DoF design. This approach offers the advantages of directly using a well-development design with minor modifications and the performance can be more precisely controlled. However, this also brings concerns in coupling between two motion axes due to manufacturing and alignment errors and this issue is examined experimentally. By integrating feedback control with the stage, it is possible to perform precision positioning and vibration suppression for improving the dynamic performance. This cascaded structure design can effectively reduce the system complexity and can be further extended for additional degrees of freedom. Based on the test results, the designed stage can achieve a closed loop bandwidth up to 100 Hz and a steady state resolution less than 50 nm using a model reference sliding mode controller. In addition, a shaping-control integration approach is also demonstrated for providing faster positioning while maintaining the robustness against possible external disturbances. Meanwhile, the experimental results indicate that the coupling due to manufacturing and assembly errors exists but this can be effectively reduced by proper trajectory planning with incorporating of dual-axis control. In summary, this study has realized a structurally-simple and low-cost positioning system and is able to achieve high-precise motion. It is hope that this study can be further expanded to longer stroke and higher precise positioning system, and integrates with cutting edge technologies for developing more superior precise instrument in the future.

1. Introduction

With the advancement in manufacturing of semiconductors and display products, the demand in product inspection becomes more rigorous in both performance and throughput requirements. Consequently, those requirements impose stringent demands on high precision positioning controls [1–4]. Taking the *Automatic Optical Inspection* (AOI) system as an example, AOI play an important role on modern industries for performing large-area defect inspection. Typical AOI systems contain CCD cameras mounted on a gantry [5]. By controlling the movement of the gantry, it is possible to perform the inspection task. However, the motion induced vibration during fast maneuvers could significantly increase the settling time and therefore deteriorate the inspection yield. Such a design may not result in acceptable performance and alternative design approach should be sought. In addition to the above AOI example, applications in coordinate measurement system also have similar requirements since it also requires both fast positioning and fast settling. Nevertheless, by introducing a precision stage into the original structures and incorporated with appropriate feedback control, it is possible to improve their dynamic performance.

Precision stages have been widely used in all fields requiring accurate positioning and numerous designs have been proposed [6–11]. In this work, as schematically shown in Fig. 1, a modified AOI system concept is proposed by introducing a compliant stage mounted on the gantry for carrying the CCD cameras. By this approach, it is possible to eliminate the relative vibration between the inspector and the target by actively controlling the stage with a much higher bandwidth. Previously, we have demonstrated the design and control for a 1-DoF stage as the first step to realize this approach [12]. The controlled bandwidth, approximately 100 Hz, in together with maximum stroke of 80 μm and a steady state resolution of 50 nm, proves the feasibility of suppressing motion induced vibration. In order to completely realize the proposed approach

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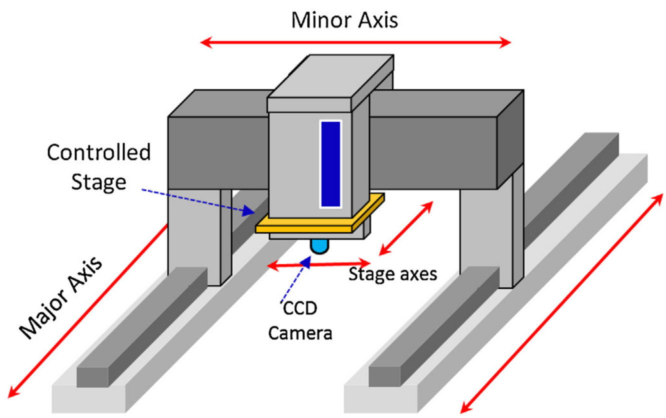

Fig. 1. Schematic plot of the stage-based AOI inspection system.

Table 1
Essential design parameters and results for stage design.

	Upper level	Bottom level
Young's modulus (GPa)	68.9	68.9
Yield strength (MPa)	255	255
Actuator stroke ΔL_0(μm)	60	60
Linkage length L1 (mm)	47.1	47
Linkage length L2 (mm)	39.5	39
Stage thickness b (mm)	15	7.5
Stage width h (mm)	4.8	5
Hinge thickness t (mm)	0.8	1
Hinge radius R (mm)	2	2
Stage stroke (μm)	95.8	100.71
Stage stiffness (N/μm)	0.37	0.29
Max. stress (MPa)	44.65	52.83
Natural frequency (Hz)	276.5	155.1
Amplification ratio	1.6	1.68
Stage mass (kg)	0.092	0.125

for a general AOI motion, a 2-DoF stage is required. There are many types of 2-DoF design approaches such as parallel kinematic design [13,14], serial kinematic design [15], and cascaded kinematic designs, which is actually a special group of the serial kinematic design with special emphasis on their orthogonality between axis. In this work, we choose the solution by extending the previous design into perform 2-DoF motion by cascading two 1-DoF designs [12]. That is, both the upper and bottom stages have the same design approach and thus the same analytical model. This approach allows us to directly use the previous knowledge and experience and the performance can be expected. However, this approach still needs to overcome certain technical difficulties. Since the upper level stage and its sensor/actuator must be attached upon the corresponding bottom level stage, it is challenging to design an effective bottom stage to incorporate the upper one with sufficient dynamic performance. The possible coupling between two major axes due to assembly and manufacturing error could also bring possible degradations in key control performance. This could be non-trivial issue since the piezoelectric does not act toward the center of mass of the stage for the purpose of amplifying the stroke by levering and such an eccentric loading could cause stage rotation and therefore coupling between motion axes. These issues will also be investigated in this work.

In addition to stage structural design, the implementation of associate control schemes is also important for achieving the final performance. Traditional PID control is usually investigated at the very beginning moment for evaluating the baseline performance of incorporating control. Other more sophisticated schemes such as robust, optimal, or multi-variable controls are then followed for further improving the performance. In this work, the PID control for the stage will be firstly investigated as before. Due to the possible payload variation during service, the robustness of the stage is particularly important and the sliding mode control will also be implemented. The performance of these two controller design will be addressed in this work. Finally, an open-loop based input shaping method is also investigated since it can usually result in very fast response. However, such a scheme cannot resist possible external disturbances. As a result, the hybrid shaping-control integration scheme is used. That is, with proper design, the system should have faster response by input shaping and sufficient disturbance rejection and robustness provided by its feedback controller. Furthermore, the feasibility of incorporating two-axis feedback controls for reducing the manufacture and assembly induced coupling behavior will also be investigated.

The remainder of this paper presents the design, testing, and control of the stage in detail. The conceptual design analysis is performed in Section 2 and followed by the finite element structural design and dynamics simulation, as well as the dynamic characterization, in Section 3. The system dynamics modelling and control design analysis is then addressed in Section 4 and followed by the experimental performance evaluation of these controllers presented in Sections 5. The dual axis control and demonstration of the final performance of the stage is then shown in Section 6. Essential issues regarding to the contribution and key lessons learned in this work are discussed in Section 7. Finally, Section 8 concludes this work.

2. Design analysis

As mentioned above the cascaded stage design utilized two orthogonal stages with a similar design. The upper and bottom level stages, as well as the entire assembly of the stage, are shown in Fig. 2 for the purpose of illustration. The upper stage is essentially the same as our previous design [12] except for adding an extension arm for transduction purpose. On the other hand, the bottom stage looks more complicated because it needs to carry the entire upper level stage and the associated sensors and actuators, as well as their supporting structures. As a result, the size and the main stage body are significantly changed and a focus on designing for low-mass is required to avoid degradations in dynamic performances. Nevertheless, it still adopts the same compliant design by using the same amount of notch and the same amplification design. As a result, both stages actually have the same analytical models, which are briefly addressed below.

The stage design flow essentially follows our previous work addressed in [12] and is briefly presented here. For technical development in compliant mechanisms design, one can refer to [16–18] for details. First, consider a compliant notch schematically shown in Fig. 3a, the rotating angle under a moment M of the notch can be expressed as [17]

$$\theta_Z = \frac{24kRM}{Ebt^3}, \tag{1}$$

where R, b, t are the notch radius, width, and the minimum thickness shown in Fig. 3a and k is a dimensionless correction factor. By replacing the bending moment M as a force F times the moment arm L, and approximating θ_Z as a lateral displacement x divided by the arm length L, the stiffness of each notch structure can be expressed as

$$K \equiv \frac{F}{x} = \frac{Ebt^3}{24kRL^2}. \tag{2}$$

Eq. (2) serves as the fundamental equation for modeling the stiffness in this work. Table 1 shows the key parameters of the upper and the bottom stages, respectively. The design, shown in Fig. 3b, contains 8 notches with four smaller linkages L_2 and two notches