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A Novel Compliant Stage with Input-Output Decoupling Based on a Parallel Mechanism

Yifan Wang[1,a,*]

[1]*Beijing Forestry University, Haidian District, Beijing, 100083, China*
a. 787924294@qq.com
**corresponding author*

Abstract: Due to the low stiffness and loose structure of some previously studied large-stroke XY positioning stages, this paper presents the design of a novel XY micropositioning stage based on a leaf-shaped flexible parallel mechanism. By modularizing the parallel mechanism and combining individual modules, a compact XY flexible stage with mixed series and parallel kinematics is developed. The stage is driven by a voice coil motor to decouple the input and output directions. In the mechanism design, the mechanical characteristics of single parallel, double parallel, and hybrid series mechanisms are studied in detail. A symmetrical layout is adopted to combine these mechanisms according to their individual characteristics, resulting in the novel flexible stage. Theoretical calculations and finite element simulation (FEA) analysis are performed to evaluate the stage's overall characteristics, including its range of motion, stiffness, and natural frequency. The stage can be accurately positioned within a working space of 15.4 mm × 15.4 mm and exhibits a high natural frequency.

Keywords: Decoupling, flexible mechanism, micropositioning, compact structure, FEA

1. Introduction

Advancements in science and technology have increased the demand for micro/nano positioning stages in precision engineering. Their application areas include biomedical imaging[1], semiconductor testing and manufacturing[2, 3], dynamic modulation of meta-surfaces[4],and micro-operation systems[5], among others. As micro/nano positioning stages are used in more high-tech fields, the performance requirements for these stages have become more demanding. Traditional positioning stages have exposed many shortcomings when facing these challenges, such as insufficient positioning accuracy, limited travel range, and lack of compact structure[6].

Flexible mechanisms have significant advantages in the construction of micro/nano positioning stages. Due to their elastic deformation capabilities, they can achieve high-precision repeated motion ranging from the nano to centimeter scale. Flexible joints do not suffer from dry friction, gaps, or wear, ensuring stable and accurate motion. The simple structure not only facilitates processing and assembly but also simplifies the input and output of motion, enhancing precision and repeatability. These advantages play an important role in many precision positioning applications[7].

In traditional designs, if the displacement between axes is not compensated, it often results in significant coupling displacement. Large coupling displacements can severely affect the stage's positioning accuracy. Reducing coupling is an important issue to address when designing a successful positioning stage. According to the literature, there are many methods for reducing coupling. For

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example, Xu Qingsong and Wan Sicong proposed a dual-layer positioning stage based on the Roberts mechanism, which uses a symmetric structure to reduce the impact of asymmetry on the system[8]. Zhen Zhang, Peng Yan, and Guangbo Hao suggested adding redundant constraint modules to reduce parasitic error motion and improve the system's decoupling capability[9]. Shorya Awtar and Gaurav Parmar proposed using dual parallelogram flexible modules to achieve high geometric decoupling of two motion axes, avoiding geometric over-constraint and reducing parasitic error motion[10]. Steven I. Moore and others also proposed a serial kinematic arrangement that successfully softened the in-plane axes to increase displacement gain and reduce cross-axis coupling[11].

In this paper, I will attempt to design a novel compact planar flexible positioning stage. The mechanism cleverly connects and combines parallelogram flexible modules in series or parallel to achieve high decoupling of the two motion axes. The mechanism is driven by two voice coil motors (VCMs) and can achieve small volume, large stroke, high positioning accuracy, and fast response.

2. Mechanism Design

In this section, the basic characteristics of the parallelogram mechanism are introduced, along with its modular combination design in both parallel and serial kinematics. The individual modules are combined to design a highly decoupled, compact large-stroke positioning stage.

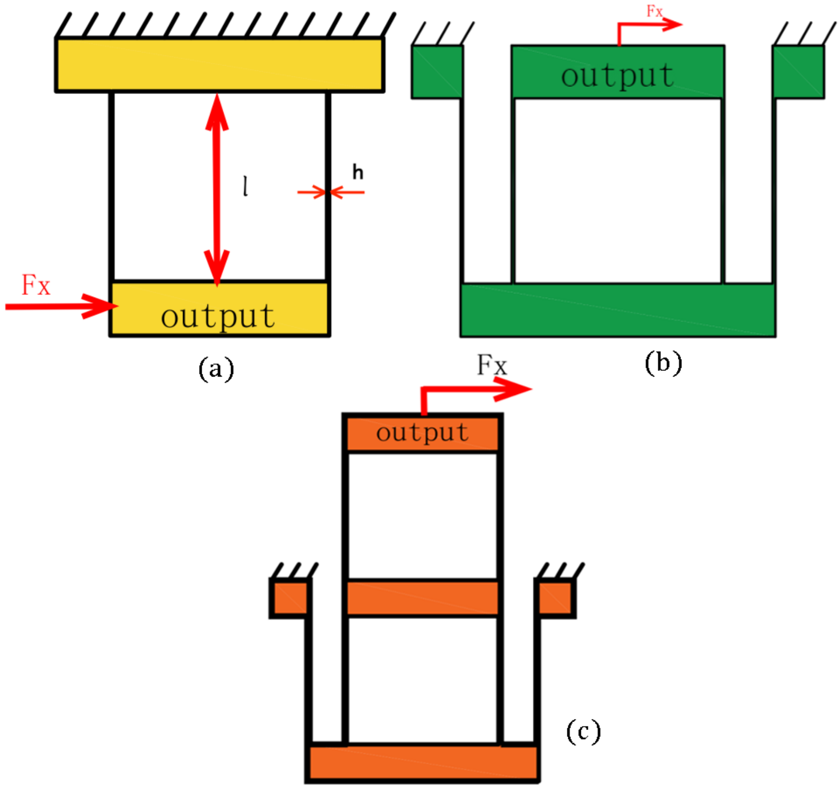

Figure 1: Basic Module Models of the Stage
(a) Single parallel mechanism (b) Double parallel mechanism (c) Hybrid serial mechanism

2.1. Single Parallel Mechanism

The single parallel mechanism is relatively common in the application of flexible mechanisms. It uses leaf-shaped flexible beams[12], as shown in (a) of Fig. 1. Its high stiffness in the y-direction and extremely low stiffness in the x-direction result in high decoupling in the plane. Although circular or other shaped flexible beams can be used[13], this paper uses straight beams for ease of calculation.

When a force F is applied at the end of this mechanism, the displacement in the x-direction can be calculated based on the beam deflection formula. The stiffness of the single parallel mechanism is given by:

$$K_1 = \frac{F}{X} = \frac{2Ebh^3}{l^3} \tag{1}$$

where l and h represent the length and width of the flexible sheet, respectively. Additionally, b denotes the thickness of the plate.

2.2. Double Parallel Mechanism

The double parallel mechanism is formed by serially connecting two single parallel mechanisms. When analyzing its stiffness, it can be thought of as a series of springs. When a force F is applied at the end of this mechanism, the displacement x can be expressed as:

$$K_2 = \frac{F}{X} = \frac{Ebh^3}{l^3} \tag{2}$$

Compared to the single parallel mechanism, the double parallel mechanism, with its lower stiffness, can output a larger displacement. Many large-stroke flexible positioning stages use composite parallel mechanisms to achieve large-stroke functionality in the plane. The lower stiffness also helps soften the beams, increasing displacement gain and reducing cross-axis coupling. To achieve large stroke in mechanism design, multi-stage serial connection of parallel mechanisms can be employed. Xu refers to this as multi-stage parallelogram flexible hinge mechanisms (MCPF)[14]. This is shown in (b) of Figure 1.

2.3. Hybrid Serial Mechanism

As mentioned earlier, decoupling is crucial for flexible positioning stages. It improves motion control accuracy, makes the movements of the axes independent, avoids interference between axes, and meets high-precision positioning requirements. It simplifies the control strategy, reduces the mutual influence of control parameters, and lowers control complexity and costs. It also enhances system stability, reduces the impact of instability factors, and extends the stage's lifespan. Moreover, it expands the application range, allowing the stage to flexibly achieve complex motion trajectories and positioning tasks. To achieve more complete decoupling, this paper introduces a single parallel mechanism in series between the guiding mechanism and the double parallel mechanism to provide greater displacement and reduce coupling. This is shown in (c) of Figure 1.

The hybrid serial mechanism is formed by serially connecting a double parallel mechanism and a single parallel mechanism. Similarly, when analyzing its stiffness, the mechanism is equivalently treated as a spring, and using the spring series formula, we can derive the stiffness of this structure as:

$$\frac{1}{K_3} = \frac{1}{K_1} + \frac{1}{K_2} \tag{3}$$

$$K_1 = \frac{2Ebh^3}{l^3} \tag{4}$$

$$K_2 = \frac{Ebh^3}{l^3} \tag{5}$$

$$K_3 = \frac{2Ebh^3}{3l^3} \tag{6}$$

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By appropriately combining the guiding mechanism with the hybrid mechanism, the basic units of the positioning stage based on the parallel leaf-shaped flexible beam design have been completed. The addition of the guiding mechanism ensures pure translational motion of the VCM, improves its positioning accuracy, and greatly contributes to decoupling the input and output directions of the stage[15].

3. Finite Element Analysis (FEA)

Finite Element Analysis (FEA) is a numerical analysis method used to obtain approximate solutions to complex engineering problems. It discretizes a continuous object into a finite number of elements and analyzes the mechanical behavior of these elements to obtain the mechanical characteristics of the entire object.

ANSYS Workbench is a powerful engineering simulation software that provides an integrated stage for performing various types of finite element analysis. In this section, we will simulate each of the modules mentioned in the previous section to verify the correctness of the theoretical calculations and the rationality of the model structure.

3.1. Establishment of Finite Element Model

Before performing finite element analysis, it is essential to first establish an accurate finite element model. The creation of this model considers multiple aspects such as motion range, stiffness, resonance frequency, out-of-plane load-bearing capacity, manufacturing tolerances, and structural compactness. Optimizing the flexible beam's length, width, and thickness enhances stability, reliability, and positioning accuracy while achieving a large stroke.

To improve computational efficiency and ensure the accuracy of the model, some details were appropriately simplified. Since this section is used for the verification of the mechanical performance of the mechanism, some minor geometric features, such as small chamfers and rounded corners, were ignored, provided that the overall mechanical performance remains unaffected.

In the simulation model, modular design was used for the convenience of stiffness calculation. Each module uses the same parameters for the flexible beams, as shown in Table 1.

Table 1: Main Structural Parameters of the XY Stage.

Variable Code	Size Value	Unit
l	35	mm
h	0.5	mm
b	10	mm

3.2. Simulation of Single Parallel Mechanism

Based on the stiffness of the single parallel mechanism, a set of forces was chosen for simulation analysis in ANSYS Workbench. A 2mm mesh size was used to discretize the model. A fixed constraint was applied to one segment of the single parallel mechanism, and a transverse load was applied to the end face of the other segment. Data was recorded for multiple sets of forces, and a curve of transverse force versus displacement was plotted and compared with the stiffness curve calculated in Section 2.1. The simulation used forces of 10N, 20N, 30N, 40N, 50N, 75N, and 100N, and a linear function curve was obtained with only a small error compared to the theoretical model analysis. The simulation results are shown in (a) of Figure 2.

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3.3. Simulation of Double Parallel Mechanism

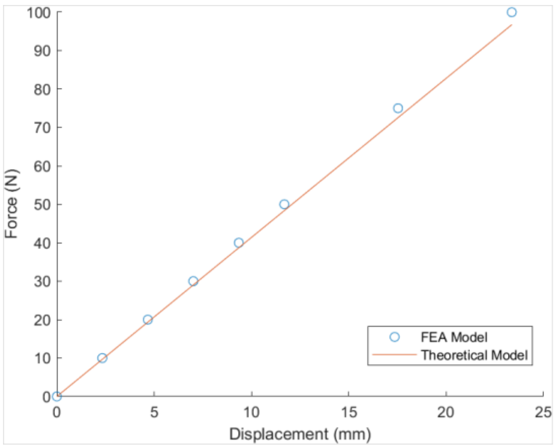
The double parallel mechanism, as analyzed in Section 2, was understood to be two single parallel mechanisms connected in series, with a stiffness half that of the single parallel mechanism. Using the same set of forces as in Section 3.2, a linear function curve was obtained, which was very close to the theoretical curve. The displacement was twice that of the single parallel mechanism under the same force. The simulation results are shown in (b) of Figure2.

Additionally, symmetrical guiding beams were specifically set at the input end of the VCM, which helped to stabilize the force output direction while increasing the mechanism's stiffness.

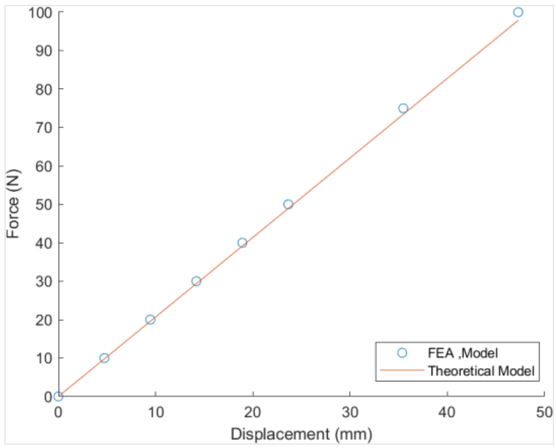
3.4. Simulation of Hybrid Mechanism

The hybrid mechanism is formed by serially connecting a single parallel mechanism to a double parallel mechanism in another configuration. The longitudinal series connection further reduced the mechanism's stiffness. Finite element simulation analysis, as performed in Section 3.1, yielded a simulation curve very close to the theoretical analysis curve. The simulation results are shown in (c) of Figure 2.

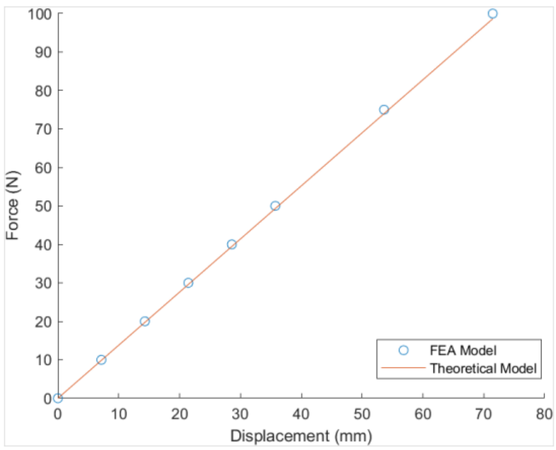
The finite element simulation curves for all three mechanisms are very close to the theoretical curves, further demonstrating the feasibility of the mechanism model and verifying the correctness of the theoretical analysis.



(a) Single parallel mechanism



(b) Double parallel mechanism



(c) Hybrid serial mechanism

Figure 2: Comparison of Simulation and Theoretical Results

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4. Finite Element Analysis of the Overall Structure

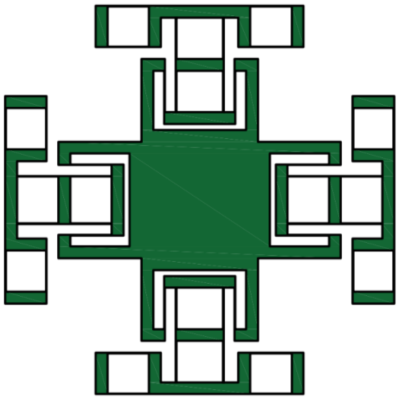

Figure 3: Stage Model

4.1. Establishment of the Overall Structural Finite Element Model

In the structural design, the goal is to minimize the stage's volume while maximizing its output displacement, and to achieve a high natural frequency. A successful positioning stage must also achieve decoupling between degrees of freedom. We can combine the modules mentioned in Chapter 2 symmetrically to obtain the structure shown in Figure 3, thereby achieving decoupling.

4.2. Motion Range

The maximum unilateral translation of the XY stage on each axis can be obtained using the following formula:

$$x_{max} = \frac{\sigma_s l^2}{3\eta E h} \tag{7}$$

where η is the safety factor, σ_s is the material's yield strength, E is the Young's modulus of the material, l is the length of the leaf spring, and h is the thickness of the leaf spring.

Using the material parameters for aluminum alloy ($\sigma_s = 280\text{MPa}$, $E = 71000\text{MPa}$), and the stage's module parameters ($l = 35\text{mm}$, h=0.5mm), with a safety factor $\eta = 1.2$, the maximum unilateral displacement of the stage is approximately 7.7mm.

Thus, the stage’s maximum working space is approximately 15.4mm × 15.4mm, offering a large stroke range.

4.3. Stiffness

As noted in Section 2, the stiffness of the single parallel mechanism is Equation (1).

As shown in the figure, the guiding mechanism is actually composed of a pair of single parallel mechanisms connected in parallel. Therefore, the stiffness of the guiding mechanism is:

$$K_4 = 2K_1 = \frac{4Ebh^3}{l^3} \tag{8}$$

The stiffness of the hybrid mechanism was already provided in Section 2 and validated in Section 3, as given by equation (6).

In this paper, the known stiffness of the flexible mechanisms is simplified to a spring for easier analysis. Since the overall mechanism adopts a symmetric configuration, the analysis is carried out along the x-axis direction as an example.

In the x-axis direction, the compliant stage is primarily formed by two guiding mechanisms and one parallel hybrid mechanism. Therefore, the stiffness along the x-axis is:

$$K = \frac{26Ebh^3}{3l^3} \tag{9}$$

The model was imported into ANSYS for simulation, with forces ranging from 50N to 200N applied to the stage. The simulation results are shown in Figure 4.

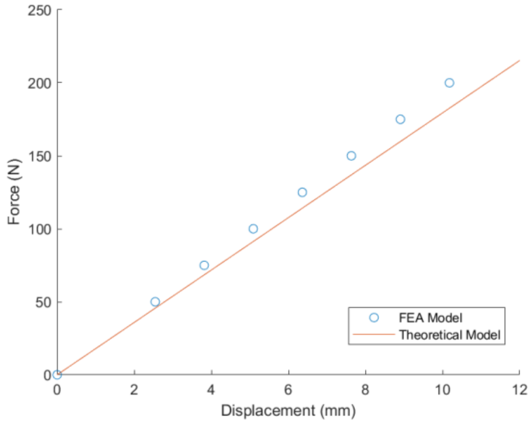

Figure 4: Comparison of Theoretical Stiffness and Simulated Stiffness Curves.

The theoretical and actual stiffness of the stage, as seen from the simulation curve, are quite similar, demonstrating the feasibility of the symmetric structure.

4.4. Modal Analysis

A servo system with a high natural frequency can achieve faster response speed and higher stability. Therefore, a high natural frequency is essential for an excellent flexible stage. In this paper, we perform modal and finite element simulation analysis to verify the feasibility of the stage structure.

When analyzing the entire stage, although the mass of the leaf spring is small compared to the entire system, neglecting it would artificially increase the stage's overall natural frequency, leading to inaccurate performance estimations. The leaf spring in this stage can be simplified as a simply supported beam or a cantilever beam. According to material mechanics, the equivalent mass of the leaf spring during free vibration can be calculated.

The equivalent mass of the simply supported beam is $\frac{17}{35}$ of its static mass, i.e., $m_1 = \frac{17}{35}m_0$.

The equivalent mass of the cantilever beam is $\frac{33}{140}$ of its static mass, i.e., $m_2 = \frac{33}{140}m_0$.

The equivalent mass of the stage is approximately 876.07g. The stage's stiffness, as derived from equation (8), is 17939.75N/m.

Substituting this into the formula for natural frequency:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{10}$$

The natural frequency of the stage is calculated to be 22.78Hz.

Meanwhile, modal simulation was performed in ANSYS, and the predicted results for the first six resonant frequencies were compiled as shown in Table 2, with corresponding mode shapes shown in Fig. 5. The theoretical natural frequency is very close to the simulated first-order natural frequency.

Table 2: Modal Simulation Results of the Stage Model.

Mode	1	2	3	4	5	6
Theoretical	22.78Hz	22.78Hz	—	—	—	—
FEA	26.64Hz	26.65Hz	83.59Hz	83.87Hz	85.09Hz	85.09Hz

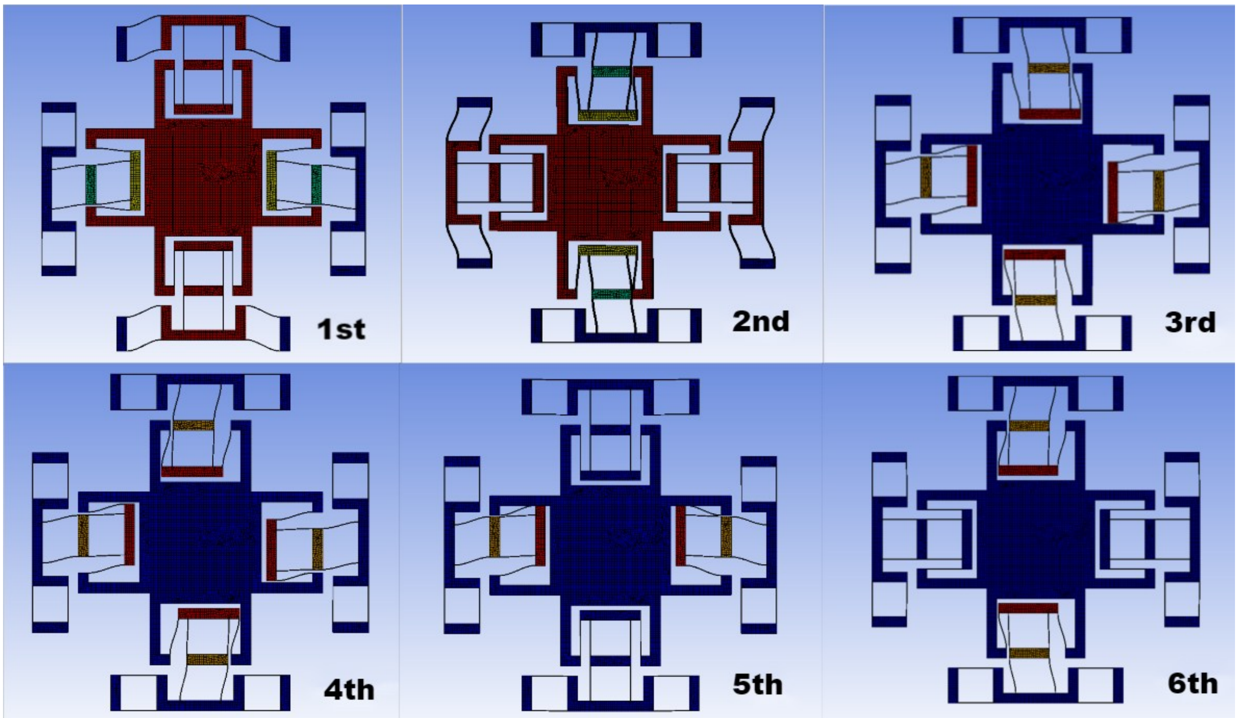

Figure 5: First Six Resonant Mode Shapes of the XY Stage.

From the FEA simulation results, for the 1st and 2nd modes, the stage's natural frequency reaches about 26.64Hz. After the 2nd mode, the stage's natural frequencies are more than three times higher than those of the 1st and 2nd modes, reaching above 83.59Hz. This indicates that the stage's translational motion performance in the working direction is relatively stable.

5. Conclusion

This study successfully designed and validated a novel XY micro-positioning stage based on a leaf-spring flexible component parallel mechanism. In terms of mechanism design, an innovative approach was adopted by organically combining single parallel mechanisms, double parallel mechanisms, and hybrid serial mechanisms to create a unique compact structure. The single parallel mechanism achieves planar decoupling by utilizing the distinctive stiffness characteristics of the leaf-spring flexible beam in different directions; the double parallel mechanism reduces stiffness through serial connection to obtain greater displacement, thereby laying the foundation for a large stroke; the hybrid serial mechanism further optimizes the decoupling effect and displacement output capability; and the guiding mechanism helps achieve more thorough decoupling and more precise positioning. Each mechanism complements the others, providing a new solution to the problem that traditional stages struggle to balance stroke and compactness, and laying a solid structural foundation for high-precision positioning. Finite element analysis predicted the stiffness of each sub-mechanism as well as the overall stiffness and natural frequency of the stage, which highly matched the theoretical calculation results, verifying the rationality and feasibility of the model and laying a solid foundation for physical experiments.

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