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Miniature active damping stage for scanning probe applications in ultra high vacuum

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Scanning probe microscope (SPM) experiments demand a low vibration level to minimize the external influence on the measured signal. We present a miniature six-degree of freedom active damping stage based on a Gough-Stewart platform (hexapod) which is positioned in ultra high vacuum as close to the SPM as possible. In this way, vibrations originating from the experimental setup can be effectively reduced providing a quiet environment for the SPM. In addition, the hexapod provides a rigid reference point, which facilitates wiring as well as sample transfer. We outline the main working principle and show that for scanning tunneling microscopy (STM) measurements of a Si(111) 7 × 7 surface, the hexapod significantly improves the stability and quality of the topographic images. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3689769]

I. INTRODUCTION

Scanning probe microscopes (SPMs) are experimental tools to investigate local physical phenomena on surfaces.[1,2] The observed measurement signal is extremely sensitive to variations in the distance between tip and sample. Already small mechanical vibrations of the SPM can have very large influences on the measured signal. For measurements with good resolution a variation in the distance between tip and sample of less than a picometer is desirable. This can be done by design considerations to reduce the response of the tip-sample distance to external vibrations,[3] but in general it is advantageous to have a low vibration level to begin with. Decoupling the whole experimental chamber from the lab environment is accomplished by a combined use of a set of external active and/or passive damping stages. However, these damping stages are usually ineffective against vibrations originating from the setup, e. g., vibrations from boiling cryoliquids or cooling stages (e. g., 1 K-pot). Therefore, it is desirable to include additional damping stages as close as possible to the actual SPM measurement head.

A standard technique to introduce sufficient damping close to the SPM is the use of eddy current damping.[4–6] Since the forces generated by the eddy currents are comparatively small and in order to keep a low resonance frequency, the SPM has to be weakly attached by soft springs to the surrounding structure, so that the damping can be effective. As a result, additional mechanisms have to be included into the system in order to restrain it, when the SPM has to be accessed from the outside, e. g., for sample transfer or maintenance. Furthermore, because the eddy currents are induced by magnetic fields, the approach is not applicable, if strong magnetic fields are part of the experimental setup itself. An alternative approach, which overcomes these drawbacks, is to decouple the SPM from the surrounding by the use of an active mechanical system with a stiff connection to the experimental chamber.

Here, we describe the use of an active mechanical damping system for a scanning tunneling microscope (STM) to operate in ultra high vacuum. We have adapted the concept of the Gough-Stewart platform or hexapod[7–9] to be incorporated between the STM and the surrounding structure of the experimental chamber. A hexapod is a special kind of parallel kinematic machine,[10] which consists of a base plate and a payload plate connected by six legs or struts with variable length. It enables the control of all six degrees of freedom in space (three translations and three rotations). Hexapods are widely used as positioning devices, e.g., for flight simulators.[9,11] Their usefulness as machine tools is a topic of ongoing research.[12,13] Since the beginning of the 1990s, the capabilities of hexapods for the purpose of vibration isolation are investigated.[14] Preumont *et al.*[15–17] further developed these control strategies showing that it is possible to damp prominent resonances in truss structures over a broad frequency spectrum while keeping the ability to control the position of the attached device.

Following the results of Preumont *et al.*, we designed a miniature hexapod and combined it with a decentralized active damping strategy featuring local controllers for each strut of the hexapod. It decouples the STM from the rest of the structure and can achieve a sufficiently high damping over a broad frequency spectrum. Furthermore, a robust stability of the system is guaranteed by the chosen control algorithm. In the following, the key features of the hexapod setup and the control algorithm will be explained. Measurements of the sensor signal from the hexapod struts as well as of the tunneling current with the STM feedback loop deactivated show the effectiveness of the chosen damping approach. Finally, images of a Si(111) 7 × 7 surface demonstrate the increase in stability

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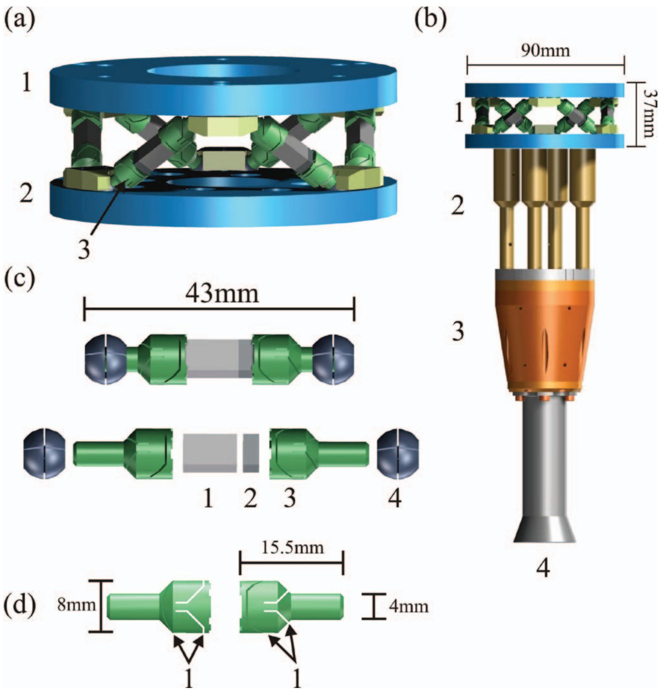

FIG. 1. (Color online) Schematic of the hexapod and its implementation in the STM. (a) Schematic of the hexapod: (1) base plate, (2) payload plate, (3) active struts. (b) Schematic of the STM assembly with hexapod: (1) hexapod, (2) rods connecting hexapod and STM, (3) STM, (4) tip and sample transfer. (c) Detailed view of an active strut: (1) piezo actuator, (2) piezo sensor, (3) flexible joint, (4) ball spring. (d) Detailed view of the flexible joints with dimensions: (1) slits cut by wire erosion to soften the radial spring constant. The left piece is rotated by 90° with respect to the right piece.

and measurement quality for STM topography measurements. Due to the flexibility of the hexapod, its application is not restricted to STM setups as described here, but can be applied to essentially all scanning probe techniques or experiments that demand a low vibration level.

II. DESIGN

The hexapod as shown in Fig. 1(a) consists of two plates, the base plate (1) which is mounted to the experimental chamber and the payload plate (2) to which the STM is attached (see Fig. 1(b)). The plates are connected by six identical struts each of which contains a collocated actuator/sensor pair (3).[16,18,19] The hexapod has an outer diameter of 90 mm and a height of 37 mm.

Each strut consists of a piezo actuator and a piezo force sensor in series with both ends connected to a flexible joint and a ball spring, see Fig. 1(c). The piezo actuator can generate forces in longitudinal direction of the strut, thus increasing or decreasing its length.[20] Correspondingly, the sensor is used to measure forces acting along the longitudinal direction. Force sensors have been chosen over acceleration sensors, because they usually provide a higher sensitivity although from a control theory point of view they would be equivalent.[21] The signal from every force sensor[22] is proportional to the force acting at the sensor position. It is amplified by a charge amplifier[23] with a sensitivity of 1 V/pC and passed on to a digital signal processor (DSP) board,[24] which allows for easy implementation of the control algorithms for the active struts. The corresponding output voltage of the DSP board is applied to the piezo actuators.[22] The actuators are a stack of piezo plates with a square base (5 mm × 5 mm) and a length of 9 mm. They have a maximum extension of 9 μm at a maximum applied voltage of +150 V. The minimum allowed voltage is −30 V. The sensor directly attached to the actuator, has a length of 2 mm, and a sensitivity of 600 pC/N at room temperature. With the sensitivity from the charge amplifier this translates to an overall conversion factor of 1.7 mN/V. The dimensions of the piezo were chosen such that it matches the design of the hexapod in general, i.e., a small piezo cross section makes the hexapod too fragile to handle. The inherent hysteresis of the piezo actuators is of no concern for this type of application.

The flexible joints are inserted at the ends of each strut in order to prevent bending, which would distort the sensor measurements or in the worst case could damage the piezos. They are stiff along the axis of the strut and soft perpendicular to it, so that only longitudinal forces are transmitted. In order to accommodate the limited space available, the flexible joints were home built and machined by wire erosion (see Fig. 1(d)). The slits were designed such that the ratio axial vs. radial stiffness is about 1000:1. The slits have a width of 0.3 mm reducing the material of the joint to a minimal thickness of 1 mm. The piezos can be directly glued to the flexible joint on one side and the ball springs attached on the other side. The ball springs are included for easy mounting of the struts and in order to mount the piezos without tension. With these struts the hexapod as such forms a rigid connection between the STM and the experimental chamber. Therefore, no additional mechanism is necessary to stabilize the STM for tip and/or sample transfer. In addition, no particular requirement for thin wires is necessary to connect to the STM, because the stiffness of the cables is negligible compared to the stiffness of the hexapod. This greatly simplifies the experimental setup close to the STM.

The struts are arranged in a mutually orthogonal configuration connecting the corners of a cube as shown in Fig. 2. The bold lines indicate the position of the active struts, while the

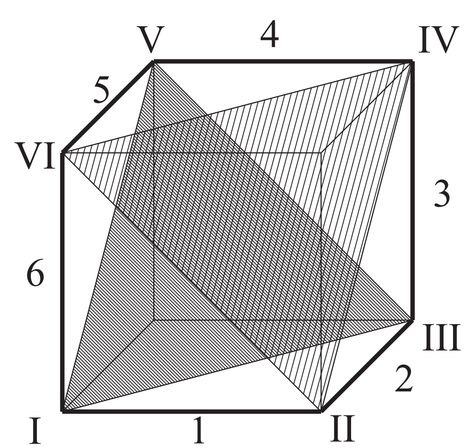

FIG. 2. Cubic design rule of the hexapod. Bold edges indicate the position of the active struts 1-6. The corner points I, III, and V define the plane of the base plate, while II, IV, and VI define the plane of the payload plate.

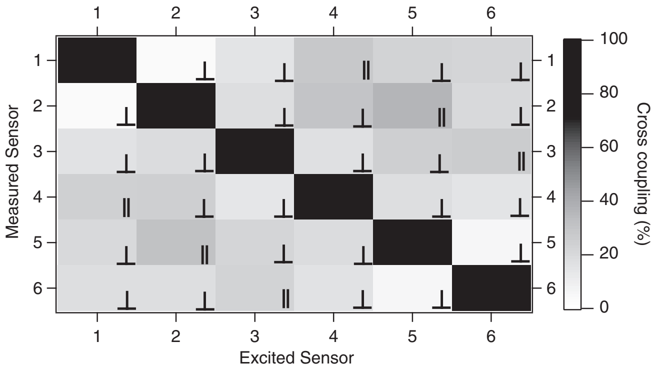

FIG. 3. Measurement of the cross coupling between the active struts. Symbols in the matrix fields indicating parallel (‖) or perpendicular (⊥) struts. Results have been normalized with respect to the sensor signal of the excited strut.

triangular areas depict the base (nodes I, III, V) and payload plate (nodes II, IV, VI). This architecture is chosen, because it provides uniform control capabilities as well as a uniform stiffness in all directions. Furthermore, it minimizes the cross-coupling between actuators. Figure 3 shows a measurement of the remaining cross coupling between the struts. Each actuator is successively excited with a sine signal, while the resulting sensor signal in each strut is observed. The controllers are switched off during these measurements. The horizontal and vertical axes in Fig. 3 correspond to the excited and measured struts, respectively. The matrix fields show the normalized magnitude of the measured response, i.e., the diagonal elements are correspondingly equal to one. The inset in each matrix field indicates the relative orientation of the respective struts. As is to be expected, the smallest cross coupling, which is around 15%, can be observed between the struts perpendicular to each other. For the parallel struts the cross coupling is around 30%. In general, the cross coupling remains on a tolerable level for the control algorithm described in Sec. III.

III. CONTROL ALGORITHM

Because the struts of the hexapods are only weakly coupled among each other and the acutator/sensor pairs are collocated, a decentralized control algorithm acting independently on each active strut can be chosen. Control algorithms based on collocation are most frequently used for active damping, since they guarantee closed-loop stability. In addition, they are usually easy to implement and tune.[21,25] For the control of the active struts of the hexapod, an integrated force feedback (IFF) is implemented, since the forces acting in the struts are readily available with the force sensors. Generally, control algorithms based on force sensors are more robust than acceleration sensors.[21] This control concept is well suited for damping the resonances in the system up to the frequency range where the piezos themselves become resonant. The basic principle of the IFF is to generate the actuator output signal u directly from the time integral of the axial force F acting on the piezo

$$u = -g \int F dt, \tag{1}$$

where g is the control gain. The IFF aims at increasing the damping in the system. As the damping in a mechanical system is proportional to the velocity, the force signal, which is proportional to acceleration, is integrated. For the digital implementation with the sample time T, the control algorithm is transformed into the corresponding difference equation using a bilinear or Tustin transformation:

$$u_{i+1} = \alpha u_i - g\frac{T}{2}(F_{i+1} + F_i), \tag{2}$$

where i denotes the ith time step. The forgetting factor α is introduced to prevent saturation of the integral control algorithm.[21] It has to be chosen slightly smaller than one, so that no saturation occurs but the performance of the controller is not affected. More details on the control algorithm and the underlying principles of active damping can be found in Ref. 21.

Since the design of the hexapod is symmetric and orthogonal, equal values of g and α can be chosen for all struts, resulting in a uniform behavior, when the controller is switched on or off. The control algorithm is implemented as a Simulink model in MATLAB[26] independently for each active strut and transferred to the memory of the DSP board. The tuning of α and g is done heuristically starting with a low value for the control gain g and a value of α very close or equal to one. The value of g is then increased until the stability limit of the controller is reached. Unconditional stability can only be guaranteed with IFF for ideal systems without a finite sampling time, no input/output delays, crosstalk, etc. For real systems, the control loop will eventually become unstable, if g is chosen just high enough. Then the forgetting factor α can be adjusted, so that the system becomes stable again. However, if α is chosen too small, the control algorithm will loose its integral behavior and the performance of the controlled system will degrade significantly. Thus, if no further improvement in the system behavior can be achieved by adjusting g and α, the optimal values are found.

IV. RESULTS AND DISCUSSION

A first test of the damping performance of the hexapod can be made by comparing the sensor outputs of the six active struts for the open loop and the closed loop case, see Fig. 4. The amplitude of time signal for the open loop case (blue/dark gray curve) is approximately twice as large as for system with activated control (orange/light gray curve). This behavior can be observed in all six sensor signals. The voltages applied to the actuator is commonly on the order of 1 V or less, which is less than 1% of the maximum allowed voltage. The advantage here is that the heat generation through the hexapod is quite low, which may become an important aspect in low temperature applications. The Fourier transformations (FT) of the time signals in Fig. 5 show a similar reduction of at least a factor of two for most resonance peaks. Prominent resonances at about 100 Hz are even completely suppressed. A low frequency vibration at around 2 Hz can still be observed in the closed loop data. This frequency is cut off by a 3 Hz high pass filter in the charge amplifier, so that the controller cannot effectively reduce such low lying vibrations. A high pass

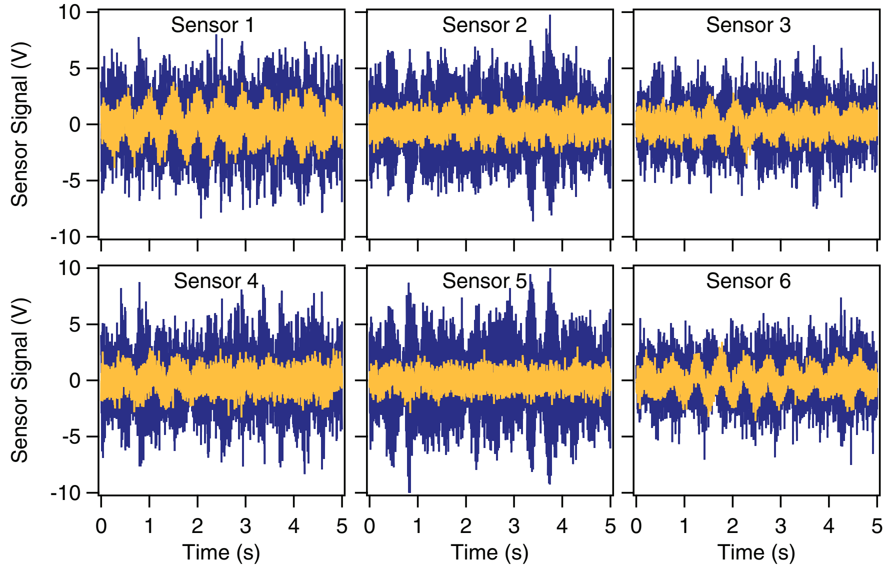

FIG. 4. (Color online) Time signals of the six vibration sensors in the hexapod struts. Open loop (blue/dark gray) versus closed loop (orange/light gray). The signal is not calibrated so that the value is given in volts. The sampling rate is 1 kHz.

filter with a lower cutoff frequency should solve this issue. Nevertheless, these measurements clearly prove the validity of previously made assumptions of a small enough cross coupling between the struts allowing for independent control as well as the local effectiveness of the chosen approach.

Since the goal of the hexapod implementation is not to achieve a sufficiently damped behavior locally in the active struts, but to improve the signal quality in the STM itself, measurements of the tunneling current and topography images are presented in the following. They demonstrate clearly the effectiveness of the hexapod to reduce the transmission of detrimental mechanical vibrations to the STM. We have measured the tunneling current with and without activated hexapod while the STM control loop is switched off. The tunneling current depends exponentially on the distance between tip and sample, which are directly influenced by the mechanical vibrations transmitted to the STM. Thus, the tunnel junction itself can be used as an extremely sensitive probe for vibrations.

Before the actual measurement, the tip is stabilized at a current of 0.3 nA and an applied bias voltage of 2.6 V with the STM control loop switched on. Then, the STM control loop is switched off for five seconds while the tunneling current is measured. Figure 6 shows the resulting time signal and the FT of the tunneling current. The results show an even bigger reduction than the results for the individual struts. The vibration level in the current signal can be damped significantly by about a factor of four. Correspondingly, most prominent resonances appearing in the FT are similarly reduced, especially the broad peak around 100 Hz, which is again

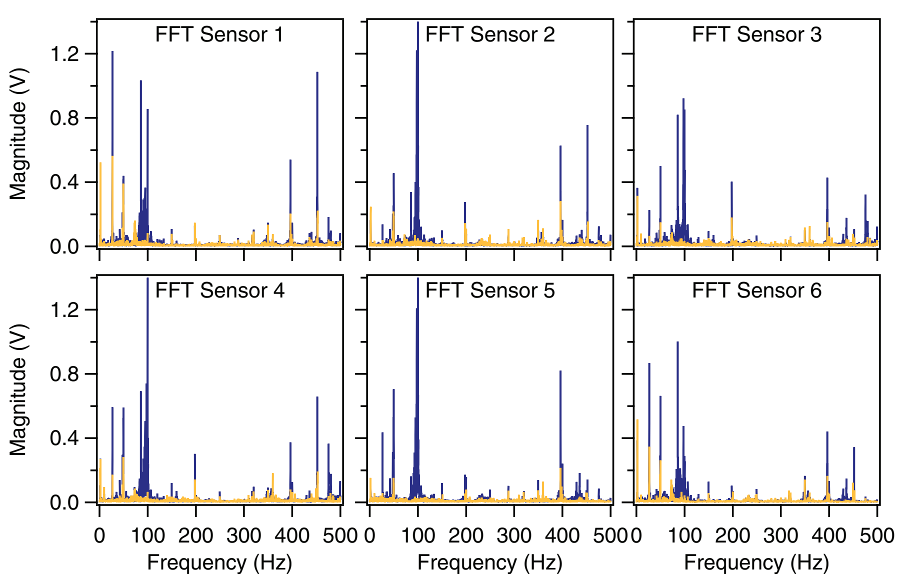

FIG. 5. (Color online) Fourier Transformation of the sensor signals of the hexapod struts. Open loop (blue/dark gray) versus closed loop (orange/light gray). The signal is not calibrated so that the value is given in volts. The sampling rate of the corresponding time signal is 1 kHz.

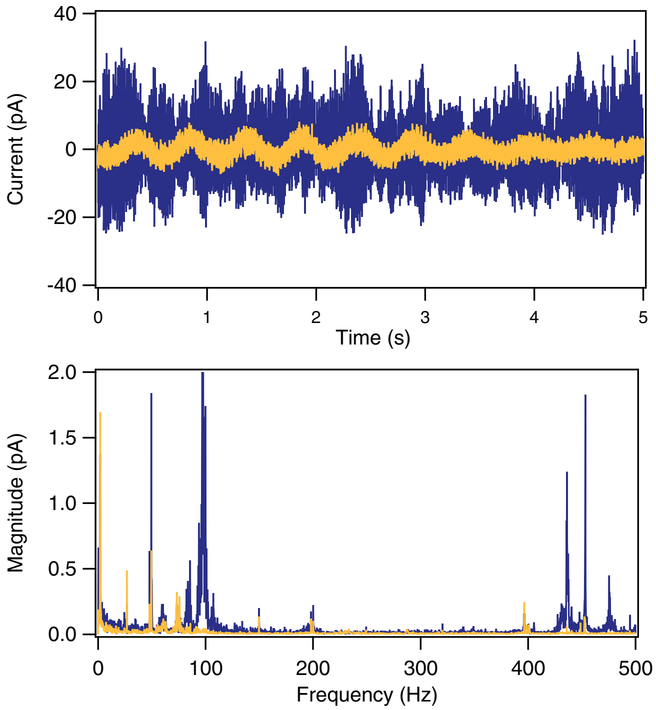

FIG. 6. (Color online) Tunneling current with deactivated feedback loop of the STM controller measured on a Si(111) 7 × 7 surface: (a) Time signal of the tunneling current and (b) the FT of the time signal. Open loop (blue/dark gray) versus closed loop (orange/light gray). The sampling rate is 10 kHz.

completely suppressed. The low frequency vibration around 2 Hz can again be related to the high pass filter in the charge amplifier (see above). These measurements clearly show that the local damping achieved by each individual strut in combination with the cubic design of the hexapod is capable to decouple the STM from most of the transmitted mechanical vibrations from the inside of the experimental chamber.

To finally show that the reduction of the transmitted mechanical vibrations close to the STM has a direct effect on the measurement quality and stability, Fig. 7 shows two topography measurements of a Si(111) 7 × 7 surface. The measurements were taken in constant current mode with an applied bias voltage of 1.0 V and a current set point of 0.8 nA at room temperature. The topography in Fig. 7(a) taken with the hexapod controller switched off shows an enhanced noise level. The noise level is absent in Fig. 7(b), which was taken with

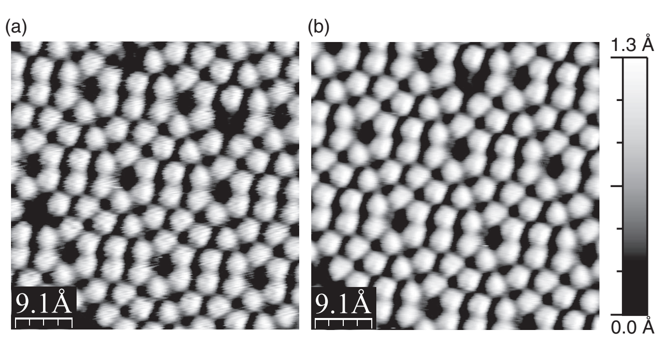

FIG. 7. Scanning tunneling microscopy image of a Si(111) 7 × 7 surface: (a) Topography image taken with deactivated hexapod (b) Image of the same scanning area (slightly shifted by thermal drift) with hexapod activated.

activated hexapod control. Thus, including the active damping stage close to the STM leads to a significantly improved measurement quality.

V. CONCLUSION

In conclusion, we have presented a novel approach for STMs to greatly reduce the transmission of mechanical vibrations to the sensitive measurement tip. It consists of a UHV compatible miniature hexapod as an additional active damping stage implemented as close as possible to the actual STM. Due to the orthogonal design, it can be controlled with a decentralized integrated force feedback algorithm, as was already shown by Preumont *et al.*[21] The resulting system is able to reduce the mechanical vibrations transmitted to the STM tip by at least a factor of two over a broad frequency spectrum. Correspondingly, the presented topography images of a Si(111) 7 × 7 surface show a clear reduction of the noise level, when the hexapod is activated. Furthermore, the hexapod simplifies the design of the experimental setup in general as no particular requirement for thin wires is imposed nor a special stabilization mechanism is needed for tip/sample transfer. Even though we tested the hexapod only in UHV and at room temperature, from design considerations we project that it can also operate at low temperatures and high magnetic fields. This makes the miniature hexapod a versatile active damping stage not only for STM applications, but for small vibration sensitive experiments in general.

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