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Stable five axes cryogenic photoemission manipulator without a differentially pumped rotary feedthrough

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We report on the design and construction of an ultrahigh vacuum compatible cryogenic manipulator for angle resolved photoemission spectroscopy. Unlike designs that have been used so far, our design allows five motions (three translational and two angular) without a differentially pumped rotary feedthrough. The design greatly reduces the sample motion upon rotation, which is crucial in automatic data acquisition over a large area in the momentum space. The constructed manipulator shows smooth motions in vacuum and the lowest temperature it could reach is about 8 K at the sample position. Angular reproducibilities are found to be about 0.02° for both of the angular motions. The wobbling motion from the rotation around the vertical rotation axis is found to be virtually nonexistent (less than 0.1 mm). © *2005 American Institute of Physics.*
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I. INTRODUCTION

Angle resolved photoelectron spectroscopy (ARPES) has been widely used in the study of electronic structures of solids.[1] In the past 10 years, ARPES technology has seen great improvements, which enabled us not only to obtain high quality data but also to have unprecedented data acquisition capabilities.[2] The contributions were mainly from the advances in analyzer and detector technologies. Current state-of-the-art analyzers, which are commercially available, have 0.1° angular resolution and sub-meV energy resolution combined with parallel data acquisition capability (so called angle mode).[3] On the other hand, there has been little improvement in the sample manipulation technology in a sense that there is more room for improvement. Sample manipulation is a vital part of the APRES technology and the manipulator could be a source of inefficiency. Often measurements are constrained by the motions provided by the manipulator. It is therefore desirable to have a similar degree of improvement in the sample manipulation technology.

For an ARPES system to work properly, the sample manipulator needs five motions—three translations and two rotations as defined in Fig. 1(a). The three translations are used to position the sample at the photon beam spot which should coincide with the focal point of the electron spectrometer, while the two rotations are used to cover a certain range of the solid angle or the momentum space. The horizontal rotation axis, defined as ϕ in Fig. 1(a), can be either parallel to (normal ARPES type, ϕ_{ARPES}) or perpendicular to the sample surface (x-ray photoelectron diffraction type, ϕ_{XPD}). An ideally designed manipulator would have the rotation axes exactly on the sample surface, so that the sample is kept in a fixed *XYZ* position while it is rotated. This is especially important when one experiments with a very small sample and an automated routine that collects data over a wide angle range. In addition to these motions, leading edge experiments require a wide temperature range provided by a helium cryostat and a heater, and sample transfer capability.

In a typical system as depicted in Fig. 1(b), three translational motions are obtained by using an *XYZ* linear stage and the two rotational motions are provided by a combination of a differentially pumped rotary feedthrough (DPRF) and a rotary motion feedthrough which is connected to the ϕ

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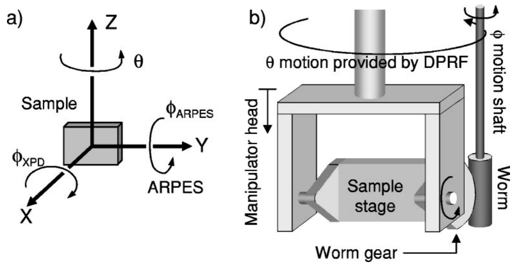

FIG. 1. (a) Definitions of the three translational and two rotational motions. The ϕ rotation axis can be either x (ϕ_{XPD}) or y axis (ϕ_{ARPES}). (b) Schematic of a typical five-axis sample manipulator. This particular one has the y axis as the ϕ rotation axis (flip stage). The flipping motion (ϕ rotation) of the sample stage is provided by the ϕ rotation shaft and the worm gear. The θ motion is typically provided by a DPRF (not shown). The θ motion rotates the whole manipulator, that is, the manipulator head and the ϕ rotation shaft together, hence the worm and worm gear are always engaged.

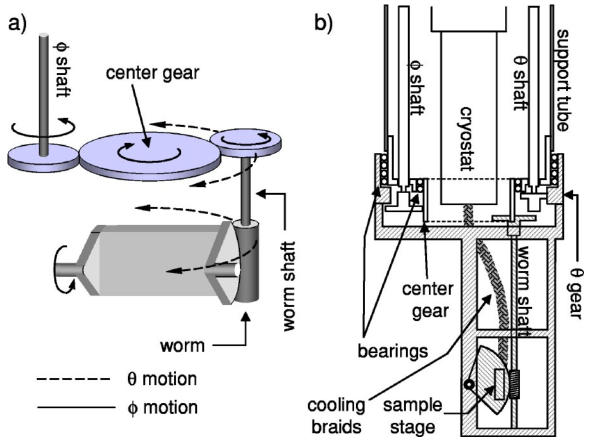

FIG. 2. (a) The role of the center gear. The worm shaft rotates with the manipulator upon the θ motion. However, its spur gear remains engaged with the center gear through which the torque is transferred. (b) Schematic of the manipulator head. Hatched parts which include the worm shaft undergo θ rotation.

motion shaft in the figure. The DPRF gives the rotation around the vertical axis while the rotary motion feedthrough the rotation around the horizontal axis [Fig. 1(b)]. The design of this type of manipulator has a few caveats. First of all, adoption of a DPRF gives a hostile environment for experiments; hanging vacuum hoses, attached small high vacuum pump (normally an ion pump), twisting of electrical cables upon rotation, and rusting of parts by condensing water. More seriously, the long vertical rotation axis set by the length of the manipulator inevitably gives a wobbling motion of the sample, i.e., the vertical rotation (θ motion) produces horizontal translational motions of the sample. As a result, one has to reoptimize the sample position almost every time the sample undergoes the θ rotation. With a modern day motorized manipulator, automatic data acquisition is becoming very important as one often scans a large area in the momentum space. The wobbling motion of the sample caused by the θ rotation is a problem that has to be resolved if one wants to accomplish an automatic data acquisition scheme. In this article, we will to describe a scheme that removes these problems.

II. DESIGN AND CONSTRUCTION

As described above, the combination of a DPRF and a long cryostat produces a wobbling motion that is detrimental to the stability of the manipulator. We should note that the whole length of the manipulator ($\sim$1 m) is rotated for the rotation of a small sample, usually on the order of 1 mm. Having such a long vertical rotation axis (length of the manipulator) is the cause of the wobbling motion. It is therefore essential to make the vertical rotation axis short. This can be achieved by limiting the θ rotation motion to the end of the manipulator, that is, by turning only the head of the manipulator in Fig. 1(b) just as for the ϕ rotation mechanism. Because the θ motion is provided by a DPRF, this scheme requires an additional rotation shaft for the θ motion compared to the typical design in Fig. 1(b) where there is only one rotation shaft for the ϕ motion. One advantage of this scheme is that it removes the necessity for the DPRF, thus eliminating other problems mentioned earlier.

Even though the idea appears simple and may remove the problems that a typical design has, it poises different difficulties. Going back to Fig. 1(b), we imagine adding a θ motion shaft to rotate the manipulator head only while everything above the head including the ϕ motion shaft remains fixed. We then encounter an apparent problem. The worm gear now rotates relative to the manipulator with the head and so does the worm. However, the ϕ motion shaft is fixed to the manipulator. We thus have conflicting requirements that the worm has to move while the shaft for it needs to be fixed to the manipulator. Therefore, it is necessary to devise a way to transfer the torque to the moving worm.[4] The θ which rotates the head does not have the problem as will be described below.

The key idea of our design is adoption of a center gear. The idea is illustrated in panel (a) of Fig. 2. The ϕ rotation of the shaft is coupled to the center gear whose axis coincides with the θ rotation axis. Then the torque is transferred through this center gear to the worm shaft which is fixed to the manipulator head and revolves around the center gear. The spur gear of the worm shaft remains engaged with the center gear even when the worm shaft moves with the manipulator head upon the θ motion. This is because the rotation axes of the center gear and θ motion coincide. Therefore, we have ϕ motion even when only the manipulator head is rotated for the θ motion. In this design, the ϕ motion is not independent of the θ motion as the motion of the worm shaft around the center gear turns the worm. This poses a slight inconvenience but can be corrected with relative ease (the actual coupling is very minor because of the large gear reduction ratio of the worm gear).

A schematic of the designed manipulator is shown in Fig. 2(b). The manipulator head is attached to the θ gear which rotates on a bearing on the support tube. The spur gear on the shaft moves the gear on the inner circumference of the θ gear, hence rotating the manipulator head. Even though the warm shaft rotates with the manipulator head, the spur gear at the end of the worm shaft remains engaged with the tube type center gear. The center gear, which is supported by a bearing on the support tube, can transfer the rotation from the ϕ shaft to the worm shaft. As a result, rotation of the ϕ shaft can provide the flipping motion of the sample stage

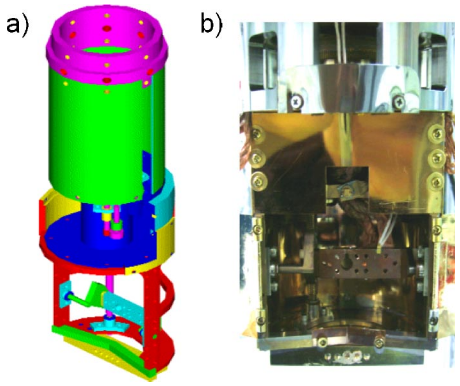

FIG. 3. (Color online) (a) A three dimensional CAD drawing of the designed manipulator and (b) a picture of the constructed manipulator.

independent of the θ position. The vertical positions of the spur gears for the ϕ and worm shafts are off so that they do not collide upon θ rotation. At the same time, we tried to reduce the height difference between the two as much as possible to minimize the torque which may twist the center gear (this is to maximize the ratio between the diameter of the center gear and the height difference). The design allows a free θ motion which is only limited by the twist of the cooling braids from the cryostat to the sample stage while minimizing the possibility of jamming of the center gear bearing due to the twist. We point out that, with a minor change of the design, one can choose to make the phi shaft provide the azimuthal rotation (ϕ_{XPD}) rather than the flipping motion (ϕ_{APRES}). This can be easily done, for example, by using the worm gear in Fig. 2(b) for the ϕ_{XPD} motion.

As stated earlier, leading edge experiments require a wide temperature range. Therefore, the center gear needs a large enough hole to allow copper braids from the cryostat to the sample stage to go through. This is accomplished by using a bearing with a large diameter but thin for the center gear. Such bearing is also used for the θ gear. How thin the bearing can be, while durable, is an important factor as it greatly affects the space for the braids and wires that run within the manipulator head. Another factor that is considered is the thermal expansion/contraction of the cryostat upon temperature change. Since one has to minimize the temperature dependence of the sample position, the manipulator head needs to be mechanically detached from the cryostat. Instead, the manipulator head and the θ gear are supported by a tube, shown as "support tube" in Fig. 2. The manipulator head is thermally insulated from the θ gear by putting a vespel between them. Therefore, the support tube and the θ gear remain at room temperature. This scheme of minimizing the thermal motion of the sample is already used for various ARPES manipulators.[5] Other design considerations include a standard radiation shield outside of the manipulator head to prevent radiation heating of the sample stage. The frame of the manipulator head and the shield are cooled by copper braid from the 50 K element of the cryostat.

Based on the scheme described above, a manipulator has been designed. Figure 3(a) shows the actual computer aided design (CAD) drawing of the manipulator. The most challenging part of constructing the manipulator was connecting the 50 K element of the cryostat and the radiation shield by copper braids and at the same time making sure that the braids do not touch other parts upon the θ rotation. Since the space is limited inside the support tube, the assembly of the manipulator had to be carefully considered, resulting in some design change in the construction process. Another challenge was to find thin bearings for the center and the θ gears to allow maximum space for the cooling braids. In addition, these bearings should work in vacuum. A picture of the constructed manipulator is shown in Fig. 3(b).

TABLE I. Test results for angular reproducibilities and vertical rotation axis wobbling motion.

θ reproducibility	ϕ reproducibility	Vertical axis wobbling
0.02°	≤0.02°	≤0.1 mm

III. TEST RESULTS

The angular reproducibilities and resolutions were checked outside the vacuum chamber. Angles were measured by mounting a small mirror at the sample stage and tracing the laser reflection off the mirror. The angular reproducibility with backlash correction and the resolution of the θ motion were found to be better than 0.02° and 0.005°, respectively.[6] We find similar or better values for the ϕ motions. Considering that the angular resolutions of the state-of-the-art analyzers are no better than 0.1°, these resolutions are more than enough for mapping in the momentum space. The overall motions were again tested in vacuum at 77 K to ensure their performance at a realistic experimental condition. The motions were smooth as was in atmospheric pressure at room temperature. A silicon diode was mounted on the sample stage to measure the temperature. We measured the lowest temperature of 8 K at the sample position. With a minimal He flow, we were able to maintain the temperature of 12 K for more than 72 h with 100 l of liquid helium. This is a typical helium consumption for a well built cryogenic manipulator. Finally, the wobbling motion upon the θ motion was checked by measuring the movement of a small mark on the sample holder when θ is rotated by 60°, by looking at a telescope with a scale attached to it. The wobbling motion was undetectable (less than 0.1 mm) as the rotation axis for the motion is very short as described above. The test results are summarized in Table I.

ACKNOWLEDGMENT

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[1] S. Hufner, *Photoelectron Spectroscopy: Principles and Application* (Oxford University Press–Springer, New York, 1995).

[2] See, for example, ⟨http:\\www-bl7.lbl.gov⟩

[3] A. Chainani *et al.*, Phys. Rev. Lett. **85**, 1966 (2000).

[4] This is equivalent to rotating ϕ shaft with the head without using a DPRF.

[5] For example, the manipulator for the the BL5-4 ARPES system at the Stanford Synchrotron Radiation Laboratory uses the scheme.

[6] Reproducibility is defined as the angle within which the manipulator head can return to the original angular position after a motion. Resolution is defined as the smallest angular step that the manipulator can take.