SYNOPSIS
The purpose of this paper is to demonstrate a detachable fixture system that can provide, (1) positioning with sub-micron repeatability and accuracy and (2) rapid (100 Hz) scanning. Such systems may be used in nano-instrumentation (e.g. SEM, STM, AFM) and nanomanufacturing equipment to repeatably fixture, accurately position in a quasi-static mode, and/or execute fast scanning motions. This device is called a dual-purpose fixture-positioner (DPF) due to its ability to perform as a fixture and positioner.

INTRODUCTION
Exact constraint fixtures, such as the kinematic coupling shown in Fig. 1A, are capable of sub-micrometer repeatability. The accuracy of such a device depends on the geometric quality of their components and the accuracy of their assembly [1]. Their accuracy is typically limited to 10 micrometers [2].

However, one may actively adjust an exact constraint fixture’s geometry so as to modify the relative location of the fixtured components, thereby improving fixturing accuracy. Achieving this can be done for instance by repositioning the balls or grooves via external actuation.

This has been demonstrated by creating kinematic couplings, a type of exact constraint fixture, wherein two [3] and three [4] axis corrective motions may be achieved. For ultra-precision applications it is important to be able to have accurate alignment in all six axes. This makes it possible to (1) achieve any combination of position-orientation and (2) to correct parasitic alignment errors. Recently, several devices have been created for this purpose – a manually adjustable coupling based upon adjustable links [5], a DPF that uses an eccentric ball-shaft to adjust position [2] and a DPF wherein motion was generated via a moving groove design [6,7].

In this paper, we investigate the performance of a miniaturized moving groove DPF. Whereas preceding DPFs were designed for static operation, the scaling down to the present miniaturized design (lower mass to stiffness ratio) enables fast motions.

CONCEPT AND DESIGN DETAILS
A cross-section of a ball-groove joint from a moving groove DPF is shown in Fig. 1B. The grooves are attached to a guiding bearing and actuated along the horizontal by actuators (Act). In the miniDPF design, the grooves sit atop a guiding flexure (FGU) as shown in the miniDPF-specific ball-groove joint of Fig. 1C. As each of the j grooves (j = 6) may be actuated an amount, gj, it is possible to achieve displacements in all six degrees-of-freedom. The components of the miniDPF are shown in Fig. 2A. The dimensions of the prototype are roughly 5 x 5 x 5 cm.
The miniDPF consists of a top component (stage) to which the balls are rigidly attached and a bottom component that contains flexures and piezo actuators (piezos) that work together to cause changes in the fixtured position/orientation. Figure 1C and 2A show how the flexures and actuators are integrated within the DPF.

Within this design there are:

(a) Six guide flexures – The guide flexures guide the motions of the groove flexures as shown in Fig. 1B and 1C. The groove flexures are part of the monolithic base as shown in Fig. 3A.

(b) Six piezo actuators – The actuators are assembled into the monolithic base by preloading within their respective guide flexures. The piezos interface with the guide flexures via a dowel pin on one end and a sphere on the other end. The guide flexures are sized so that the series of sphere-piezo-dowel pin is slightly oversized with respect to the fit with the guide flexures. During assembly, the guide flexure therefore deforms when the sphere, piezo and dowel are set into place. This provides a preload that is necessary to extract the best stiffness-range combination from the piezos. The dowel pin and sphere are used to avoid over constraining the piezo.

(c) Six groove flexures – A pair of groove flexures form each contacting groove surface of the device. A detail of a groove flexure is shown in Fig. 3B. The groove flexures are stiff in the direction normal to the ball-groove contact and compliant in directions perpendicular to the normal contact. This layout of stiffness and compliance maintains a stiff coupling while permitting flexing for adjustment of position and orientation. A more detailed justification for the groove flexures follows.

When the grooves are actuated, the balls must slide along the grooves in order to maintain geometric compatibility between the ball and groove patterns [2]. Figure 2B shows the wear marks that result from a ball sliding along a groove when groove flexures are not used. The groove flexure are important as they prevent relative sliding between the balls and grooves. That is, if there is an impetus for the balls to move parallel to the groove surface, it is the groove flexure deformation that allows this motion rather than an undesired, relative sliding between the balls and grooves.

Kinematic couplings have been made by replacing the ball-groove contacts with air bearings [8], but here we have chosen flexure bearings as they are vacuum compatible and require no supporting electronics or fluid systems. They have also demonstrated utility in other fixture applications, for instance to minimize friction hysteresis effects [9], to prevent over constrain [10, 11] and to enable sealed contact [12]. Figure 4 shows top and bottom views of the miniDPF base with all flexures and actuators assembled.

EXPERIMENTAL RESULTS

The HPF was designed according to the physical principles and models used to design a large-scale, moving groove DPF [6,7]. The miniDPF is shown encapsulated within a cap probe-based metrology system in Fig. 5A. Six probes take displacement readings on the positions corresponding to the numbered locations in Fig. 5B. The measurements were taken while a magnet preload was applied between the top and bottom components.
In our first experiment, we conducted repeatability tests on the device in fixture mode. In this mode, the actuators are energized to a constant state. They are not actively adjusted in order to improve the accuracy or repeatability of the fixturing operation between cycles. This enables us to test the repeatability of the exact constraint interface. Figure 6 and Table 1 show the results of the repeatability test.

The miniature piezo actuators used in the device are not equipped with sensors that allow us to perform closed loop control. We are therefore only able to run the piezos in open loop and measure the resultant motions via the metrology system. This means that there is to be a certain degree of hysteresis and creep expected in the piezo actuators that will be reflected in the device behavior. This is indeed seen via the raw experimental data shown in Fig. 7A. When this data is corrected to remove the piezo creep and hysteresis effects, the motion better-resembles the commanded x-y raster scan profile. A section of the corrected scan data is shown.
enlarged in Fig. 7B. The variation from linear is within the $6\sigma$ capability of the sensing system. This range is denoted by the shaded region in Fig. 7B.

**SUMMARY**

To date, this work has shown the capability of a DPF to serve as a high-speed, sub-micron precision dual-purpose fixture-positioner. We have obtained a few hundred nanometer repeatability and tens of microradian repeatability. We have demonstrated that the device has the potential to scan at 100 Hz with accuracy on the order of tens of nanometers. Achieving this in a practical way will require the addition of closed-loop control. Current efforts are focused upon fulfilling this goal. Additional tests are under way to ascertain the worn-in repeatability of this device. Past work has shown that the incorporation of groove flexures into kinematic couplings can improve their repeatability to better than 100 nm, possibly improving this to tens of nm. Continued work seeks to determine if the worn-in repeatability of the miniDPF will approach these results.

**REFERENCES**

7. Varadarajan, MK. Culpepper, ML. A Dual-purpose Positioner-Fixture for Six-axis Nanopositioning and Precision Fixturing – Part II: Experiment and Calibration. Submitted to Precision Engineering.