ME – PhD Thesis Colloquium

Compact, Electromagnetically Actuated Stages Suspended by Compliant Elements for Large-Range Nano-Positioning

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ABSTRACT

Micro- and nano-precision positioning systems are critical to a wide range of scientific and technological applications. Electromagnetic actuators are well-suited for driving these systems from the viewpoints of actuation range, high range-to-footprint ratio, ability to achieve direct-driven multiple degrees of freedom actuation, linear operation, and simple construction. However, they are either not compact or possess low stiffness and force generation capability. To improve the dynamic behavior of the positioners, a mechanical compliant suspension is a good choice, but they have limited actuation range.

This thesis aims to develop large-range, compact multi-DOF nano-positioning stages with improved dynamics to take advantage of both diamagnetic-levitated and mechanically suspended electromagnetic actuation systems. Compliant suspensions are introduced to raise the theoretical upper limit of trapping stiffness, thereby increasing the actuation bandwidth. At the same time, the limited range of tethered compliant mechanisms has been addressed. This thesis has investigated the design and development of passive suspension systems based on compliant elements for long-range nanopositioning with a very compact form factor and multiple degrees of freedom capabilities. The design and development of two categories of electromagnetic nanopositioning stages have been proposed.

The first category of compliant stages is tethered mechanical suspensions. Here, low stiffness in-plane actuation has been achieved via tethered compliant suspensions made of strings, and compliant suspensions that employed stiffness-reduction mechanisms to achieve an enhanced range without compromising actuation speed. Two stiffness-reduction methods are proposed; the first type employed a magnetic negative stiffness system, and the second type employed stiffness reduction near critical buckling due to preloading. The developed systems with string suspension and stiffness-reduction-based mechanical compliance both achieved approximately 22.85% and 10% range-to-footprint ratios, respectively, which were about 12.6 and 5.5 times better than reported mechanically suspended electromagnetic actuators or voice coil motor (VCM) systems. The string suspension-based positioning system achieved a p-p range of 8mm and 140nm RMS positioning precision, resulting in a dynamic range of 95dB. Positioning system employing magnetic negative stiffness achieved a p-p range of 0.969mm and 2.91nm RMS positioning precision, resulting in a dynamic range of 110dB. Positioning system employing preloading-buckling based stiffness reduction, achieved p-p range of 3mm and 2.34nm RMS positioning precision, resulting in a dynamic range of 122dB. The second category of compliant suspension system utilized untethered mechanical suspension. Unlike tethered mechanical stiffness, electromagnetic trapping stiffness results in zero additional reaction force on the actuator and stage, offering an arbitrarily large range of motion.

Furthermore, the printed circuit board (PCB) based actuation systems were improved by optimizing the trace width to achieve sinusoidal in-plane force and developing designs that enable continuous in-plane rotation of the stage about any given point. The developed mechanical suspension systems improved the upper limit of trapping, ranging from 51-fold to 526-fold, compared to the diamagnetic levitation system, which increased the theoretical upper limit on bandwidth by 7.1-fold to 22.9-fold. The positioning system demonstrated smooth rotational actuation with a p-p rotation range of 720 degrees at multiple points within a single actuation zone. The positioning system also achieved a p-p translation range of 30mm and 13.31nm RMS positioning precision, resulting in a dynamic range of 127dB. The untethered positioning system was compact with a footprint of 32.7mm, thus showcasing a 91.7% range-to-footprint ratio, viz., 50.4 times better than reported VCM systems.

ABOUT THE SPEAKER

R. Krishna is currently pursuing a Ph.D. under the guidance of Prof. G. R. Jayanth in the Department of Mechanical Engineering, Indian Institute of Science, focusing on electromagnetic planar nanopositioning systems. He received a B.Tech in Mechanical Engineering from Rajiv Gandhi University of Knowledge Technologies, Basar, in 2016, and an M.Tech in Structures and Design from the Aerospace Engineering Department, Indian Institute of Space Science and Technology, Thiruvananthapuram, in 2019. His research interests include electromagnetic planar actuation systems for nanopositioning applications such as scanning probe microscopy and micro-robotics, as well as the dynamics and control of electromechanical devices. Beyond academics, he enjoys sketching and playing cricket.