Introduction to the special issue on MEMS dynamics and control

Microelectromechanical systems (MEMS) have been widely used to develop high-performance transducers, such as accelerometers, gyroscopes, pressure sensors, and microphones, as well as radio frequency (RF) signal processing components, including filters, switches, and clocks, among many other high-value devices. Due to their small size, repeatable batch fabrication processes, straightforward integration with microelectronics, and high performance, MEMS have replaced a number of conventional technologies. Some of the largest application domains for MEMS include mobile communications, consumer products, such as smartphones and tablets, the automotive industry, and industrial sensing. Over the last decade, the global MEMS market has doubled and is now over $10 billion per year, with many new applications on the horizon.

While the progress of MEMS in the last three decades has been astounding in terms of performance and reliability, the vast majority of research in the field has yet to embrace concepts from the fields of dynamic systems and control even though MEMS are highly dynamic. Instead, there has been a focus on optimizing the design, fabrication, and integration of MEMS to make exceptionally linear, passive devices with uncomplicated electromechanical dynamics. There are exceptions, such as the development of closed-loop gyroscopes for inertial navigation, but even here advanced control system approaches are rarely employed. Due to the maturity of many MEMS sensors and components, however, it is becoming difficult to make performance improvements through continued modifications to the electromechanical design and fabrication. For example, passive capacitive accelerometers have become commodity components with minimal performance improvements in recent years. As a result, there is growing interest in using systems theory to better understand and modify the dynamic behavior of MEMS to achieve levels of performance that surpass those of current passive, linear devices.

The main goals of this special issue are to provide a snapshot of the state of the art for the dynamics and control of MEMS and to highlight how performance can be improved through dynamic systems and control approaches. Among the accepted papers, there is a clear division between three areas of research: 1) motion control of MEMS optical scanners and positioning mechanisms, 2) control of physical sensors, such as gyroscopes, accelerometers, and force sensors, and 3) the nonlinear dynamics of MEMS resonators.

Scanners and positioners. MEMS optical scanners based on movable micromirrors are used for video projectors, light detection and ranging (LIDAR), and endoscopic medical imaging. MEMS positioning mechanisms are often applied to micromanipulation for manufacturing and medical research, scanning probe microscopy, and adaptive optical components. The control of MEMS scanners and positioners has many of the same challenges found in the precision motion control of macroscale actuators, such as model uncertainty, perturbations, and nonlinearities. However, for MEMS, these challenges are typically more pronounced, particularly nonlinear actuation dynamics (e.g., electrostatic, piezoelectric). In addition, MEMS often have faster dynamics, requiring higher control bandwidth, and accurate sensing can be difficult due to the small device volume and cross-coupling between sensing and actuation. Several of the papers in this special issue address these issues.

Schroedter et al. [1] demonstrate the application of nonlinear control, both open-loop and closed-loop, to the motion tracking of a MEMS scanning mirror with electrostatic actuation. By making use of the flatness property of the scanning mirror and by limiting the maximum jerk in the trajectory, they show that a flatness-based closed-loop nonlinear controller with state estimation can significantly improve tracking performance. Escareno et al. [2] investigate tracking control for a multi-degree-of-freedom piezoelectric actuator for micromanipulation, where hysteresis, creep, and cross-coupling between motion axes are limiting factors. Rather than model these nonlinearities and disturbances, the authors make use of an extended-state linear Kalman filter to estimate their contributions to the dynamics and reject them with a Lyapunov-based controller. Precision motion control of a rotational electrostatic actuator that is unstable is presented by Andonian et al. [3]. A combination of feedforward and feedback control through differential capacitive sensing has been shown to provide motion resolution at the nanometer level over a wide bandwidth.

Physical sensors. Sensing has been the largest driver for the development of MEMS and physical sensors that measure mechanical quantities have received the most attention in the field. MEMS gyroscopes, accelerometers, and force sensors have proved to be invaluable for inertial navigation in aviation and robotics and automotive stabilization and drivetrain systems, among many other applications. Most MEMS sensors operate as passive devices without feedback control. However, closed-loop operation is required in applications that need enhanced accuracy, stability, and dynamic range, as described in several of the papers in this special issue.

A new approach for minimizing the mode separation within a MEMS gyroscope using a combination of feedforward electrostatic trimming and coarse and fine feedback control is presented by Hu et al. [4]. This approach results in a modal mismatch of only 10 mHz, which directly translates into a reduction of the rate error and angular drift of the gyroscope. Chen et al. [5] have demonstrated that MEMS gyroscopes can be calibrated with an embedded MEMS motion stage using capacitive sensing to transduce the prescribed motions that are applied to the gyroscope. This approach allows gyroscopes to be intermittently calibrated during operation, which will improve accuracy by several orders of magnitude compared to a gyroscope that is only calibrated at the beginning of operation. Feedback control can also be used to extend the dynamic range of MEMS sensors, as shown by Maroufi et al. [6] for a force sensor operating in the range of micronewtons. By combining closed-loop stiffness tuning and damping, they have shown that the compliance and dynamic range can be adapted for a given application.

Nonlinear and coupled mechanical resonators. Mechanical resonators are used for RF filters, chip-based clocks, and chemical sensing, in addition to the physical sensors described above. In most work to date, there has been an emphasis on developing resonators that operate with a highly linear dynamic response in order to maximize the stability and repeatability of the resonator output. However, some research over the last decade has focused on leveraging these nonlinearities, and even enhancing them, to achieve better performance and enable new functionalities. Al Hafiz et al. [7] present an approach for using a micromechanical beam resonator to perform logic operations by introducing variable axial compression in the beam. They demonstrate NOR and XOR operations with the resonator, which could be useful for applications requiring low-power logic that can operate in environments with high electromagnetic interference. Similar to the leveraging of nonlinearities, coupled mechanical resonators are being explored to overcome the performance limitations of a single resonator. Ilyas et al. [8] have developed a device that couples two mechanical resonators with a cross-beam that links their motion. This results in a wide-bandwidth frequency response that is a summation of the resonances for the two resonators, which can be used for adaptive RF filtering.

The research areas described above track closely with trends in the literature for MEMS dynamics and control. Therefore, this special issue is expected to be of interest to experts in the field, as well as for those looking for a curated introduction. We hope that it will encourage more mechatronics researchers to embrace this exciting but underrepresented subject in their own work.

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