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A Compact Series Elastic Actuator for Robots in MRI Scanners

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***Abstract*—In this research, we have developed a compact, efficient rotary series elastic actuator (SEA) module compatible with MRI environments, driven by velocity-sourced ultrasonic motors. Through a DoB-based controller tailored for velocity-sourced SEA, we demonstrate robust torque control for our SEA module against varying external impedance, crucial for medical procedures guided by MRI. Tests conducted in a 3 Tesla MRI scanner confirm the SEA's effectiveness, with quick response time (0.1 seconds) and minimal error in torque output (within 2% of peak torque). Our control system performs consistently well across various impedance scenarios, offering a significant improvement over traditional controllers, especially in low-impedance situations.**

SEA Design: The proposed compact SEA module incorporates a spring element, a planetary gearbox, and a Tekceleo WLG-75-R USM. At the peak SEA output torque of 0.96 $\mathrm{N\cdot m}$, this USM provides to a maximum velocity of 5.2 $\mathrm{rad\cdot s^{-1}}$ at the SEA output and yielding a peak output power of 5.0 W. Unlike previous MRI-compatible SEA designs, our module incorporates a transmission force sensing series elastic actuator structure, with four off-the-shelf compression springs strategically placed between the gearbox housing and the motor housing. This design features a compact size, thus expanding possibilities for a wider range of MRI robotic applications.

MRI Compatibility: The extent of interference in MR imaging processes is largely contingent on the magnetic susceptibility and conductivity of materials. The spring element, gearbox, and bearings of our SEA module are fabricated from non-magnetic and non-conductive polymers, with only a small volume of metals utilized in the helical compression springs and fasteners. However, the primary source of imaging interference remains the commercial USM. Nonetheless, this distance requirement can be addressed in an integrated design of the robot. The compact nature of our SEA contributes to fulfilling this requirement.

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Experimental Setup: In our experimental setup, the SEA is controlled by a NUCLEO-F446RE MCU in (a), which gathers position measurements from encoders and sends motor velocity commands to the USM driver. The perturbation testbed in (b) consists of our SEA module on the left and an additional USM on the right, serving as the perturbation source. The outputs of these two actuators are connected through a shaft coupler. In our MRI test setup depicted in (d), a SEA pendulum testbed in (c) is positioned at the center of the bore of a 3T MRI scanner. The motor driver and MCU are located outside the MRI room, transmitting power and control signals through 10-meter-long cables, as illustrated in (d).

Results: To achieve precise torque control, we develop a controller that incorporates a disturbance observer tailored for velocity-sourced motors. This controller enhances the robustness of torque control in our actuator module, even in the presence of varying external impedance, thereby augmenting its suitability for MRI-guided medical interventions. Experimental validation demonstrates the actuator's full functionality in a 3 Tesla MRI scanner, achieving a torque control settling time of 0.1 seconds and a steady-state error within 2% of its maximum output torque. Notably, our force controller exhibits consistent performance across low and high external impedance scenarios, in contrast to conventional controllers for velocity-sourced series elastic actuators, which struggle with steady-state performance under low external impedance conditions.

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