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Subject title

Transparent, Backdrivable, and Reliable Actuation for Robot-Assisted Surgery

Sections where the subject must be presented.

- EM - Robotics and Mechatronics
- Biomedical engineering

Subject longer description.

Transparent, Backdrivable, and Reliable Actuation for Robot-Assisted Surgery:

In robot-assisted and haptic-enabled surgical systems, the actuator is central to achieving high transparency, accurate force rendering, and safe tool-tissue interaction. Transparency, the ability to convey tactile cues to the operator with minimal distortion, is critical in microsurgical procedures where forces are often close or even below human perception thresholds, and minor deviations can have serious consequences. This demands actuators with low friction, minimal impedance, high control bandwidth, and mechanical precision. Simultaneously, these systems must be reliable over repeated use, resistant to degradation, and suitable for compact integration into clinical tools.

A variety of actuation mechanisms have been studied and implemented in surgical and haptic devices. Cable and tendon driven systems are widely used to enable remote actuation, reducing distal mass and improving maneuverability, particularly in handheld or minimally invasive tools. Direct-drive motors offer excellent backdrivability and precise control, making them well-suited for micromanipulators, although they are often limited in terms of torque density and size. Piezoelectric and ultrasonic actuators, known for their compactness and high-frequency response, have been deployed in ophthalmic and neurosurgical instruments for applications requiring sub-micron positioning. Fluidic actuators, including pneumatic and hydraulic systems, provide high force outputs in compact configurations, although they pose challenges in terms of controllability and dynamic response.

This proposal also explores hybrid actuation systems that combine stiff, high-resolution position controlled actuators with torque/force controlled mechanisms. These configurations aim to exploit the benefits of both domains offering ultra-precise positioning for steady manipulation and compliant interaction for force-sensitive environments. Such systems are particularly promising for scenarios requiring both stability near static targets and responsiveness to dynamic interactions, such as intraocular injections or membrane peeling. This thesis will analyze and compare these actuation strategies through modeling, simulation, and experimental validation, focusing on their transparency, reliability, and suitability for clinical integration in robotic-assisted surgical platforms.

Objectives:

Survey: Review of actuation mechanisms suitable for haptic/robot-assisted surgery.

Modeling: Simulate actuator dynamics and transparency using MATLAB/Simulink or equivalent tools.

Reliability Study: Analyze degradation effects (e.g., backlash, friction) and their influence on force rendering.

Experimental Validation: Build and test a prototype actuator with high backdrivability and transparency for an application like needle insertion.

Design Recommendations: Summarize insights into how actuator designs can be optimized for surgery.

Research Phases:

Phase 1 (20%): Literature review and definition of metrics for transparency, backdrivability, and reliability. Selection of one or more actuator types for study.

Phase 2 (40%): Simulation and analysis of selected actuator types. Study dynamic behavior, control bandwidth, and response under failure-like conditions (e.g., added friction or backlash).

Phase 3 (40%): Prototyping and experimental validation of a selected actuator. Measurement of transparency, impedance, and force feedback fidelity using sensors. Evaluate robustness under repeated loading and identify improvement strategies.

Learning Outcomes:

The student will gain a thorough understanding of actuator behavior in high-precision robotic systems and their role in safety-critical applications like surgery. They will develop skills in:

Modeling and simulating mechatronic systems.

Understanding haptic system requirements and evaluation metrics.

Designing and controlling backdrivable actuators.

Performing hands-on experimental validation, including sensor integration, data acquisition, and performance testing.

Interpreting experimental results to guide design improvements.

Interest and Contact:

Are you interested in contributing to the next generation of surgical robotic systems by exploring the heart of haptic feedback, and precision actuators?

Contact me at Amin.khorasani@vub.be for more information.