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DOCTOR OF ENGINEERING SCIENCES

of **Muhammad Usman**

The public defense will take place on **Thursday 27th February 2025 at 1pm** in room **I.2.01** (Building I, VUB Main Campus)

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ENHANCING COLLABORATIVE ROBOTS: FLEXIBLE SHAFT BASED REMOTE ACTUATION FOR HIGH-PAYLOAD ROBOT ARMS

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Abstract of the PhD research

In the modern world of robotics and AI, human accessibility and collaboration with robots are crucial for reducing labor costs and minimizing downtime due to inflexible automation. Advances in AI-driven software are accelerating the development of safer, more intelligent robots with the support of high computational power and advanced sensing. Conversely, hardware safety improvements rely on human intelligence and manufacturing capabilities, emphasizing lightweight design for low energy consumption and safety. Novel lightweight and efficient actuation solutions are emerging to reduce mass and energy consumption. Elasticity, using spring elements to smartly save and release energy, and off-joint transmission, relocating actuators to the robot’s base, are fundamental principles in lightweight and energy-efficient robot design. Combining these principles can increase mechanical and control complexity, particularly with higher payloads, introducing non-linearity and scalability issues. This research explores flexible shafts as an off-joint transmission for high-payload robot arms, offering both elasticity and off-joint actuation in a single element. Benchmarking characterizes flexible shafts’ physical properties and dimensions, using nine shafts with varying lengths and diameters to model changes in physical characteristics. A model is proposed to estimate the flexible shaft’s stiffness and inertia by accessible physical measurements. An inertial spring damper model studies the shafts’ inertial, elastic, and damping effects.

The research also proposes a design methodology for an energy-efficient, lightweight actuator design using flexible shafts for high-payload robot arms. Three progressively advanced prototypes of off-joint transmission using a flexible shaft elaborate on each technique’s advantages and disadvantages. This led to the development of a torque-dense robot joint using flexible shaft-based remote actuation, achieving 95 Nm nominal torque in a 1.8 kg robot joint. For design validation of these prototypes, two 3-DOF anthropomorphic robots were made, with the elbow joint powered by a flexible shaft. The final 18 kg payload robot prototype, reduced elbow joint mass to 1.8 kg compared to the 4.3 kg on-joint actuator. The research also provides guidelines for optimal off-joint actuation module synthesis, comparing techniques based on gravitational torque, moving mass, and total mass of a robot. A case study analyzes the impact of different transmission techniques on a 3-DOF robot arm. Flexible shaft-based actuation is compared with other methods, showing similar mass reduction potential but with added elasticity. However, they introduce structural loads that are difficult to model due to 3-dimensional deformation.

Finally, the elastic effects of flexible shafts on a 3-DOF robot arm are studied using a test bench. Empirical models are developed to select desired elasticity at robot joints, with an algorithm to utilize these models for elastic effects. The study concludes with insights into dynamic models and low-level control of flexible shaft-based off-joint actuation. In conclusion, this thesis explores the design, modeling, and low-level control of flexible shaft-based off-joint actuation modules to reduce high-payload robot arms’ mass and energy consumption. It provides a detailed understanding of flexible shafts as an off-joint transmission, supported by physical prototypes and design guides. The research shows that flexible shafts significantly enhance the roboticist’s repertoire of off-joint transmission techniques, offering high torque density and built-in gravity compensation at high payloads.