Doctoral Dissertation
Doctoral Program in Mechanical Engineering (38thcycle)

Hands-Free Human Machine Interfaces

Design and test of two approaches for rider assistance of electric-powered wheelchairs

By

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Politecnico di Torino
2026

Abstract

This doctoral dissertation addresses the critical socio-technical challenge of enhancing mobility and autonomy for individuals with severe motor impairments, specifically those with tetraplegia or advanced neuromuscular disorders who cannot operate traditional manual joysticks. As the global population ages and the prevalence of motor disabilities increases, the demand for non-invasive, Hands-Free Human-Machine Interfaces (HMIs) for electric-powered wheelchairs (EPWs) has moved from a niche clinical need to house and home nursing assistance and now is becoming also a useful requirement of Human-Centric Smart Manufacturing (HCSM) and assistive robotics.

The primary contribution of this research is the conceptualization, implementation, and rigorous comparative analysis of two distinct sensing paradigms designed for high-fidelity head-pose estimation:

- **Stereovision-based HMI**: This system leverages a synchronized stereo camera assembly to perform real-time extraction of facial landmarks. By applying 3D triangulation and perspective-n-point algorithms, the interface calculates the rider's head orientation relative to a dynamically calibrated neutral pose. The resulting Tait-Bryan angles (pitch, roll, and yaw) are translated into velocity commands. While high in precision, this modality's performance was evaluated against environmental constraints such as varying ambient illumination and the occlusion of facial features.

- **Proximity sensor-based HMI**: To overcome the limitations of vision-based systems, a second, novel modality was developed using an array of Time-of-Flight (ToF) distance sensors. Because proximity data from a moving human head is inherently non-linear and susceptible to noise (particularly from hair and irregular surfaces), a Deep Learning framework was implemented. A

stacked Long Short-Term Memory (LSTM) recurrent neural network was trained to map temporal distance distributions into accurate angular signals. This approach ensures robust intent estimation even in the absence of visual features or optimal lighting.

Both interfaces are unified by a specialized Intention Estimator module. This module employs a 5th-order polynomial mapping function to govern the transition between the neutral deadzone and active movement. This mathematical smoothing is critical for reducing jerk in omnidirectional platforms, ensuring that the high-responsiveness of head movement does not translate into uncomfortable or dangerous mechanical oscillations.

The systems were integrated and validated on two state-of-the-art omnidirectional platforms: the Italian MoviWE.Q from Politecnico di Torino and a Japanese motor-steering platform developed at the Institute of Science Tokyo. These platforms allow for 3-Degree-of-Freedom (3-DOF) holonomic movement, facilitating simultaneous longitudinal, lateral, and angular velocities, a capability that traditionally complicates hands-free control.

The validation framework followed a dual-path approach. First, high-fidelity simulations in Gazebo/ROS 2, complemented by single-subject real-world sensor validation trials, were used to tune control parameters, establish safety protocols, and quantitatively benchmark the Hands-Free HMIs against a gold-standard 3-axis joystick. These tests revealed that while the Hands-Free HMIs exhibit a marginal increase in latency (approximately 0.5 seconds), they offer superior control decoupling for lateral maneuvers. Second, a usability campaign was conducted with a cohort of 25 participants performing navigation tasks in constrained indoor environments. Qualitative assessments via the System Usability Scale (SUS) and NASA Task Load Index (NASA-TLX) confirmed that the systems are intuitive and achieve a Technology Readiness Level (TRL) of 6, providing a viable pathway toward clinical deployment and commercial integration in the assistive technology sector.