



UNIVERSITÀ DEGLI STUDI DI NAPOLI
FEDERICO II

itee^{PhD}
information technology
electrical engineering



Fabrizio Lo Regio

Metrological Framework for XR-based Natural Human-Machine Interfaces Interaction Engineering in Industry 5.0

Tutor: Leopoldo Angrisani

Cycle: XXXVIII

Year: III

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Candidate's information

- MSc degree
 - Biomedical Engineering
- DIETI Research group/laboratory
 - Measurement group (Tutor Prof. Leopoldo Angrisani)
- PhD start date – end date
 - 01/01/2023 – 31/12/2025
- Scholarship type
 - PNRR, Partenariato Esteso PE14, RESEARCH and innovation on future Telecommunications systems and networks (RESTART)
- Period abroad
 - 26/02/2025 – 05/06/2025
 - Biomimetics and Intelligent Systems Group, University of Oulu, Oulu, Finland

Summary of study activities

PhD Courses

- Statistical Data Analysis and Measurement Uncertainty
- Quantum Technologies
- Attended the "Italo Gorini" International PhD School (2023) focused on measurement instrumentation.

Seminars

- Engaged in a broad spectrum of seminars covering AI, Neuroscience, Quantum Computing, and Project Management.

Conference Participation & Dissemination

- Flagship International Conferences: Active contributor to premier IEEE venues, including I2MTC 2024 (Glasgow, UK) and ICNSC 2025 (Oulu, Finland) and ICEEE 2025 (Istanbul, Turkey).
- Thematic Focus on XR: Consistent presentation of findings at IEEE MetroXRINE editions (2023 & 2024), establishing expertise in metrology for eXtended Reality and Neural Engineering.
- National & Specialized Forums: Presented research at the IX National Forum on Measurements, the Workshop on Metrology for Sustainability, and the AHL Conference on Active and Healthy Living.

Research Area

Interaction Engineering & Advanced Metrology for Industry 5.0

Transition from usability to metrological characterization

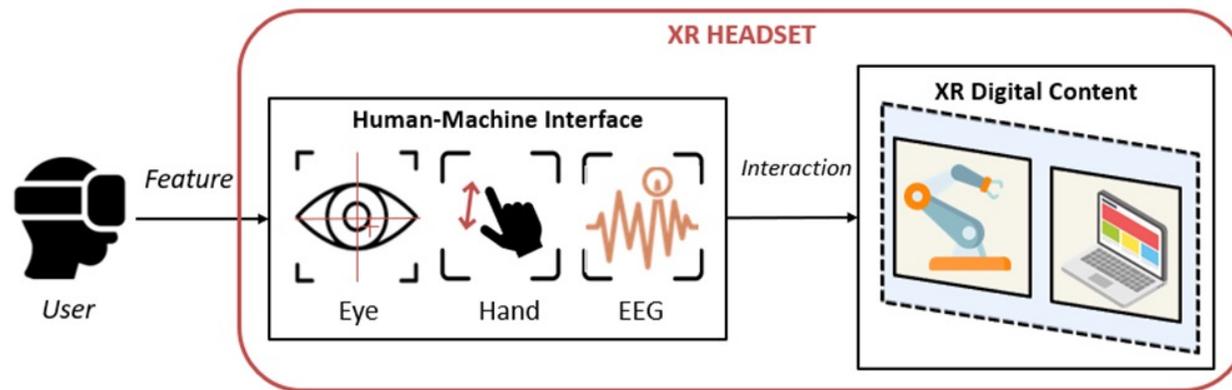
1. Human-Edge platforms: The Human Node
2. Distributed robotic networks: The Mobile reconfigurable Node
3. Secure Infrastructure: The Quantum Link



Research Area 1

Human-Edge platforms: The Human Node

- Lack of standardized, quantitative metrics to assess the reliability of Natural Human-Machine Interfaces (NHMI)
- Opacity of commercial hardware specifications
- Definition of a **GUM-compliant methodology** (Guide to the Expression of Uncertainty in Measurement)



Research Area 2

Distributed robotic networks: The Mobile reconfigurable Node

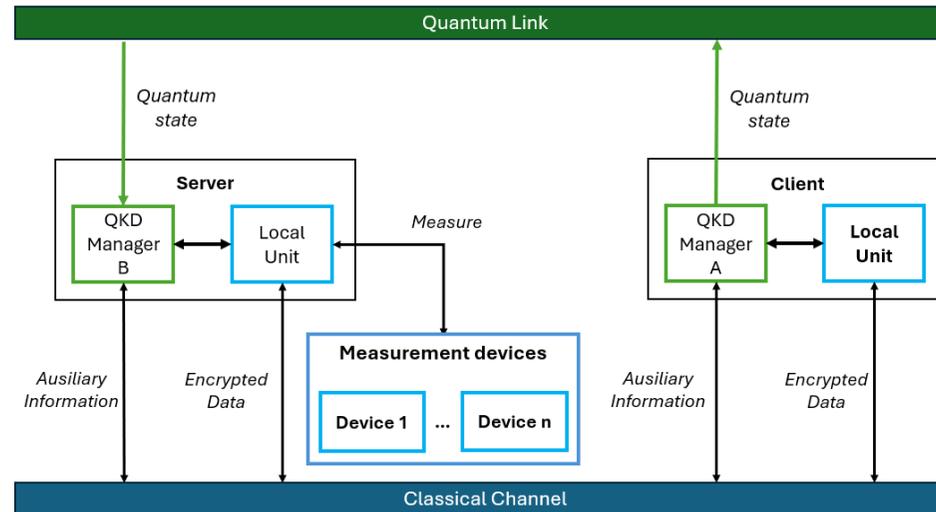
- Redefined the concept of distributed networks, moving from static arrays to reconfigurable measuring instruments.
- Mobile robots dynamically adapt their configuration real-time to optimize measurement
- Analyzed state-of-the-art control techniques to maximize measurement performance in distributed environments.
- Broadened the research scope to integrate sustainability goals. Shifted from purely functional metrics to a holistic evaluation model that assesses both the system's environmental monitoring capabilities and its operational energy footprint

Research Area 3

Secure Infrastructure: The Quantum Link

- Data integrity in critical measurement networks without compromising real-time system responsiveness.

Scientific Result: Development of a distributed measurement system based on Quantum Key Distribution (QKD) for secure data transmission



Fabrizio Lo Regio

Research products (1/3)

[P1]	L. Angrisani, P. Arpaia, E. De Benedetto, L. Duraccio, F. Lo Regio, A. Tedesco Wearable Brain-Computer Interfaces based on Steady-State Visually Evoked, Potentials and Augmented Reality: a Review, IEEE Sensors Journal 23 (15), pp. 16501-16514, 2023, DOI: 10.1109/JSEN.2023.3287983
[P2]	L. Angrisani, M. D'arco, E. De Benedetto, L. Duraccio, F. Lo Regio Broadband Power Line Communication in Railway Traction Lines: A Survey MDPI Energies 16 (17), pp. 6387, 2023, DOI: 10.3390/en16176387
[P3]	L. Angrisani, E. De Benedetto, L. Duraccio, F. Lo Regio, R. Ruggiero, A. Tedesco Infrared Thermography for Real-Time Assessment of the Effectiveness of Scoliosis Braces MDPI Sensors 23 (19), pp. 8037, 2023, DOI: 10.3390/s23198037
[P4]	L. Angrisani, M. D'arco, E. De Benedetto, L. Duraccio, F. Lo Regio, A. Tedesco A Novel Measurement Method for Performance Assessment of Hands-Free, XR-Based Human–Machine Interfaces IEEE Sensors Journal 24 (19), pp. 31054-31061, 2024, DOI: 10.1109/JSEN.2024.3444472
[P5]	L. Angrisani, M. D'arco, E. De Benedetto, L. Duraccio, F. Lo Regio, A. Tedesco A method for the metrological characterization of eye-and head-tracking interfaces for human–machine interaction through eXtended Reality head-mounted displays Measurement 243, pp. 116279, 2025, DOI: 10.1016/j.measurement.2024.116279

Research products (2/3)

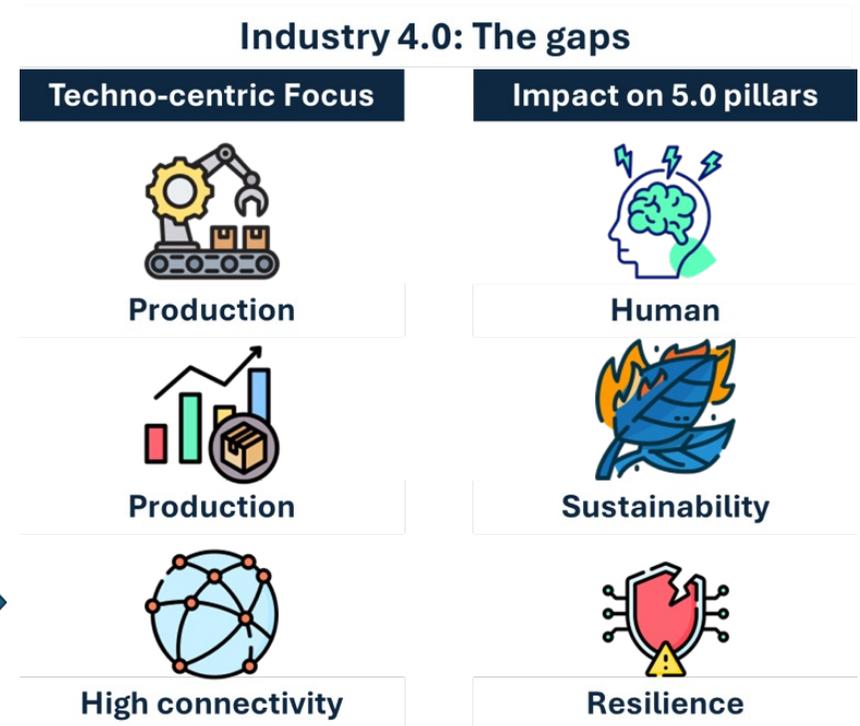
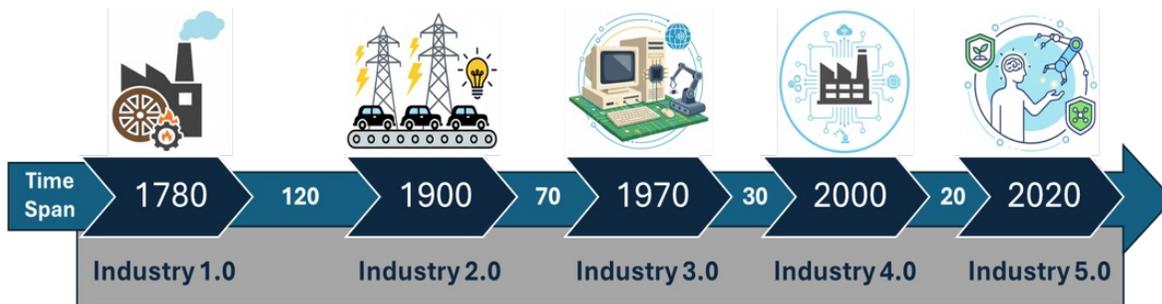
[P7]	<p>A. Procopio, A. Tedesco, F. Lo Regio, G. Cesarelli, L. Donisi, C. Ricciardi, A. Merola, A. Maria Ponsiglione, M. Romano, F. Montefusco, C. Cosentino, F. Amato, A General Framework for Closed Loop Negative Feedback Multivariable Physiological Control Systems: Existence, Uniqueness, and Stability of Homeostatic Equilibrium Points, IEEE Access 13, pp. 17630-17651, 2025, DOI: 10.1109/ACCESS.2025.3532846</p>
[P8]	<p>L. Angrisani, M. D’arco, E. De Benedetto, L. Duraccio, F. Lo Regio, M. Sansone, A. Tedesco Performance Measurement of Gesture-Based Human–Machine Interfaces Within eXtended Reality Head-Mounted Displays MDPI Sensors 25 (9), pp. 2831, 2025, DOI: 10.3390/s25092831</p>
[P9]	<p>L. Angrisani, P. Arpaia, E. De Benedetto, M. D’Iorio, L. Duraccio, F. Lo Regio, A. Tedesco An open Steady-State Visually Evoked Potentials Dataset for Augmented Reality-based Brain-Computer Interfaces IEEE Sensors Journal 25 (20), pp. 38957-38965, 2025, DOI: 10.1109/JSEN.2025.3605813</p>
[P6]	<p>L. Angrisani, P. Arpaia, E. De Benedetto, L. Duraccio, F. Lo Regio, A. Tedesco Expanding the Frontiers of Wearable Brain-Computer Interfaces Combining Augmented Reality and Visually Evoked Potentials, 2023 IEEE INTERNATIONAL CONFERENCE ON Metrology for eXtended Reality, Artificial Intelligence and Neural Engineering Milan, Italy, 25-27 October 2023, pp. 58-62, DOI: 10.1109/MetroXRINE58569.2023.10405702</p>

Research products (3/3)

[P10]	<p>F. Lo Regio, L. Angrisani, M. D'arco, E. De Benedetto, L. Duraccio, A. Tedesco Experimental procedure for metrological characterization of AR-based eye-tracking interfaces 2024 IEEE International Instrumentation and Measurement Technology Conference (I2MTC) Glasgow, United Kingdom, May 2024, pp. 1-6, DOI: 10.1109/I2MTC60896.2024.10561006.</p>
[P11]	<p>L. Angrisani, E. De Benedetto, L. Duraccio, F. Lo Regio, M. Sansone, A. Tedesco Exploring Variability in Human-Machine Interaction through Gesture Recognition based on Hand-Tracking within XR 2024 IEEE International Conference on Metrology for eXtended Reality, Artificial Intelligence and Neural Engineering (MetroXRINE) St Albans, United Kingdom, October 2024, pp. 816-820, DOI: 10.1109/MetroXRINE62247.2024.10796138.</p>
[P12]	<p>L. Angrisani, P. Arpaia, M. D'Arco, E. De Benedetto, L. Duraccio, F. Lo Regio A Metrological Approach to the Performance Characterization of Eye- and Head-Tracking Interfaces in eXtended Reality 2024 IEEE International Conference on Metrology for eXtended Reality, Artificial Intelligence and Neural Engineering (MetroXRINE) St Albans, United Kingdom, 2024, pp. 816-820, DOI: 10.1109/MetroXRINE62247.2024.10796138.</p>
[P13]	<p>F. Lo Regio; M. D'Iorio; L. Angrisani; C. Brusino; P. Ercolano; M. D'Arco; A. Giuliana; L. Parlato; M. Peluso; G. P. Pepe, Proof-of-concept of a QKD-secured distributed measurement system, 2025 12th International Conference on Electrical and Electronics Engineering (ICEEE), Istanbul, Turkey, September 2025, pp. 371-375, DOI: 10.1109/ICEEE67194.2025.11261974.</p>

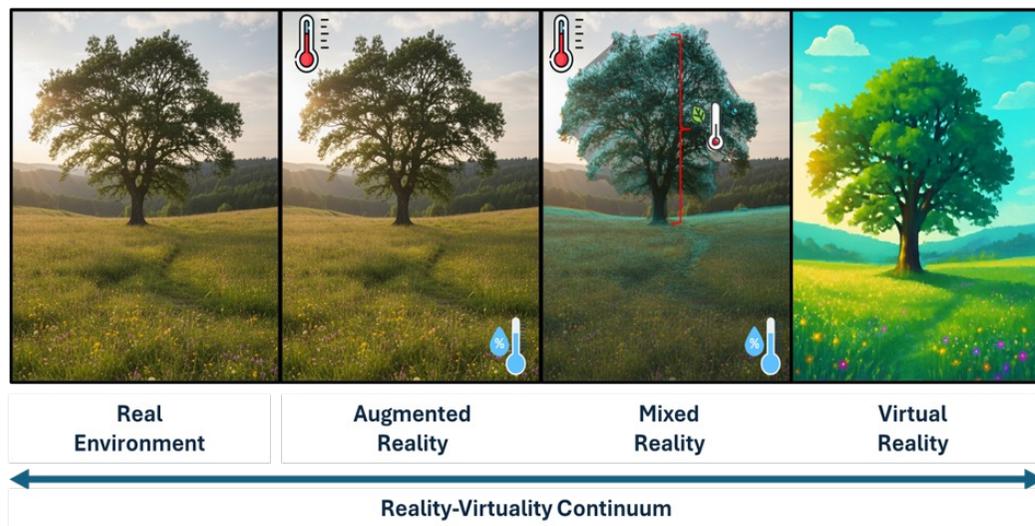
PhD thesis Overview

The Transition from Industry 4.0 (Techno-centric) to Industry 5.0 (Human-Centric) places the operator in the control loop

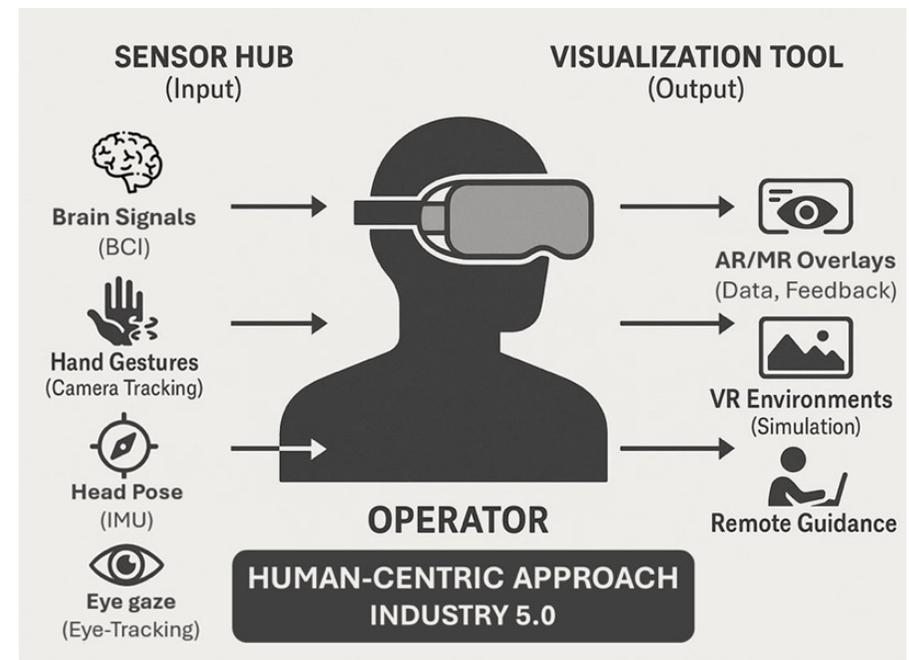


PhD thesis Overview

eXtended Reality (XR) is the enabling platform, where the Head-Mounted Display (HMD) acts as the critical edge node

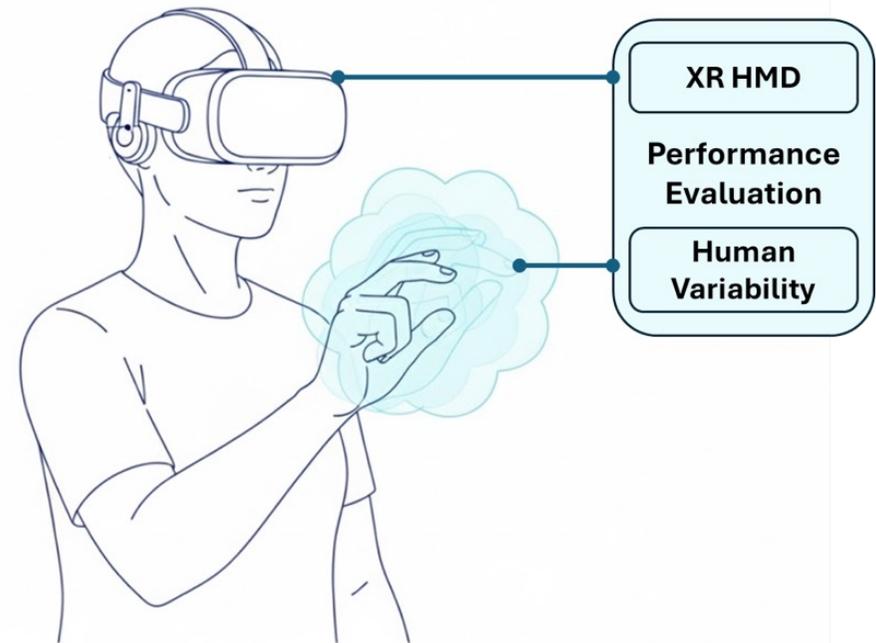


Operator interacts via Natural Human-Machine Interfaces



PhD thesis: The problem

- **Lack of Trustworthiness:** Reliability of the telecommunication chain is compromised if data generation at the source (Human-Edge) is not trustworthy
- **Inadequate Evaluation Methods:** Current assessments rely on qualitative usability studies (HCI approach) or opaque manufacturer specifications (Black Box)
- **Unquantified Variability:** There are no standardized protocols to quantify the stochastic impact of the human operator on system performance.



PhD thesis: Objective

- **Primary Objective: Interaction Engineering**

Establish the discipline of Interaction Engineering, shifting the paradigm from a subjective assessment of usability to a rigorous metrological characterization.

1. To treat the NHMI not as a consumer gadget, but as a **Measuring Instrument**
2. To develop a Unified Metrological Framework compliant with international standards

Main goals

1. To characterize performance beyond simple accuracy
2. To model the human operator as a component of the measurement chain

PhD thesis: Methodology

- 1. New Taxonomy**
- 2. Standardized Testbed & Protocol**
- 3. Performance metrics**
- 4. The Uncertainty Budget (GUM Compliant)**
- 5. Novel Metrics**

PhD thesis: Methodology

1. New Taxonomy

Moving beyond "Hands-free vs. Hands-based" and "Native vs. External" to a rigorous classification:

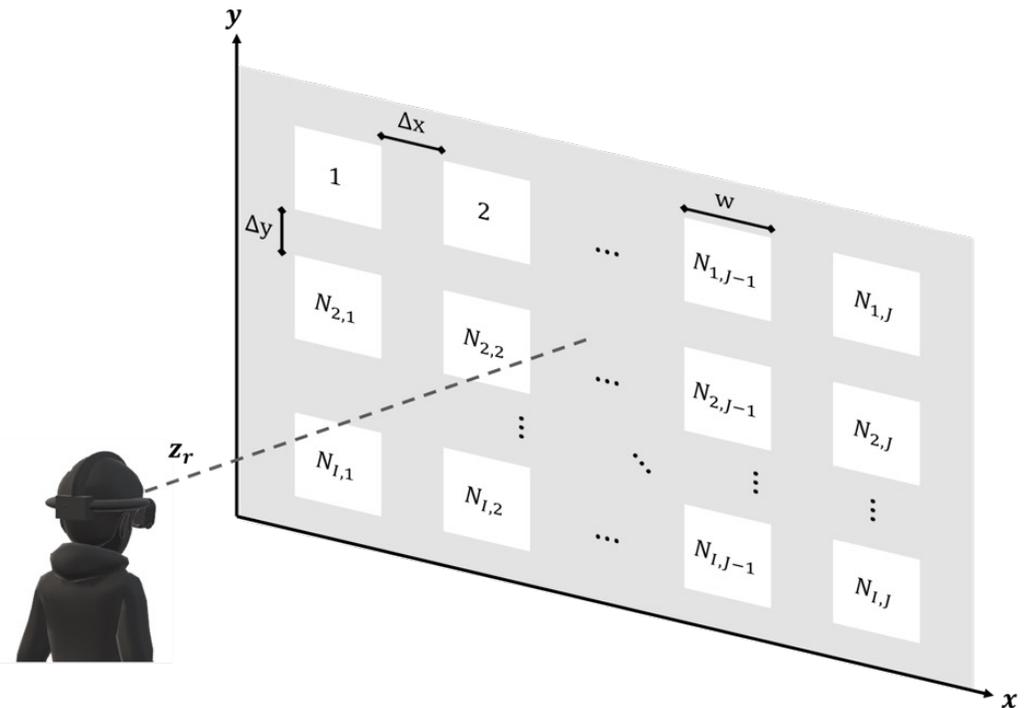
- **Spatial Tracking Interfaces:** Eye-Tracking, Head-Tracking, Gesture Recognition
- **Bio-Signal Interfaces:** Steady State Visually Evoked Potentials (SSVEP) – Brain Computer Interfaces (BCIs)

Interface	Type	Taxonomy	
		Functional	Architectural
Keyboard	Traditional	Hands-based	External
Controller	Traditional	Hands-based	Device-dependent
Head-Tracking	NHMI	Hands-free	Native
Eye-Tracking	NHMI	Hands-free	Device-dependent
Gesture-recognition	NHMI	Hands-based	Device-dependent
Speech Recognition	NHMI	Hands-free	Device-dependent
BCI	NHMI	Hands-free	Device-dependent
Electromyography	NHMI	Not applicable	External

PhD thesis: Methodology

2. Standardized Testbed and Protocol

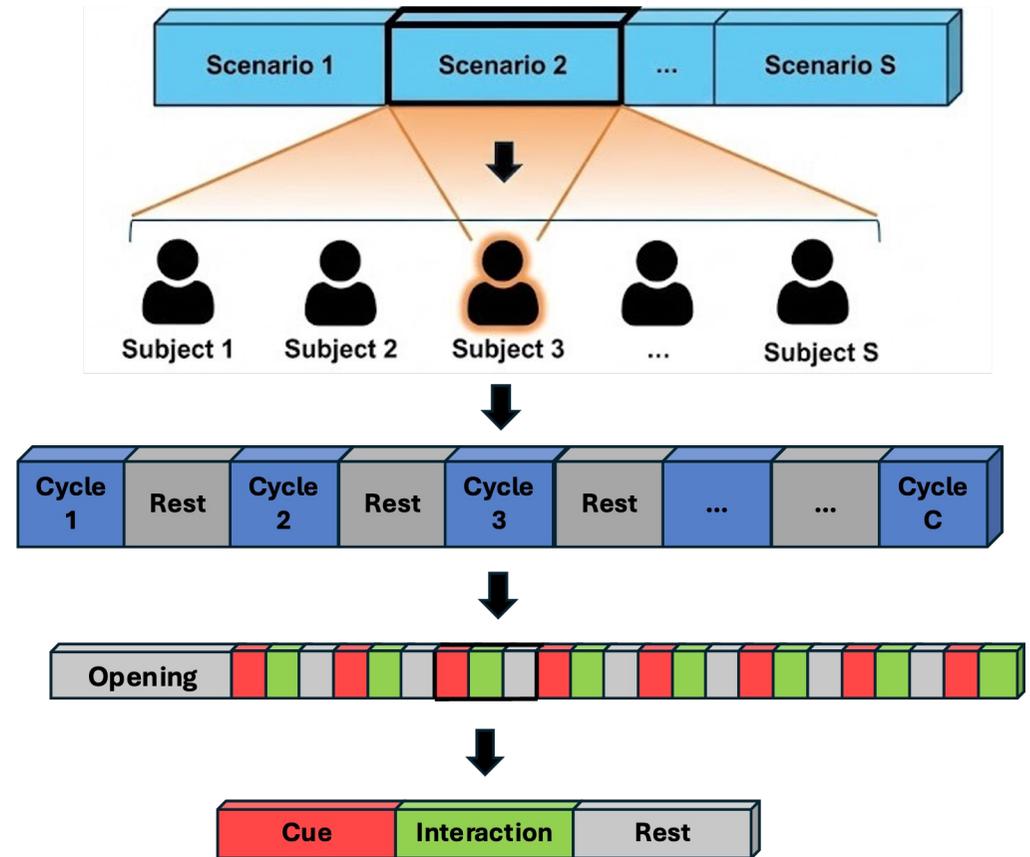
- Design of a modular, reproducible XR Testbed
- Strict temporal protocols (Cue-Guided Tasks) to isolate system latency from human reaction time.



PhD thesis: Methodology

2. Standardized Testbed and Protocol

- Design of a modular, reproducible XR Testbed
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PhD thesis: Methodology

3. Performance Metrics:

Beyond Selection Accuracy – Towards ITR

- Selection Accuracy

$$A = \frac{N_c}{N} \cdot 100 \quad [\%]$$

- Selection Time T : time elapsed from the onset of the visual cue to the instant of target recognition
- Information Transfer Rate

$$ITR = \left[\log_2(N) + p \log_2(p) + (1 - p) \log_2 \left(\frac{1 - p}{N - 1} \right) \right] \frac{60}{T} \quad [bit/min]$$

PhD thesis: Methodology

3. Performance Metrics:

Spatial Metrics

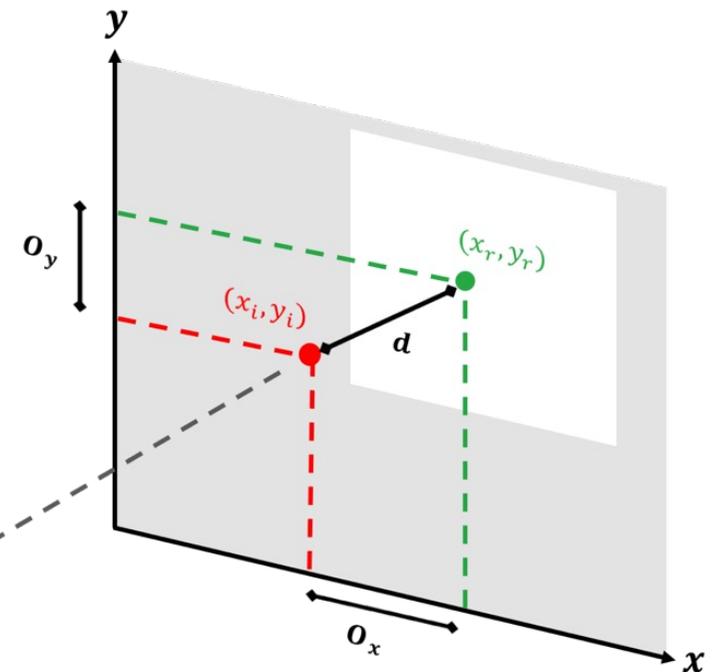
- Horizontal and Vertical Offset

$$O_x = x_i - x_r$$

$$O_y = y_i - y_r$$

- Euclidean Distance

$$d = \sqrt{(x_i - x_r)^2 + (y_i - y_r)^2} = \sqrt{O_x^2 + O_y^2}$$



PhD thesis: Methodology

3. The Uncertainty Budget (GUM Compliant)

- Measurement results in terms of Best Estimate and Measurement Uncertainty

Given n independent observations, the metric Q is defined according to:

$$\bar{q} = \frac{1}{n} \sum_{k=1}^n q_k$$

$$u(q) = \sqrt{u_A^2(q) + u_B^2(q)}$$

PhD thesis: Methodology

3. Decomposing Human Variability (GUM Compliant)

A novel mathematical formulation decomposing Total Uncertainty u_{Tot} into three distinct sources: Given S subjects performing M cycles, each with best estimate $q_{s,M}$

$$u(q_s) = \frac{\sigma(q_{s,1}, q_{s,2}, \dots, q_{s,M})}{\sqrt{M}}$$

Intra-Individual Variability

$$\overline{u(q_s)^2} = \text{mean}(u^2(q_1), u^2(q_2), \dots, u^2(q_S))$$

Inter-Individual Variability

$$u(\bar{q}) = \frac{\sigma(\bar{q}_1, \bar{q}_2, \dots, \bar{q}_S)}{\sqrt{S}}$$

PhD thesis: Methodology

4. Novel Metrics: The Maximum Number M_N

A novel figure of merit defining the maximum density of interactive elements a device can support based on user precision

$$M_N = \left\lfloor \frac{A_t}{A_c} \right\rfloor$$

Confidence Area A_C : area within which the system determines that the user's interaction falls

$$A_C \propto \alpha_R (d + u(d))$$

Total Virtual Area A_t : entire interactive area available to the user at distance z_r

$$A_t \propto z_r^2 \cdot \alpha_R^{-1} \cdot FOV$$

PhD thesis: Results

1. Validation of the Metrological Framework

The proposed framework bridges the gap between qualitative usability and rigorous performance characterization

2. Operational Hierarchy of NHMIs

- Head-Tracking: Validated as the **gold standard** for reliability and high-precision
- Gesture Recognition: significant intra-individual variability due to learning curves.
- Eye-Tracking limited by saccadic instability
- SSVEP-BCI: Characterized by high inter-individual variability

3. The Human-in-the-Loop as a Stochastic Component

Trustworthiness is primarily driven by the operator

4. Taxonomical Dichotomy

Continuous geometric pointers vs discrete classifiers

