ingenieur
wissenschaften
htw saar

Hochschule für
Technik und Wirtschaft
des Saarlandes
University of
Applied Sciences

Master-Thesis

zur Erlangung des akademischen Grades
Master of Science (M. Sc.)
an der Hochschule für Technik und Wirtschaft des Saarlandes
im Studiengang Praktische Informatik
der Fakultät für Ingenieurwissenschaften

Design and Development of an XR Assistance System for Industrial Workers

vorgelegt von
Nick Bretz

betreut und begutachtet von
Prof. Dr.-Ing. Steffen Knapp
Dr. Eric Wagner

Saarbrücken, Tag. Monat Jahr

Selbständigkeitserklärung

Ich versichere, dass ich die vorliegende Arbeit (bei einer Gruppenarbeit: den entsprechend gekennzeichneten Anteil der Arbeit) selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Ich erkläre hiermit weiterhin, dass die vorgelegte Arbeit zuvor weder von mir noch von einer anderen Person an dieser oder einer anderen Hochschule eingereicht wurde.

Darüber hinaus ist mir bekannt, dass die Unrichtigkeit dieser Erklärung eine Benotung der Arbeit mit der Note "'nicht ausreichend"' zur Folge hat und einen Ausschluss von der Erbringung weiterer Prüfungsleistungen zur Folge haben kann.

Saarbrücken, Tag. Monat Jahr

Nick Bretz

Zusammenfassung

Kurze Zusammenfassung des Inhaltes in deutscher Sprache, der Umfang beträgt zwischen einer halben und einer ganzen DIN A4-Seite.

Orientieren Sie sich bei der Aufteilung bzw. dem Inhalt Ihrer Zusammenfassung an Kent Becks Artikel: `http://plg.uwaterloo.ca/~migod/research/beckOOPSLA.html`.

We have seen that computer programming is an art,
because it applies accumulated knowledge to the world,
because it requires skill and ingenuity, and especially
because it produces objects of beauty.

— Donald E. Knuth [1]

Danksagung

Hier können Sie Personen danken, die zum Erfolg der Arbeit beigetragen haben, beispielsweise Ihren Betreuern in der Firma, Ihren Professoren/Dozenten an der htw saar, Freunden, Familie usw.

Contents

1 Introduction

In modern industrial environments, ensuring the safety and well-being of workers is an increasingly complex challenge. This is due to the rise in automation of factories, which has led to workers being exposed to a range of risks from moving parts to robots. Traditional safety measures (e.g., warning signs, training programs) are often static and thus insufficient for modern dynamic workspaces. They do not adapt to the real-time context of the worker, leading to potential oversights.

Consider a typical workstation on an assembly line: a robotic arm picks components from a moving conveyor and places them onto a workbench, where a human operator performs detailed finishing tasks. The process is fast-paced, and both the worker and the robot operate in close proximity. A moment of inattention could result in the worker reaching into the robot's operational area, or adopting a strained posture while handling a part, creating risks of both acute injury and long-term musculoskeletal strain. Traditional safety would not be able to provide the necessary real-time feedback to prevent such incidents since they rely on the worker's ability to notice and process external warnings while engaged in their primary tasks.

To adress these shortcomings, a new approach that leverages real-time data and immersive technologies can provide more effective assistance. By integrating real-time physiological and spatial data with immersive and haptic feedback, it is possible to create a system that enhances worker safety in dynamic environments. Such a system can make risks visible, posture perceptible, and hazards tangible, thereby supporting workers in making safer decisions and maintaining ergonomic practices.

Advances in extended reality (XR) and wearable technology, such as full-body haptic suits and immersive head-mounted displays, are opening new possibilities for real-time assistance and feedback systems. These technologies are no longer confined to research labs or entertainment industries but are being increasingly considered for applications in healthcare, rehabilitation, training, and industrial safety. This increased availability of XR and wearable devices presents the opportunity to develop such adaptive assistance systems that can provide real-time, personalized feedback to workers.

Current approaches at such systems often focus on one mode of feedback, or do not provide real-time, personalized assistance, resulting in them not utilizing the full potential of XR and wearable technologies. Additionally systems utilizing only a singular modality (e.g., only visual feedback) can lead to information overload through excessive visual stimuli, which can distract workers from their primary tasks. By combining multiple modalities—such as visual, auditory, and haptic feedback—these systems can provide more intuitive and effective warnings that are less likely to be ignored or seem distractive.

This thesis presents the design and development of an XR-based assistance framework for industrial workers that integrates real-time physiological and spatial data from wearable sensors with immersive visual and haptic feedback. The system is tailored for dynamic, collaborative work environments, such as assembly lines where humans and robots operate in close proximity, and aims to enhance situational awareness, promote ergonomic posture, and reduce the risk of accidents without disrupting workflow.

2 Motivation

Modern industrial environments are increasingly characterized by high levels of automation, dynamic workflows, and close interaction between human workers and complex machinery. While these developments have improved efficiency, they have also introduced new safety challenges. Workers are required to perform physically demanding tasks in proximity to moving parts, robotic systems, and other potential hazards. In such conditions, it is hard for workers to maintain constant situational awareness, leading to an increased risk of accidents and injuries.

Returning to the typical workstation on an assembly line, an XR based assistance system utilizing information about it's environment Traditional safety measures—such as fixed signage, floor markings, or general training programs provide an essential baseline but are inherently limited. They rely on the worker's ability to notice and process external warnings while engaged in their primary tasks. This static approach does not account for the worker's individual posture, or the evolving state of their environment. As a result, critical risks may go unnoticed until it is too late.

There is a clear need for safety systems that are adaptive, personalized, and context-aware. Such systems must continuously monitor the worker's physical state and spatial position, detect unsafe situations as they emerge, and deliver warnings through intuitive, non-disruptive channels. Advances in Extended Reality (XR) and wearable technologies offer a unique opportunity to meet these requirements. Head-mounted displays can overlay hazard information directly into the user's field of view, while full-body haptic suits can provide spatially localized alerts that are instantly understood without diverting visual attention.

The XR-based assistance framework proposed in this thesis addresses these needs by combining immersive visualization with real-time haptic feedback, powered by continuous analysis of physiological and positional data. Unlike existing solutions, it adapts its feedback to the worker's specific context, enabling timely interventions without breaking the flow of work. In doing so, it has the potential to reduce the risk of acute injuries, prevent the development of musculoskeletal disorders, and improve overall situational awareness in industrial environments.

The urgency for such a solution is amplified by current industry trends: increasing automation, a growing focus on occupational health, and the wider availability of high-performance, affordable XR and wearable devices. Now is the right time to explore how these technologies can be integrated into practical safety systems that protect workers without compromising efficiency.

3 Theoretical Background

This chapter outlines the conceptual and scientific foundations relevant to the development of an XR-based assistance system for industrial workers. It introduces key technologies, principles of ergonomics, human-machine interaction modalities, and architectural tools that enable real-time support in complex environments.

3.1 Extended Reality in Industrial Contexts

Extended Reality (XR) technologies—encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) are increasingly being explored beyond their origins in gaming and entertainment. In recent years, they have shown significant promise for applications in healthcare, education, training, and particularly in industrial environments. These immersive systems offer novel ways to visualize information, monitor surroundings, and interact with complex machinery or digital twins in real time.

In industrial settings, XR can bridge the gap between human workers and automated systems by enhancing spatial awareness, reducing cognitive load, and supporting ergonomically sound behavior. By embedding visualizations directly into the user's perceptual field and supplementing them with spatially anchored cues or haptic feedback, XR opens new pathways for context-sensitive assistance. This is especially relevant in environments that involve repetitive tasks, heavy machinery, or dynamic hazards—scenarios in which traditional safety protocols may fall short.

This section introduces the conceptual foundations of XR, outlines its most common industrial applications, and discusses the key challenges and opportunities associated with deploying XR systems in real-world industrial settings.

3.1.1 Definition and Taxonomy

Extended Reality (XR) is an umbrella term encompassing a spectrum of technologies that combine or replace real-world perception with computer-generated input. The conceptual foundation for this spectrum was introduced by Milgram and Kishino in their seminal work on Mixed Reality visual displays [3].

At the core of their model lies the *Reality–Virtuality Continuum*, which represents a scale between the completely real environment and the fully virtual environment. Technologies within this continuum can be classified as follows:

- **Real Environment (RE):** The physical world, unmediated by digital augmentation.
- **Augmented Reality (AR):** Systems that overlay virtual elements onto the real world while maintaining real-time interaction and correct spatial registration. Examples include visual annotations or digital twins of industrial machinery displayed through XR headsets.
- **Mixed Reality (MR):** A broader concept encompassing AR, but also allowing for deeper integration where virtual and real elements interact and are spatially and temporally consistent. In MR, digital and physical objects can influence each other.

- **Augmented Virtuality (AV):** Mostly virtual environments that incorporate some real-world data—such as sensor streams or camera feeds.
- **Virtual Reality (VR):** Fully immersive digital environments with little or no real-world input.

XR, as used in this thesis, refers to the entire continuum and highlights systems that combine immersive visualization (e.g., via head-mounted displays) with real-world input data (e.g., motion capture, spatial localization, physiological sensors). This definition is especially relevant in safety-critical industrial contexts, where virtual feedback must accurately reflect physical risks and user behavior in real time.

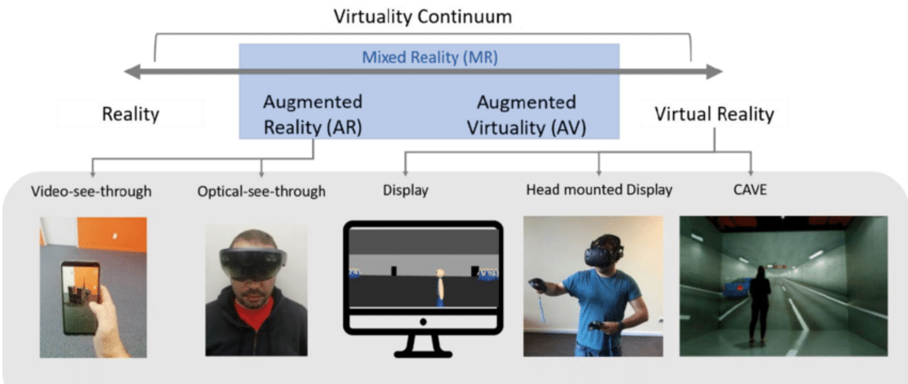

Figure 3.1: The Reality–Virtuality Continuum, adapted from Milgram and Kishino [3].

3.1.2 Applications of XR in Industry

3.1.3 Challenges and Opportunities

3.2 Human Factors and Ergonomics

3.2.1 Rapid Upper Limb Assessment (RULA)

As Posture Assessment Method, this thesis utilizes the Rapid Upper Limb Assessment (RULA) to evaluate the ergonomic risk associated with a worker's posture. RULA is a survey method designed to assess biomechanical and postural loading on the upper limbs [2]. It is particularly useful in environments where workers perform repetitive tasks or maintain static postures for extended periods. Due too limiting factors of the Teslasuit, a limited version of RULA is used excluding loads carried and arm support. The assessment involves scoring various body segments, including the upper arms, lower arms, wrists and neck based on their angles and positions. Each segment is assigned a score based on its deviation from neutral posture, with higher scores indicating greater ergonomic risk. The scores are then combined to produce an overall RULA score, which categorizes the risk level and suggests the urgency of intervention. The RULA method is widely used in occupational health inform ergonomic interventions aimed at improving workplace safety and comfort.

3.2.2 Common Industrial Posture-Related Injuries

3.2.3 Need for Real-Time Monitoring

3.3 Wearable Technologies for Assistance

3.3.1 Overview of Industrial Wearables

3.3.2 The Teslasuit

3.3.3 Capabilities and Limitations

3.4 Haptic Feedback and Multimodal Warning Systems

3.4.1 Perception of Haptic Stimuli

3.4.2 Design Principles for Effective Feedback

3.4.3 Visual vs. Haptic Alerts

3.4.4 Cognitive Load and Safety Feedback

3.5 Spatial Awareness and Localization in XR

3.5.1 XR Tracking Technologies

3.5.2 The Meta Quest 3

3.5.3 Spatial Consistency with Teslasuit Data

3.6 Multisensor Integration and Synchronization

3.6.1 Challenges in Multimodal Systems

3.6.2 LabStreamingLayer (LSL)

3.6.3 Integration of MQTT and Environment Data

3.7 Related Work

3.7.1 XR in Industrial Safety

3.7.2 RULA in Industrial Applications

4 Concept

4.1 Introduction

This chapter presents the conceptual design of an XR-based assistance system aimed at enhancing the safety and ergonomics of industrial workers. Building on the theoretical foundations outlined in Chapter 3, it details the system requirements, architectural framework, posture analysis and hazard detection concepts, feedback modalities, interaction design, and evaluation criteria. The goal is to provide a comprehensive blueprint that addresses the identified challenges while leveraging the capabilities of wearable technologies and XR environments. This conceptual framework serves as a foundation for the subsequent implementation and evaluation phases of the project.

4.2 System Requirements and Constraints

4.2.1 Functional Requirements

-Real-time posture monitoring -Hazard detection in XR environment -Haptic and visual feedback for unsafe postures and hazards -Data logging for ergonomic assessment -User-friendly interface for workers -Integration with existing industrial systems (GAIA)

4.2.2 Non-functional Requirements

-Latency -Intrusiveness -Reliability -Usability

4.2.3 Hardware and Software Constraints

-control center only runs on windows so component running windows is required for the teslasuit -teslasuit not that precise and cant detect whether body part rested on something or not

4.3 Framework Architecture

-due to the software limitations the Framework is distributed between the Meta Quest 3 and a windows PC which will handle the data and most of the computation

4.3.1 Hardware Components

-Meta Quest 3 -Teslasuit -Windows PC -GAIA system -potential addtional sensors (smart watch etc)

4.3.2 Data Flow and Integration via LSL

4.3.3 Communication Protocols

4.4 Posture Analysis Concept

-Real-time joint angle data acquisition from Teslasuit -Ergonomic assessment using RULA

4.4.1 Joint Angle Data Acquisition

4.4.2 Ergonomic Assessment Model

4.4.3 Mapping to Ergonomic Risk Levels

4.5 Hazard Detection Concept

-Using XR environment to define and visualize danger zones -Integration of real-world data for dynamic hazard detection

4.5.1 Spatial Alignment of XR and Real-World Coordinates

-

4.5.2 Definition of Danger Zones

4.5.3 Sensor and XR Data Fusion

4.6 Feedback Modalities

4.6.1 Haptic Feedback

4.6.2 Visual Feedback

4.6.3 Rationale for Feedback Choice

4.7 Interaction Design

-Aside from setup and calibration the system should require minimal interaction from the worker -The system should provide clear and concise feedback without overwhelming the worker - The system should be non-intrusive when no hazards or poor posture is detected

4.7.1 Worker Interaction with the System

4.7.2 Avoiding Information Overload

-Prioritization of Alerts -Haptic vs Visual Feedback -low intensity haptic feedback for posture correction -stronger haptic feedback for hazard alerts -visual feedback for immediate/ dangerous hazard alerts

4.7.3 Safety-Critical Design Considerations

4.8 Conceptual Evaluation Criteria

4.8.1 Relation to Research Questions

4.8.2 Success Criteria for the Concept

4.9 Summary and Transition

Bibliography

[1] Donald E. Knuth. "Computer Programming as an Art". In: *Communications of the ACM* 17.12 (1974), pp. 667–673.

[2] Lynn McAtamney and E. Nigel Corlett. "RULA: a survey method for the investigation of work-related upper limb disorders". In: *Applied Ergonomics* 24.2 (1993), pp. 91–99. ISSN: 0003-6870. DOI: `https://doi.org/10.1016/0003-6870(93)90080-S`. URL: `https://www.sciencedirect.com/science/article/pii/000368709390080S`.

[3] Paul Milgram and Fumio Kishino. "A taxonomy of mixed reality visual displays". In: *IEICE TRANSACTIONS on Information and Systems*. Vol. 77. 12. IEICE, 1994, pp. 1321–1329.

List of Figures

List of Tables

Listings

Abkürzungsverzeichnis

Anhang

A Erster Abschnitt des Anhangs

In den Anhang gehören "'Hintergrundinformationen"', also weiterführende Information, ausführliche Listings, Graphen, Diagramme oder Tabellen, die den Haupttext mit detaillierten Informationen ergänzen.

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Kolophon

Dieses Dokument wurde mit der LaTeX-Vorlage für Abschlussarbeiten an der htw saar im Bereich Informatik/Mechatronik-Sensortechnik erstellt (Version 2.25, August 2024). Die Vorlage wurde von Yves Hary und André Miede entwickelt (mit freundlicher Unterstützung von Thomas Kretschmer, Helmut G. Folz und Martina Lehser). Daten: (F)10.95 – (B)426.79135pt – (H)688.5567pt