

Research Article

# Mirroring Humanity: Creating the Digital Twin via Advanced Human-Device Interfaces

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## ABSTRACT

The integration of Human-Device Interfaces (HDIs) is fundamentally transforming how humans interact with technology, moving from traditional inputs like keyboards toward seamless, effortless communication. This paper explores the concept of "Mirroring Humanity" through the creation of a Digital Twin, facilitated by advanced interfaces such as Brain-Computer Interfaces (BCIs), wearable sensors, and haptic feedback. By leveraging Artificial Intelligence (AI) and machine learning, these systems enable real-time decision-making and the personalization of technology to individual user needs. Drawing on case studies from ACRLAB at Universiti Malaya, this work highlights advancements in contactless navigation such as eye-driven wheelchairs and immersive virtual teaching environments. These technologies demonstrate a proof of concept for enhancing independence among disabled communities and improving efficiency across industries including healthcare and automation. However, the shift toward highly integrated digital twins introduces significant challenges regarding data security, reliability, and the ethical implications of augmenting human traits. The paper concludes that while HDIs offer immense potential for global betterment, robust regulations, ethics and inclusive design are essential to mitigate risks and ensure sustainable technological advancement.

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## 1. Introduction

Rapid technological advancement has made it possible for humans and robots to interact seamlessly, improving usability, efficiency, and overall experience [1], [2], [3], [4], [5]. User interactions have historically been dominated by inputs like keyboards, buttons, and touch screens [6]. But the future of human-device interaction lies in new technologies like gesture recognition, eye tracking, speech recognition, and brain computer interfaces (BCIs). This technological trend makes interfaces easier to use, more responsive, and improves user experience.

Artificial intelligence (AI), specifically supervised, semi-supervised, and unsupervised learning algorithms, has grown significantly in popularity in the creation of Human-Device Interfaces (HDIs). Real-time decision-making and system automation are made possible by AI's ability to process and react to input data. In addition to improving accessibility for people with impairments, these developments provide opportunities in a variety of industries, including healthcare, education, entertainment, automation, and gaming.

Recently, contactless and effortless input approaches have gained popularity for HDIs [7]. Eye movement tracking using wearable cameras or electrooculography (EOG) has made it possible to manage devices without using your hands, which has led to notable advancements in the automation and medical fields [7], [8], [9]. Brain-Device Interfaces (BDIs) and Brain Machine Interfaces (BMIs) redefine user-device collaboration and, more significantly, the user experience by enabling mental commands.

In the context of this paper, a Digital Twin can be defined as a virtual, high fidelity mirror of a human user, sustained by a continuous flow of data through Human-Device Interfaces (HDIs). It represents a seamless integration where technology doesn't just assist the user but replicates their physical, physiological, and cognitive states in a digital environment. In the context of industrial and mechanical systems, this can be done by creating a virtual shadow that mirrors physical behavior in real time. This work extends our preliminary study presented in [10], where the initial concept and framework of the proposed Digital Twin approach were first introduced.

This study aims to investigate current developments using case studies from ACRLAB, Faculty of Engineering, Universiti of Malaya, Malaysia which relates to HDI and Digital Twin.

## 2. ACRLAB, Faculty of Engineering, University Malaya

### 2.1. Aim and Mission

Under the leadership of the Faculty of Engineering, ACRLAB is dedicated to pioneering advancements in Human-Device Interface (HDI) technology, focusing on the creation of effortless, intuitive interfaces between humans, devices, and complex systems to significantly elevate the user experience. By integrating Artificial Intelligence and advanced sensing, the lab seeks to transition from traditional manual inputs to seamless, responsive digital interactions. The specific research capabilities and high-tech facilities utilized for these developments are detailed within the Case Studies section. Strategically located at Level 4, Block M of the Faculty of Engineering at Universiti Malaya, ACRLAB serves as a central hub for a robust network of national and international collaborations (Fig. 1).



Fig.1. ACRLAB location with national and international collaborators.

### 2.2. The importance of Human-Device Interfaces (HDIs)

Human-Device Interfaces (HDIs) are poised to revolutionize nearly every facet of human existence, fundamentally altering how we live, work, navigate, and engage with our daily routines, from exercise and sleep to shopping and travel. The limitations of conventional peripherals like keyboards and mice have given way to a new era of complex, networked ecosystems or devices like smartphones, wearable technology (Fig. 2), [6], [7], and AI-driven assistants. This evolution signifies a paradigm shift in technological advancement. This change is radically altering how we interact with technology and, without recognizing it, integrating it into our daily lives and environments. Central to this transformation are smartphones and wearable technologies that act as continuous data conduits. By integrating these advanced interfaces, we are moving toward a future of "Mirroring Humanity," where technology becomes an intuitive

extension of the user, facilitating a seamless, real-time connection between the physical and digital worlds.

## 3. Recent Works on HDIs

### 3.1. Wearable Technology

Smartwatches, health monitors, speech and gesture-based interfaces like SIRI, Google Assistant, AR/VR systems, and Brain Computer Interfaces (BCIs) [9] are significant advancements that present opportunities in a variety of industries, including gaming, healthcare, shopping, driving, monitoring, and more [9]. Figures 2 and 3 illustrate two instances of these technologies that were used at ACRLAB, Faculty of Engineering, Universiti Malaya [6], [7].



Fig. 2. BCIs using Electrooculogram for wheelchair navigation by ACRLAB, Universiti Malaya [6], [7].



Fig. 3. Eye driven wheelchair by ACRLAB, Universiti Malaya

Fig. 2 illustrates how BCIs at ACRLAB, Universiti Malaya, use electrooculograms for wheelchair navigation. An eye-driven wheelchair with a wearable camera for navigation is shown in Fig. 3, [6], [7]. Both pieces demonstrated the viability of improving user experience and an easy-to-use interface to help disabled groups voice their needs and become more autonomous. Fig. 4 shows the modes and states for BCI navigation using Fig. 2, [6], [7].

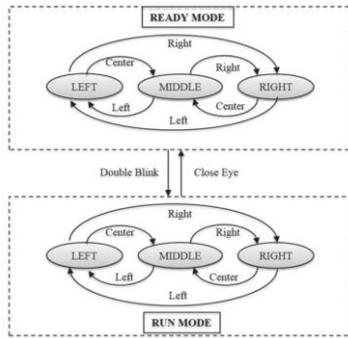


Fig. 4. The modes and state BCIs navigation by Fig. 2, [6], [7].

The commercial landscape of wearable technology is dominated by devices such as the Apple Watch, Fitbit, Garmin, and Samsung Galaxy Watch, which have become ubiquitous tools for fitness tracking, health monitoring, and seamless communication. A prime example of this integration is the Apple Watch, which possesses the capability to detect irregular heart rhythms and perform ECG tests, serving as a critical tool for identifying early indicators of heart disease. Beyond general fitness, specialized health monitoring systems like the Dexcom G6 and Abbott Freestyle Libre represent a more profound level of human-device integration; these devices continuously track blood glucose levels and transmit data to smartphones or dedicated receivers. By facilitating timely diabetes management and enhancing patient well-being, these HDIs mitigate the risk of serious complications, illustrating the transformative potential of mirroring physiological states in real-time.

### 3.2. Voice and Gesture-Based Interfaces

Propelled by advancements in Natural Language Processing (NLP) and machine learning, voice assistants such as Siri, Google Assistant, and Alexa have evolved into highly intelligent systems. These interfaces streamline daily life by simplifying complex tasks, including setting reminders, managing smart home ecosystems, and retrieving information through natural dialogue. Parallel to voice, gesture-based control facilitated by technologies like Microsoft Kinect or integrated motion sensors in smartphones enables intuitive, touchless interaction. These advancements allow users to control systems effortlessly, significantly enhancing the immersive experience in gaming and beyond. For virtual learning environments, Fig. 5 illustrates interactive design with gesture and voice recognition. To improve user experience, augmented reality (AR) and virtual reality (VR) are typically combined with speech, gesture, and adaptable virtual environments [5].



Fig. 5. Gesture and voice recognition for virtual teaching environments [5].

### 3.3. Haptic Feedback and Tactile Interfaces

Tactile Interfaces and Haptic Feedback use touch to simulate resistance or textures. For force detection, gesture translation, and touch identification, haptic sensors rely on technologies including piezoresistive, capacitive, piezoelectric, and triboelectric. Haptic sensing and feedback methods are depicted in Fig. 6 [11].



Fig. 6. Haptic sensing and feedback techniques [11].

### 3.4. Web-Based HDIs

Remote monitoring systems provide unparalleled flexibility, enabling seamless interaction with medical equipment, wearable technology, robotics, and industrial systems, as well as applications in education, gaming, and entertainment. This technology has established a "new normal" for user interfaces and digital services, facilitated primarily through mobile applications and web-based Human-Device Interfaces (HDIs). By integrating machine learning, vision-based systems, and the Internet of Things (IoT), these web-based platforms allow for the real-time streaming of data and remote stabilization of hardware, such as drones or patient health monitors. Such systems are essential for the continuous tracking of health status or industrial metrics, bridging the gap between physical locations and digital oversight which essential for digital twin for human and system.

Drone position and virtual maps for possible use in integrated monitoring and wildfire mitigation are displayed in Fig. 7 and Fig. 8, which were created by ACRLAB, Faculty of Engineering, Universiti Malaya. In order to enable remote monitoring and online streaming of data of interest through web-based applications, this study integrates machine learning, vision-based systems, GPS,

control systems to stabilize drone flying, and Internet of Things technology. By broadcasting the data to medical officers, the same idea can be used to continuously monitor the health status of patients.



Fig. 7. Drone and web-based interface (ACRLAB, Faculty of Engineering, Universiti Malaya)



Fig. 8. Illustration of drone and web-based interface

#### 4. Ethical Considerations and Challenges in Human-Devices Interfaces (HDIs)

As Human-Device Interfaces (HDIs) evolve into an indispensable component of our daily routines, they bring forth a complex array of ethical dilemmas and systemic challenges that must remain a primary concern for developers and policymakers. The transition toward "Mirroring Humanity" through digital twins necessitates a careful evaluation of the following areas:

- **Privacy and Security:** The massive integration of HDIs creates significant vulnerabilities regarding data privacy and the security of sensitive personal information.
- **Physiological and Psychological Well-being:** There are growing concerns regarding the long-term side effects of wearable devices and the profound physiological and psychological impacts they may have on both adults and children.
- **The Enhancement vs. Alteration Dilemma:** A critical ethical boundary must be established to distinguish between "human enhancement" which augments existing abilities and "alteration," which involves changing natural human traits and poses unforeseen societal consequences.

- **Societal Responsibility:** The core dilemma remains whether these technological advances will be utilized for the betterment of society or lead to potential misuse.

The dilemma is whether to use it for the benefit of society or not [11], [12], [13], [14], [15], [16].

#### 5. Challenges in HDIs Integration

The challenges in integrating Human-Device Interfaces (HDIs) are multifaceted, spanning technical limitations, ethical dilemmas, and societal hurdles.

First, the integration of Human-Device Interfaces (HDIs) faces significant technical and hardware constraints, primarily the difficult trade-off between high-performance accuracy and device portability. Current wearable sensors and Brain-Computer Interfaces (BCIs) often fail to deliver high accuracy without utilizing bulky hardware or requiring frequent battery charging, which hinders their seamless use in daily life. Furthermore, the reliability of these systems remains a major concern, as error and failure rates can compromise user safety and overall system trust. Finally, ensuring seamless compatibility across diverse HDI platforms and managing high development costs remain complex engineering and economic challenges that must be resolved to create a truly interconnected and sustainable user experience.

Secondly, for ethical and psychological dilemmas consideration needs to be included in the integration. The evolution of HDIs into daily life introduces profound ethical concerns, particularly regarding the privacy and security of sensitive biological data. A critical dilemma exists in drawing a clear boundary between human "enhancement," which improves natural abilities, and "alteration," which fundamentally changes human traits and carries unpredictable societal consequences. Furthermore, the continuous use of these devices necessitates a major concern for the physiological and psychological side effects they may have on both adults and children.

Finally, for socioeconomic and regulatory barriers perspective, integration is heavily influenced by public perception and trust, as many users are wary of invasive technologies that integrate closely with the human body. Additionally, the high costs of developing these sophisticated systems depend on a community's financial sustainability, which can limit accessibility. Because the shift toward digitization is unavoidable, there is an urgent need for global cooperation to establish comprehensive regulations, ethical standards, and accountability measures to prevent the misuse of technology.

#### 6. Conclusions

In conclusion, the integration of Human-Device Interfaces (HDIs) represents a transformative leap toward "Mirroring Humanity" by creating a seamless digital extension of the physical and cognitive self. Through the

research conducted at ACRLAB, it has been demonstrated that technologies such as Brain-Computer Interfaces (BCIs), wearable health monitors, and remote web-based systems can significantly enhance independence for disabled communities and improve efficiency across various industries. However, the path to a sustainable future requires addressing critical challenges, including hardware limitations, data security, and the complex ethical boundary between human enhancement and alteration. By establishing robust global regulations, prioritizing inclusive design, and fostering ethical accountability, society can fully harness the potential of HDIs while mitigating risks for a responsible technological future.

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### Authors Introduction

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She earned a Bachelor of Engineering (B.Eng) in Telecommunication Engineering from Universiti Malaya in 2000. She was awarded the Panasonic Scholarship to pursue her Master of Engineering (M.Eng) at Oita University, Japan (2003-2006). Additionally, she received the SLAB/SLAI scholarship to complete her Ph.D. in Electrical Engineering at Universiti Malaya (2008-2012). Between 2000 and 2002, she worked as a Telecommunication Engineer at Echobroadband Sdn. Bhd., where she contributed to upgrading cable TV networks to hybrid fiber coaxial networks in Köln, Germany. Since 2003, she has built a distinguished academic career at Universiti Malaya, where she currently serves as an Associate Professor.

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