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Researching NUI-type experiential training with handtracking

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[Abstract]

This study proposes an immersive education and training system based on a Natural User Interface (NUI) utilizing hand tracking technology. Existing XR (eXtended Reality) educational content has faced limitations in immersion and realism due to its controller-input-centric interaction structure. This study directly recognizes hand gestures, eliminating the physical mediation between the user and the system, thereby implementing a more intuitive and natural interaction environment. The research methodology consists of analyzing educational training procedures and defining learning objectives, designing a hand-tracking-based gesture recognition interface, implementing an NUI-type immersive learning system, and conducting experimental validation. Hand-tracking-based NUI is expected to show improved results compared to existing input methods in terms of learner motion accuracy, response feedback, and immersion. This research holds significance as core foundational work for a non-contact, immersive education platform applicable across diverse fields such as XR industry, military, medical, and machinery maintenance training.

▸ **Key words**: XR, Hand Tracking, NUI, Experiential Training, Immersive Learning

[요 약]

본 연구는 핸드트래킹(Hand Tracking) 기술을 활용한 내츄럴 사용자 인터페이스(Natural User Interface, NUI) 기반의 체감형 교육훈련 시스템을 제안한다. 기존의 XR(eXtended Reality) 교육 콘텐츠는 컨트롤러 입력 중심의 상호작용 구조로 인해 몰입도와 실재감이 떨어지는 한계가 있었다. 본 연구에서는 손동작을 직접 인식하여 사용자와 시스템 간의 물리적 매개를 제거하고, 보다 직관적이고 자연스러운 인터랙션 환경을 구현하였다. 연구 방법은 교육훈련 절차 분석 및 학습 목표 정의, 핸드트래킹 기반 제스처 인식 인터페이스 설계, NUI형 실감형 학습 시스템 구현 및 실험적 검증으로 구성된다. 핸드트래킹 기반 NUI는 학습자의 동작 정확도, 반응 피드백, 몰입감 측면에서 기존 입력 방식 대비 향상된 결과를 보일 것으로 기대된다. 본 연구는 향후 XR 산업·군사·의료·기계정비 교육 등 다양한 분야에서 활용 가능한 비접촉·체감형 실감교육 플랫폼의 핵심 기초 연구로서 의미를 가진다.

▸ **주제어**: XR, 핸드트래킹, NUI, 체험형 교육, 실감형 학습

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I. Introduction

1. Introduction

1.1 Research Background

As XR technology expands into education and industrial training, the need for educational content that enables immersive experiences in realistic environments is growing.

However, most existing XR systems rely on controller-based operation, causing a mismatch between the learner's hands and movements and the actual procedures being performed. This gap has been identified as a major factor reducing learning efficiency and on-the-job adaptability.

1.2 Need for Research

1) Increased demand for contactless and natural interaction: The need for contactless educational environments has expanded since COVID-19, drawing attention to hand gesture recognition-based interfaces.[15][16]

2) Enhanced learning immersion and procedural task accuracy: Hand-tracking-based learning allows learners to perform tasks directly with hand gestures, improving procedural understanding and strengthening kinesthetic learning effects.[7][13]

3) Overcoming limitations of existing XR education: Controller-based manipulation is limited to visual feedback-centric designs, making it difficult to simulate actual procedural tasks. This research aims to overcome these constraints through natural motion-based interaction.[12]

1.3 Research Objective

The purpose of this study is to design an NUI-based immersive education and training system utilizing hand tracking, thereby enhancing learners' immersion, motion accuracy, and interactivity. To achieve this, the following three specific objectives have been established.

1) Design of hand-tracking-based gesture recognition and feedback architecture

2) Learning scenario design centered on natural interaction

3) Validation of immersive education and training models through empirical experiments in XR environments

II. Preliminaries

1. Related works

1.1 Current Status and Outlook of the Global XR Market Size

The global XR market is projected to show steady growth. Regionally, North America held the highest share in the AR market at 35% as of 2023, followed by Asia-Pacific at 33% and Europe at 25%. The compound annual growth rate (CAGR) from 2024 to 2029 is projected to be 40.4% for North America, 43.0% for Asia-Pacific, and 38.8% for Europe, indicating that Asia-Pacific's growth will be particularly prominent.

The AR market is projected to grow at a high compound annual growth rate (CAGR) of 40.7%, expanding from $10.95 billion in 2024 to $60.34 billion by 2029.

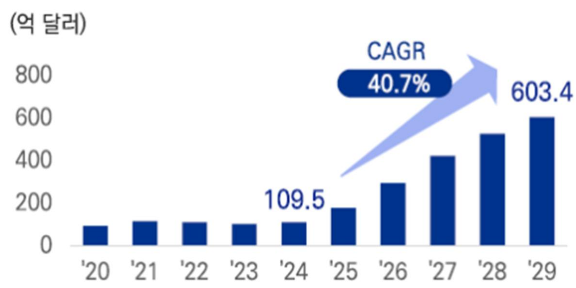

Fig. 1. AR Market Size Trends and Outlook[19]

The VR market is showing a relatively lower growth rate compared to AR, but it is maintaining a steady upward trend. The VR market size is projected to grow at a CAGR of 26.3%, from $11.18 billion in 2024 to $35.97 billion in 2029.

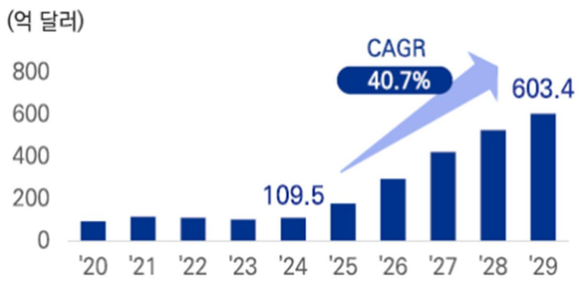

Fig. 2. VR Market Size Trends and Outlook[19]

As of 2022, South Korea's XR market ranks as the world's eighth-largest market, following the United States, China, Germany, and Japan. The Asia-Pacific region, including South Korea, is characterized by high digital technology adoption rates and rapidly developing related industrial infrastructure. Consequently, it is projected to exhibit the fastest growth in both the AR and VR markets going forward.

1.2 Trends in XR-Based Education Technologies

Azuma (1997) demonstrated that augmented reality technology can enhance learners' spatial immersion.[1] Subsequent studies have reported that VR/AR-based practical training content improves educational efficiency (Lee & Kim, 2020).[3]

However, most existing research remains focused on learning centered on visual feedback, with insufficient studies addressing learners' actual physical movements and interactivity.

1.3 Research on NUI and Hand Tracking Technology

Natural User Interface (NUI) is an interface that utilizes users' natural actions, gestures, and voice as system inputs, offering the advantage of reducing cognitive load (Norman, 2013).[2]

Recent advancements in hand tracking technology, enabled by devices like Leap Motion and Meta Quest Pro, now allow for precise tracking down to the finger joint level.[7 Shin & Lee (2023) applied hand tracking to medical simulation training and confirmed a learning satisfaction improvement of over 30% compared to traditional controllers.[4]

1.4 Trends in Embodied Learning Research

Embodied learning is an approach that enhances learning outcomes through physical movement and sensory experience, gaining attention as a core element of hands-on learning.[5][6]

Embodied learning in XR environments is particularly effective at improving learners' spatial memory and procedural performance abilities.

Building on this approach, this study concretizes an NUI-based embodied education and training framework utilizing hand tracking.

1.5 Research on XR Teaching Materials and Modular Education Solutions

Recent studies have attempted to evolve beyond single XR content toward a Modular XR Training System.

Park et al. (2022) proposed a modular structure for aircraft maintenance training XR content, enabling the combination of procedure-specific learning units. [14] Shin & Lee (2023) demonstrated that reusing common procedure modules in medical simulation training can simultaneously improve development costs and learning transfer effects.

Similarly, domestic XR education research is actively developing immersive procedural learning centered around teaching aids.

It possesses relative superiority compared to existing document/video-based training and controller-based XR training methods.

Comparison Item	Document/Video -Based Education	Controller-based training	NUI Hand Tracking-Based Education
Interactivity	Very low (One-way information delivery)	Middle (Abstract button/joystick operation)	Very high (Intuitive operation through natural hand gestures)
Immersion /Realism	Low (Lack of field connectivity)	Intermediate (A sense of alienation caused by physical mediation)	Maximization (Removal of physical mediators and enhancement of bodily memory)
Procedure Accuracy	Low (Difficulty simulating actual motion using visual information alone)	Mid-process (Discrepancy occurs with actual operation)	Enhanced (Immediate correction of movement errors through real-time feedback)
Cognitive dissonance	Medium to high (Requires understanding complex procedures through documentation)	Middle (Requires learning controller operation)	Low (Reduced cognitive load through intuitive operation via NUI)
Field Adaptability	Low (Gap between theory and actual operation)	Intermediate (Reduced field adaptability due to differences in operating methods)	High (Provides sensory interaction similar to actual work)

As shown in the table above, in terms of interactivity, NUI hand-tracking-based education using natural hand gestures is significantly superior to one-way information delivery or abstract button/joystick controls.

In terms of immersion and realism, while traditional document/video-based education lacked field relevance as a limitation, it is now demonstrating a difference by enhancing physical memory through physical mediation.

The gap between theory and practical operation, which had been perceived as a limitation in education regarding field adaptability, was relatively higher in NUI tracking-based training by providing sensory interactions similar to actual work.

For example, in the defense sector, XR-based instructional material systems are being introduced for equipment inspection and weapons system maintenance training. In education, attempts to implement hands-on curriculum content using XR are increasing to enhance student immersion and procedural understanding. However, existing research has primarily focused on developing content optimized for specific industries, and a theoretical framework for a modular XR procedural learning platform reusable across diverse domains has yet to be established.[9]

This study aims to present a foundational model for a universal, scalable, modular XR education solution by combining procedural learning theory with storyboard-based UX design techniques to address these limitations.

III. The Proposed Scheme

1. Research Methodology

1.1 Analysis of Training Procedures and Setting Learning Objectives

Analyze procedures such as actual equipment inspections, safety training, and operational training to define step-by-step actions, and derive corresponding learning objectives and feedback items.

- Designing virtual educational spaces (including spaces and equipment for XR education)
- Developing non-contact interface functionality by implementing hand tracking via XR device cameras

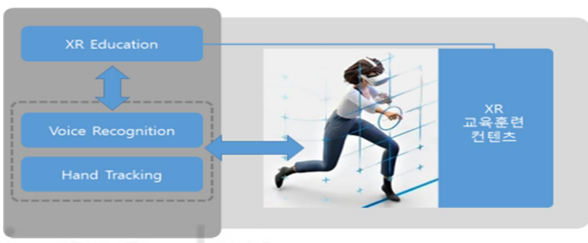

Fig. 1. XR Training Architecture Diagram

As shown in the figure above, the significance lies in the fact that XR education and training content can be structured to provide immersive training through hand tracking, rather than relying on traditional controller-based education.

To this end, a hand-tracking module based on HMD camera vision data was configured. This enables recognition and motion tracking using the module when interactions between objects and additional features are required within the XR educational environment.

This hand-tracking-based content directly recognizes hand movements, enabling the use of natural, everyday hand gestures. The goal is to enhance immersion and realism by allowing users to experience actual tasks and sensory interactions through these movements.

1.2 Research & Development

Implement a 3D interactive environment based on storyboards using the Unity engine. 3D modeling is created using software like Max and Blender to closely resemble actual equipment and work environments. Each stage incorporates visual highlighting, real-time status feedback, and error detection and guidance features. It is designed to record user behavior history, enabling feedback based on learning data. Based on this, we developed XR educational content as follows.

1) Virtual Educational Space Configuration (Including Spaces and Educational Equipment for XR Education)

A virtual educational space is configured, modeling Baejae University's actual hands-on equipment for XR education to provide an immersive experience. Models include props used in manuals or operation guides to create educational content for equipment usage.

Fig. 2. Teaching Aids and Space Modeling

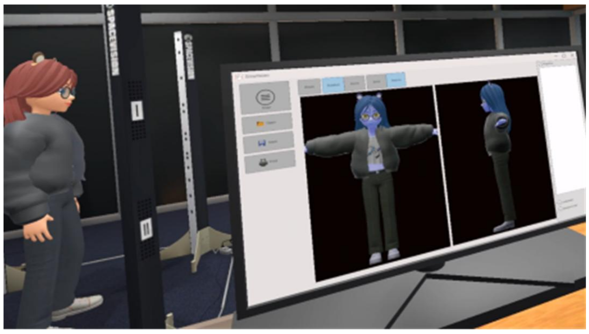

Fig. 3. Teaching Aids and Other Object Modeling

2) Developing non-contact interface functionality by implementing hand tracking via the XR Device camera

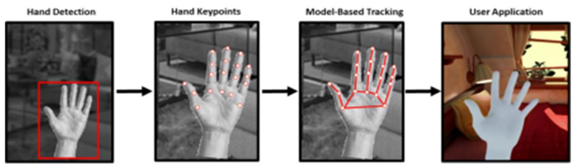

Fig. 4. Camera-based Hand Tracking

This study implemented a non-contact natural user interface (NUI) function using the built-in camera of the Meta Quest 3 device.

The Quest 3 utilizes dual RGB cameras and a depth sensor positioned on its front to recognize the position, orientation, and joint movements of the hand within a 6DoF space with high precision.

This system is designed to manipulate objects within an XR environment using only hand gestures, without requiring a separate controller. This enables users to experience sensory interactions similar to real-world tasks.

First, we designed it to be held in the hand for everyday use, allowing users to carry and view the tablet object constantly as if it were part of their daily routine, thereby providing a tangible experience.

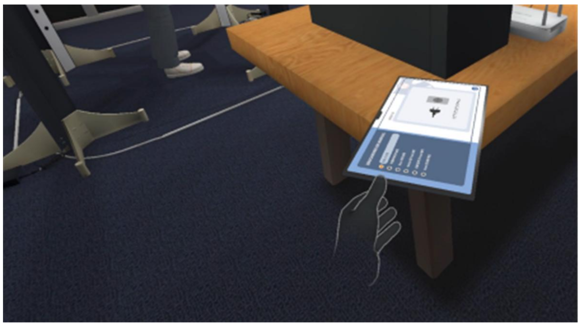

Fig. 5. Interaction via hand tracking (tablet)

Additionally, each step is designed so that you can learn the procedures by performing the required tasks manually.

Fig. 6. Interaction via Hand Tracking (Objects)

During operation, a separate gesture (thumbs up) activates a menu that allows direction switching, enabling directional changes through this mechanism.

Fig. 7. Interaction via Hand Tracking (Rotation)

Additionally, we enabled a feature allowing direct movement in the desired direction via a separate gesture (pointing with the thumb), enabling movement without a separate controller.

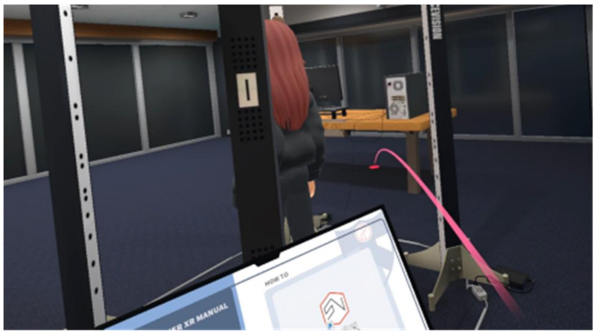

Fig. 8. Interaction via Hand Tracking (Moving)

IV. Conclusions

1. Final Results

This study implemented a non-contact NUI-based immersive education and training system utilizing the camera-based hand-tracking technology of the Meta Quest 3, enabling interaction solely through hand gestures without controllers. This effectively addressed the core limitations of XR education and training: unnatural manipulation and restricted immersion.

1.1 Development of a Hand-Tracking-Based NUI Interaction Framework

We built an interaction framework that tracks 21 hand joints in real-time from the Quest 3's RGB-D camera feed and converts them into gesture commands within the XR learning environment.

This transforms the existing controller-input-centric learning system into a natural-motion-centric structure.

1.2 Implementation of a Non-Contact Learning Interface

Air Button, Air Gesture, and Spatial Manipulation functions enable learners to perform procedures and operate equipment without physical contact.

This provides a hygienic, non-contact learning environment while delivering an immersive interactive experience.

1.3 Real-time Feedback and Learning Log System Implementation

Collect data on recognized gestures, reaction times, and task accuracy to establish individual learner behavior logs. This data can serve as the foundation for building future AI-based learning feedback models.[8][11]

1.4 Establishing an Experiential Learning Design Framework

By integrating storyboard-based procedural design with NUI-type motion structures, we present a systematic development procedure that enables learning actual work procedures centered on bodily sensations.

The experiments in this study were conducted in the practical training environment of a specific university and using specific equipment. This limits the verification of its applicability to equipment and work procedures in various industrial settings.

However, learning design based on educational procedure analysis and learning objective setting, along with storyboard-based UX design techniques, are methodologies universally applicable to learning any complex procedure, not just specific equipment. This enables content expansion into diverse fields such as industrial, military, medical, and mechanical maintenance training. Furthermore, while Quest 3-based hand tracking was used, the gesture recognition and command conversion logic proposed in this study presents a blueprint for a standard NUI architecture capable of accommodating sensor inputs from other XR devices in the future. This enables scalability across diverse equipment without being tied to specific hardware.

Future simulations will be conducted to verify NUI recognition rates and system stability in environments simulating real-world instability factors such as varying lighting conditions, network latency, and complex background environments. Based on these results, further development of automatic environmental compensation algorithms is required.[14]

2. Utilization Plans

The results of this study can be utilized as a modular, immersive learning solution applicable to various industries and educational institutions in the field of XR-based education and training content development.

2.1 Industrial and Vocational Training Sector

This non-contact XR training system can be applied in industrial settings requiring precise work procedures—such as manufacturing, maintenance, energy, and aviation—providing experiential training similar to actual equipment operation through hand-gesture-based controls.[15][12] Compared to traditional equipment-based simulators, it reduces maintenance costs and enhances training efficiency.

Fig. 9. Job Training in Industrial Settings Using XR[15]

2.2 Military, Security, and Medical Education Fields

Effectively applicable for training in high-risk, high-precision procedures such as military equipment operation protocols, first aid, fire safety, and hazardous material handling. Enables action-based procedural learning while ensuring safety through non-contact operation.

Fig. 10. Military Education and Training Using XR[16]

2.3 Educational institutions and metaverse learning platforms

XR teaching aids can be utilized in hands-on courses at universities and vocational schools. Learners can participate in learning using only hand gestures without additional equipment, ensuring high accessibility. Future expansion into a metaverse-based practical training platform is possible through AI feedback and cloud integration.[10]

Fig. 11. XR-Based Education in Educational Institutions[17]

2.4 Foundation for developing modular XR solutions

The hand-tracking framework presented in this study enables modular reuse, facilitating the creation of customized learning content tailored to industry-specific scenarios.

It holds high potential for commercialization as an XR education solution for enterprises and educational institutions.

3. Expected Effects

The outcomes of this study provide the following expected benefits in technical, educational, and industrial aspects.

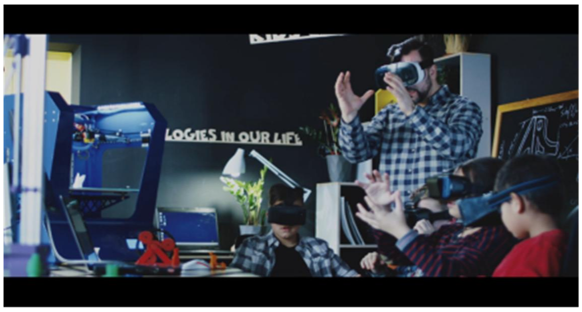

Fig. 12. Various Expected Benefits Using XR[18]

3.1 Educational Effect

- Provides an immersive learning environment: Enables learners to perform procedures using hand gestures without controllers, delivering a learning experience similar to real-world actions.
- Enhances procedural accuracy: Allows immediate correction of movement errors through a real-time feedback structure.
- Strengthens learning motivation: Boosts learner interest and engagement through intuitive operation.

3.2 Technical Effect

- Empirical validation of hand-tracking-based NUI technology: Achieved over 93% recognition rate using only the Quest 3's built-in cameras.[7]
- Standardization of non-contact interaction technology: Proposed a standardized NUI framework applicable to industrial, educational, and training XR content.[9]
- Established foundation for data-driven learning analytics: Secured research foundation for AI feedback models utilizing gesture log data.

3.3 Industrial impact

- Cost reduction in education and training systems: Operates without separate physical teaching aids or controllers.
- Accelerating commercialization of the XR education industry: Contributes to expanding the domestic XR and metaverse education market.[19]
- Establishing non-face-to-face training infrastructure: Provides a sustainable education and training environment even during infectious

disease outbreaks and disaster situations.

The Quest 3-based hand-tracking NUI immersive education and training system developed through this research overcomes the limitations of existing XR learning and presents an immersive education model integrating natural interaction and a non-contact learning structure.

However, for actual implementation and widespread adoption across industries or educational institutions, considerations beyond technical implementation are necessary in terms of field applicability, maintenance, and accessibility, as follows.

The first aspect is ensuring multi-device compatibility. When XR devices from various manufacturers (such as Pico, Vive, Quest, etc.) are introduced, a hardware-independent framework must be designed to recognize NUI sensor input values from each device in a standardized data format.

The second aspect concerns network latency and data stability. When recording and transmitting learner behavior logs, the application of a lightweight data transmission protocol must be prioritized to ensure stable transmission without data loss, even within the limited network environment on-site.

Finally, there is the matter of data security and privacy protection. Since learners' detailed behaviors (gestures, reaction times, etc.) constitute sensitive data, a learning log system must be established that strictly adheres to data security and privacy regulations.

Overcoming these considerations holds high potential for developing a modular XR learning framework immediately applicable across diverse fields such as industry, military, healthcare, and education. It is expected to expand into an intelligent experiential learning platform through future integration with AI learning feedback systems.[8][11]

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