Queen Mary University of London

VR for soft robotic exoskeletons: Realistic Weight Liquid Feedback System for Virtual Objects

DENM70 EMS715P MSc Extended Research Project 2024/25 - State of the Art Report (SOTA)

AUTHOR: Zichong Cao
SUPERVISOR: Prof. Kaspar Althoefer

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1 Introduction

With the rapid development of virtual reality (VR) technology and the increasing demand for human-computer interaction, how to provide realistic sense of weight feedback in virtual environments has become a research hotspot. Although traditional physical feedback devices can act directly on the user's skin, they are limited in consumer-grade applications due to their high cost, large size and high system complexity [1]. For this reason, pseudo-haptic feedback technology has emerged. It reduces the system cost and simplifies the hardware design by using visual information to induce a haptic experience for the user [7].

This project focus on developing the visual sensing function based on the hardware of a dual-chamber liquid wristband gravity feedback and detection system controlled by six stepper motors. The aim of this study is to realise the user's enhanced gravity feedback experience through visual manipulation in a VR environment, and to obtain feedback that is closer to the real feeling. Specifically, by repeating the operation of grasping a virtual object in the Unity virtual environment, the grasping data (including the weight and grasping state of the object) are transmitted to the Arduino Mega 2560 development board via the Bluetooth module of the JY-MCU, and the hardware system completes the liquid transmission and gravity feedback [5], [6]. The innovation of the project is to combine three visual strategies, namely object dynamic deformation, texture change and pseudo-haptic delay induction, and to explore the effects of different strategies and their synergistic effects on feedback delay and user experience through comparative experiments.

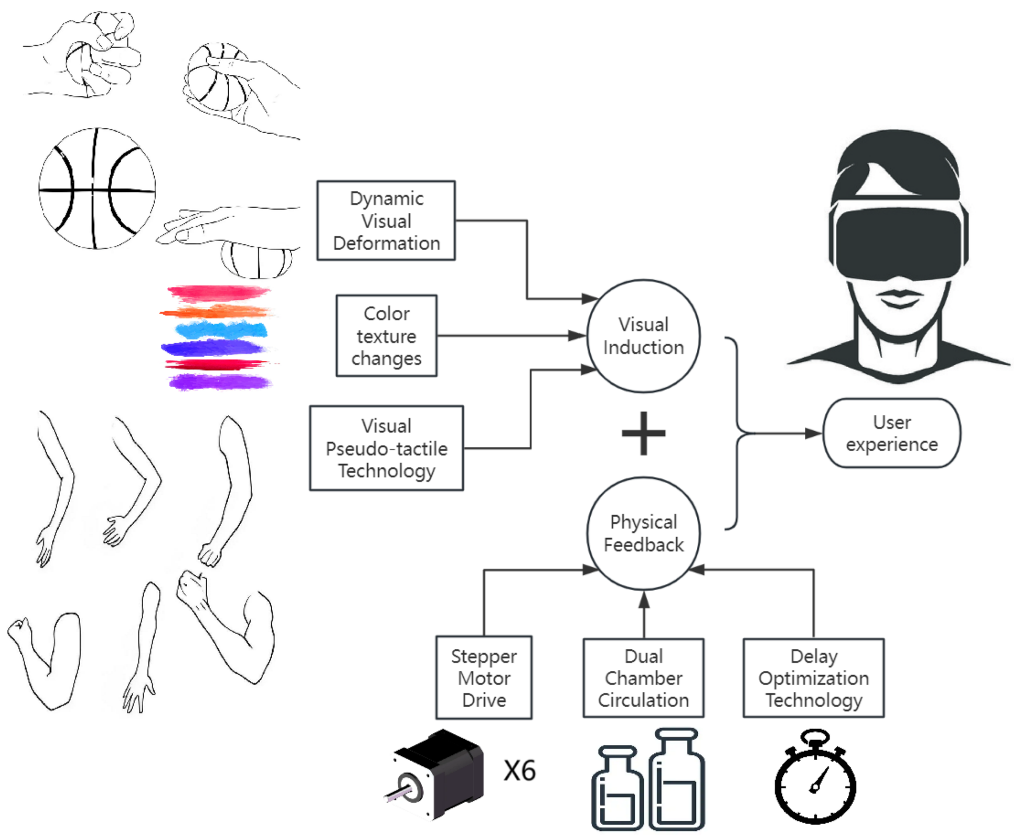

Figure 1: Technical schematic of the project

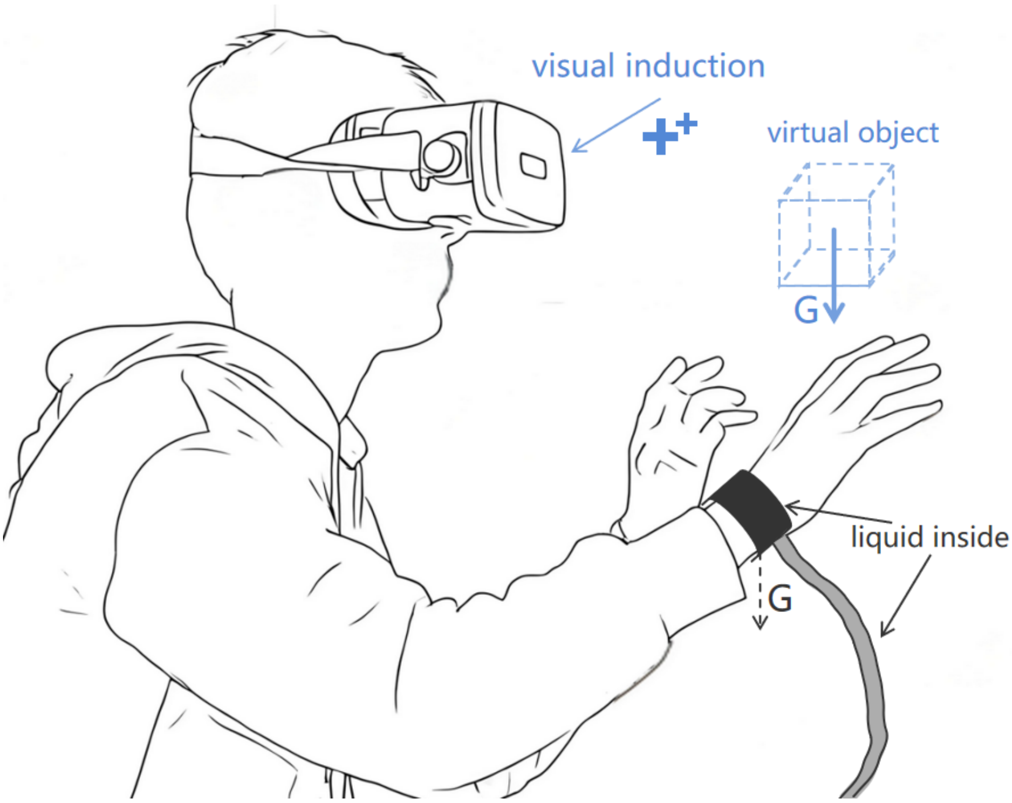

Figure 2: Project rendering diagram

2 Literature Review

2.1 Research background

With the rapid development of virtual reality (VR) technology, how to achieve realistic haptic feedback in virtual environments has been an important research direction. Traditional physical haptic feedback devices (e.g., force feedback gloves or rigid haptic devices) are limited in practical applications due to their high cost, large size and high complexity [1]. In recent years, scholars have begun to explore the research direction of 'Pseudo-haptic feedback'. Pseudo-haptic feedback uses visual information to induce a haptic experience in the user, so as to achieve a similar sensation without actually applying physical force [7].

From the perspective of perceptual psychology, vision has a significant dominant role in tactile perception. The famous 'Colavita Effect', proposed by Colavita in 1974, demonstrated visual dominance across modalities.[9] Ernst and Banks' research has shown that humans tend to use statistical optimality when integrating visual and tactile information, allowing visual cues to partially compensate for the lack of tactile information [1]. Also, the ecological theory of visual perception proposed by J. J. Gibson emphasises the complementary nature of multimodal information in the environment [2]. This theoretical foundation provides theoretical support for the implementation of gravity feedback in VR systems using visually induced techniques.

In current research, pseudo-haptic feedback is mainly used to enable users to perceive the weight or inertia of an object despite the lack of real force feedback by altering the visual representation of the virtual object (e.g., deformation, texture, and motion delay) [7]. With the popularity of various hardware development platforms, the system architecture of hardware and software working together is becoming more mature, making it possible to implement complex interactive experiences [5], [8]. In addition, the Unity platform, as a real-time development tool, also provides a convenient interface for the construction of virtual environments and data interaction with hardware systems [6]. An increase in system response latency can lead to a significant mismatch between haptic feedback and user expectations in virtual reality, thus reducing the naturalness of feedback and the overall immersion experience [4]. Therefore, it is necessary to explore the effect of system response latency on feedback naturalness.

2.2 Review of Current Technologies

2.2.1 Physical haptic feedback vs. pseudo-haptic feedback

Traditional haptic feedback devices, such as force feedback gloves or haptic vibration devices, provide a more realistic tactile sensation by generating physical stimuli through direct action on the user's skin. However, these devices often have cost and size limitations. Pseudo-haptic feedback, on the other hand, is a method that uses visual information to induce haptic sensations in the user, allowing the user to experience haptic effects without real physical stimuli [7]. The perceptual enhancement effect through cross-modal integration of human senses produces a more intense experience than a single sensory stimulus [10].

The mainstream haptic feedback devices currently on the market have high manufacturing and maintenance costs due to their sophisticated mechanical structures and control systems [1]. In addition, heavier or bulky devices are difficult to make portable, limiting their use in consumer-grade VR products.

In contrast, pseudo-haptic feedback eliminates the need for additional physical devices and offers lower cost and higher system integration [7]. For example, by designing the dynamic deformation and texture changes of virtual objects in the Unity environment, the user can perceive the change of 'weight' during the grasping operation, thus realising the virtual reproduction of gravity feedback.

Criteria	Traditional Haptic Feedback	Pseudo-Haptic Feedback
Feedback Mechanism	Applying mechanical stimuli directly to the user's skin via force feedback or vibrotactile actuators [9]	Indirectly inducing a haptic experience using visual cues such as deformation, texture changes or visual delays of objects in a virtual environment [7]
Cost	Higher system costs due to the need for precision mechanical components and complex calibration [9]	Lower cost based on existing VR hardware and software implementations without the need for additional expensive haptic devices [7]
System Complexity	Complex system architecture requiring integration of physical actuators, sensors and complex calibration [9].	Primarily relies on software algorithms and visual presentation, with simple hardware requirements and easy integration into existing VR platforms [7]
Response Latency	Low latency response can be achieved with fine tuning but may be limited by mechanical inertia and control system limitations [9]	Dependent on visual information processing, there may be some visual processing latency, but the latency problem can be managed more flexibly through software moderation [7]
User Experience	Provides direct, realistic haptic feedback but has limitations in modelling diverse haptic experiences [9]	Multiple tactile sensations can be simulated through visual illusions, which, despite the lack of physical stimulation, can effectively compensate for the lack of tactile sensation and enhance immersion in specific applications [7]
Portability	Often bulky and not portable due to high number of physical components [9]	Software-based implementation, easy to integrate into various VR devices, and high portability [7]

Figure 3: Traditional Haptic Feedback vs Pseudo Haptic Feedback

2.2.2 Application of visual entrainment techniques to gravity feedback

In recent years, several researchers have proposed a variety of visually induced methods for enhancing haptic perception in virtual environments. Dynamic deformation of objects can be used to simulate the phenomenon of compression or stretching of the internal structure of a virtual object when it is subjected to 'gravity', and

Hoppe et al. have shown that deformation based on physical simulation can significantly enhance the user's sense of immersion [3].

Changes in the surface texture of an object can also convey weight information. Texture changes may include dynamic adjustments of colour shades, roughness, and other parameters, making the object visually 'fluffy' or 'firm'. This method is commonly used in virtual material simulation and has been validated in several VR applications [3].

Pseudo-haptic delay induction simulates the response time present in real haptic feedback by artificially introducing a delay between visual and expected haptic feedback. This can give the user an unanticipated 'sense of touch' to the gravity feedback [7]. This delay-induced approach requires precise tuning of the system delay to ensure coordination between the user experience and the physiological response.

2.2.3 System Integration and Data Transfer

Meta and others have demonstrated in their VR products that optimising visual information can significantly enhance the user interaction experience [4]. In this study, dynamic deformation will be adjusted based on real-time data fed by a liquid wristband. The user will perceive the weight change through the shape and texture change of the virtual object and the change of the force-gesture of the virtual arm.

In modern interactive systems, the real-time and reliability of data transmission is crucial to the overall experience. Arduino Mega 2560, as a mature microcontroller platform, can achieve low-latency communication between user operation data and liquid transfer control by cooperating with JY-MCU Bluetooth module [5], [8]. At the same time, the Unity platform provides a rich set of interfaces and plug-ins to support bidirectional data interaction with external devices, which provides a technical guarantee for the implementation of complex visual induction algorithms [6].

Most cases have confirmed that the lack of pseudo-haptic feedback in physical feedback can be compensated to a certain extent by the close coupling of hardware and software [4], [5], [8]. In this study, the hardware and software work together through the Unity platform, JY-MCU Bluetooth module and Arduino development board.

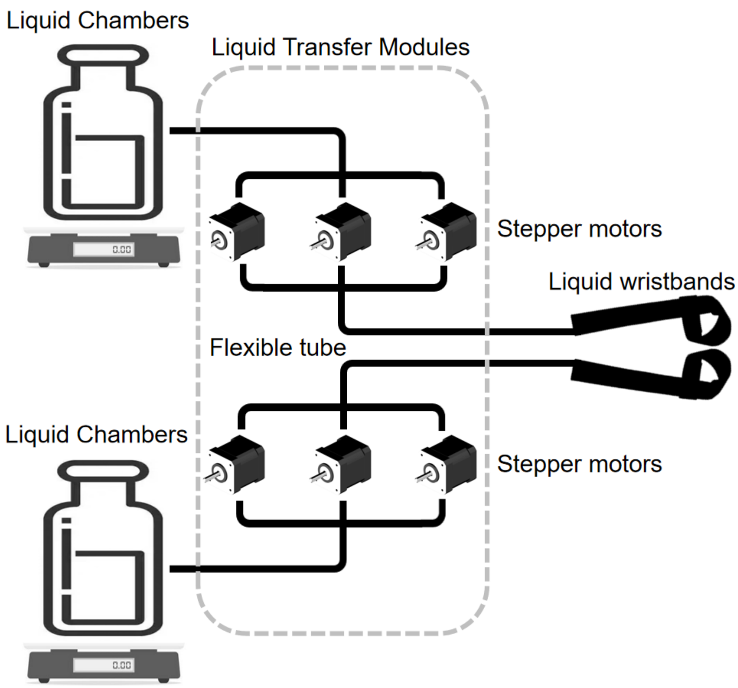

Figure 4: Schematic diagram of system structure

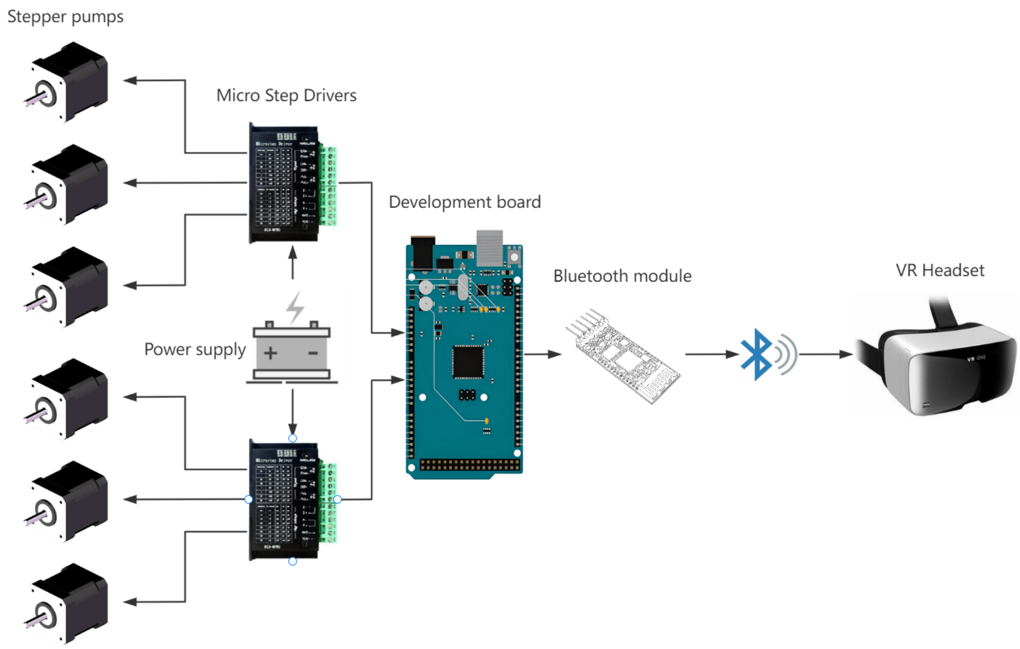

Figure 5: Schematic diagram of system working connection

2.3 Identified Research Gaps

Despite the significant advantages of pseudo-haptic feedback technology in terms of cost reduction and simplification of device structure, there are still several shortcomings of the existing technology:

1. Feedback accuracy and naturalness

Existing visual induction methods are difficult to fully simulate the real haptic experience in certain scenarios. For example, although dynamic deformation and texture changes can convey weight information, users may perceive deviations from actual physical feedback during complex operations [1], [7]. Such deviations may weaken the user's sense of trust and immersion in the virtual environment.

2. Latency sensitivity

System response latency is one of the most important factors affecting the effectiveness of pseudo-haptic feedback. Existing studies have shown that high latency can lead to a mismatch between visual and haptic information, resulting in an incongruous sensation [7]. In this study, the pseudo-haptic delay induction technique is used to explore the optimal delay parameters, and further experiments are needed to verify its effect on user experience under different delay conditions.

3. Multimodal Information Integration Challenges

Despite the compensatory effect of vision on haptics, it is still a challenge to achieve efficient integration of multimodal information (vision, haptics, motion data, etc.) in real systems.Ernst and Banks' study pointed out that there is statistical optimality in the integration of multimodal information in humans, but how to fully apply this theory in engineering practice remains to be further explored [1].

4. Individual Differences and Uncertainty in User Experience

There are large differences in users' sensitivity to pseudo-haptic feedback. The perceived effects of object deformation, texture change and delay induction may vary significantly among different users, which poses a challenge to the universality of the system. Currently, there is a lack of systematic comparative studies in the relevant literature, and how to make personalised adjustments for different users is still an important direction for future research.

In summary, although some progress has been made in the field of VR haptic feedback, there is still an obvious technical gap in how to achieve more natural and accurate gravity feedback using visual induction techniques [1],[7]. This project explores the combined effects of dynamic deformation, texture change and pseudo-haptic delay induction under different system response delays by testing the three strategies individually and synergistically. This will provide experimental basis and theoretical support for the design of pseudo-haptic feedback system based on visual induction.

Criteria	Dynamic Deformation	Texture Change	Pseudo-haptic Delay Induction
Perceived Weight Realism	High - Dynamic deformation effectively conveys information about the forces on the object and enhances weight perception [3], [7]	Medium - surface texture variations provide weak weight cues [2]	High - Delayed induction directly triggers haptic anticipation, thus simulating real weight [7]
User Immersion	High - morphing effects dramatically improve user immersion and realism [3]	Medium - Texture variation improves visual performance but has weak haptic feedback [2]	High - Precise latency modulation contributes to the user's synchronised perception of haptic feedback [7]
Sensitivity to System Delay	Moderate - Dynamic deformation is sensitive to the response delay of the system, but there is more room for modulation [7].	Low - texture variations are largely dependent on the visual display, with low sensitivity to latency [2]	High - Delay induction strategies are directly affected by system latency and their effectiveness is highly dependent on real-time response [7].
Implementation Complexity	Moderate - requires real-time deformation algorithms and physical simulation support [7]	Low - mainly involves texture mapping and material parameter adjustments, relatively simple [2]	Moderate - need for fine control of delay parameters for vision and data transmission [7]

Figure 6: A Preliminary Comparison of the Effects of Different Visual Induction Strategies on Users' Perception of Gravity Feedback

3 Research Aims and Objectives

The aim of this project is to explore and validate the effectiveness of the application of visually induced pseudo-haptic feedback technology based on liquid wristband gravity feedback system, to achieve efficient synergy between visual feedback and hardware response through the development of software modules, and then to enhance the realism of the user's perception of the weight of the virtual object.

3.1 Research Aims

1.Development of Visual Inducement Module

Design and implement three visual feedback strategies, namely object dynamic deformation, texture change and pseudo-haptic delay induction, using the Unity platform. After integrating these three strategies, the visual induction module is used to simulate real gravity feedback.

2. Construct hardware and software collaborative feedback system

Using the existing liquid wristband hardware system, data interaction is achieved through the JY-MCU Bluetooth module and the Arduino Mega 2560 development board. This realises the real-time transmission of user operation data and hardware response in the VR environment [5], [6].

3.Optimising feedback delay and user experience

To address the system response latency problem, the effects of different visual induction strategies on gravity feedback perception are evaluated through comparative experiments when applied individually and jointly. These evaluations are used to determine the optimal delay parameters to enhance the user experience.

3.2 Research Objectives

RQ1: How can the dynamic deformation of an object be used to effectively convey gravity feedback information so that users can obtain a more realistic weight perception in VR environments?

RQ2: What is the role of dynamic changes in object surface texture in enhancing weight perception? How can its parameters be adjusted to achieve the best effect?

RQ3: In pseudo-haptic delay induction, how does the delay time affect the cueing effect of virtual arm muscle and tendon force behaviours to optimize the gravity feedback experience?

RQ4: What are the similarities and differences between the performance of a single visual induction strategy and the combined application of all three under different system response delays, and how does each contribute to the user experience?

4 Methodology and Methods

4.1 Research Methodology

This project adopts Mixed Methods, combining quantitative experimental data with qualitative user experience feedback. In the quantitative part, experimental tests were conducted to collect data on object deformation, texture change and delay. The qualitative part uses questionnaires and interviews to collect user experience and feedback.

In the theoretical framework, this project is based on the multimodal perceptual integration theory to explain the mechanism of visual compensation for haptics [1]. Meanwhile, this project combines the ecological visual perception theory to guide the visual induction design [2].

4.2 Research Methods

1.Data Acquisition

This project uses the Unity platform to simulate the operation data (e.g. grasping state, object weight change, feedback delay) in the virtual environment and record the logs. Realise hardware response data (liquid transmission status, real-time delay, etc.) acquisition through Arduino Mega 2560 and JY-MCU Bluetooth module.

2.Experimental Design

This project is divided into two parts: a single vision-inducing strategy and three strategies synergistic experiments. Each group of experiments is set up with different system response delay conditions, and a flowchart is used for the experimental process and variable control.

3.Data Analysis Methods

In this study, quantitative data were analysed using statistical analysis, regression analysis and analysis of variance (ANOVA) to verify the differences in the feedback effects of different strategies. Qualitative data were analysed using thematic analysis to collate user experience feedback and combined with quantitative results for a comprehensive discussion.

5 References

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6 Appendices

Prospective user information collection form

1. Name:__________ Gender:____________

2. Age:( ) A.11-15 B.16-20 C.21-25 D.26-30 E.31-35 F.36-40 G.41-45 H.46-50
I.51-55 G.56-60 K.61-65 L.66-70 M.71-75 N.76-80 O.81-85 P.86-90

3. Experience with VR:( ) A.Totally untried. B.Less than 24 hours C.More than 1 day, less than 1 week D.More than 1 week, less than 1 month E.More than 1 month, less than 1 year F.More than 1 year

4. Visual Elicitation Strategy Measurement (Score 1-10, 10 being the best)

	Dynamic Deformation	Texture Change	Pseudo-haptic Delay Induction	D & T	D & P	T & P	Combination strategy
Weight Perception Score							
Immersion Experience Score							
Response Latency Awareness							

5. Comprehensive experience evaluation (User's open description of the overall experience)

6.Suggestions for Improvement (User suggestions for system or experimental improvements)

Figure 7: User feedback collection form (preliminary draft)