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超音波觸覺與紅外線手勢追縱之三維認知訓練系統

3D Cognitive Training System with Ultrasonic Haptic and Infrared Hand Tracking



隊伍名稱｜觸不及防 Haptic Training

隊　　長｜黃祺鈞 / 成功大學電機工程學系

隊　　員｜王竑文 / 成功大學電機工程學系

隊　　員｜曾昱誠 / 成功大學電機工程學系

隊　　員｜楊雨倫 / 成功大學機械工程學系

指導教授 ADVISOR



黃致憲 | 成功大學電機工程學系

美國德州農工大學電機工程博士，現為成功大學電機工程學系教授，長期致力於微機電與超音波相關研究，近年也開始投入電腦視覺與人工智慧用於運動科學的跨領域研究。

研究領域

微機電超音波元件、超音波創新應用、電腦視覺、人工智慧整合運動科學應用。

作品摘要

本作品為一套結合超音波觸覺回饋、紅外線手部追蹤與Unity三維互動平台的多感官認知訓練系統。隨著高齡化社會發展，以及腦中風、輕度認知障礙與注意力相關問題逐漸受到重視，如何建立一套具備可重複訓練、可量化評估且能提升使用者參與度的認知訓練平台，成為復健醫學、神經科學與人機互動領域的重要課題。現有數位化認知訓練多以螢幕視覺刺激為主，使用者長時間依賴單一視覺通道進行判斷與操作，容易造成認知負荷，也缺乏真實觸覺回饋。因此，本研究希望透過非接觸式超音波觸覺技術，將視覺、動作與觸覺整合於同一訓練平台中，建立更具沉浸感與互動性的三維認知訓練環境。

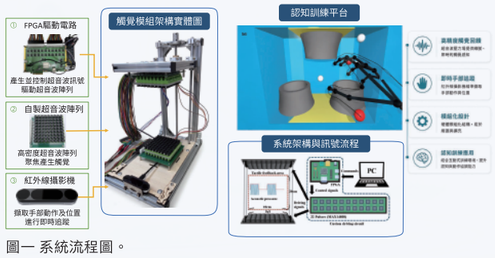
本系統主要由兩大部分組成。第一部分為超音波觸覺模組，採用上下雙層超音波陣列架構，並由FPGA進行多通道同步驅動與波束形成控制。系統可根據指定的三維焦點座標，計算各通道之間的時間延遲，使超音波在空間中產生聚焦聲場，讓使用者不需配戴手套或震動裝置，即可在空中感受到觸覺刺激。相較於傳統穿戴式觸覺設備，本系統具備非接觸、衛生、安全且互動自然的特色，也能降低使用者操作時的負擔。

第二部分為Unity認知訓練平台，並搭配Ultraleap Leap Motion Controller 2進行紅外線手部追蹤。使用者可直接以自然手勢與三維虛擬物件互動，不需要滑鼠、鍵盤或手持控制器。遊戲中設計多顆動態球體，玩家需要辨識並抓取紅色目標球，將其拖曳至指定空間並停留一定時間，使紅球轉變為白球。過程中同時包含視覺搜尋、空間定位、手眼協調、時間感知與動作控制等訓練元素。隨著關卡提升，球體數量、移動速度與停留時間皆會增加，使任務難度逐步上升，形成漸進式訓練負荷。

本作品的特色之一，是將觸覺回饋納入遊戲操作流程中。當玩家成功抓取紅球時，系統會在手指位置產生超音波觸覺刺激；當停留條件完成後，觸覺刺激消失，玩家即可藉由觸覺訊號判斷可以放手。相較於僅依賴畫面提示的操作方式，觸覺回饋能提供另一個感官通道，降低使用者對視覺資訊的依賴，並強化知覺與動作之間的即時連結。

此外，系統也具備行為數據紀錄與量化評估能力。訓練過程中可記錄玩家在固定時間內完成紅球轉白的次數、抓取後成功完成操作的比例，以及每次成功操作後到下一次操作開始之間的時間間隔等指標。這些數據可用於分析使用者的反應效率、操作準確度與任務切換能力，使本平台不只是互動遊戲，也能作為認知訓練與實驗研究工具。

整體而言，本作品整合自主開發之超音波觸覺硬體、FPGA即時控制、紅外線手部追蹤與Unity三維互動訓練平台，建立一套具備多感官刺激、自然手勢操作與量化評估能力的認知訓練系統。未來若進一步擴大觸覺範圍、優化三維視覺呈現並增加受試者測試，本系統有潛力應用於高齡認知保健、神經復健、注意力訓練、人機互動研究與沉浸式多感官訓練等領域。



圖一 系統流程圖。

Abstract

This project presents a multisensory cognitive training system that integrates ultrasonic haptic feedback, infrared hand tracking, and a three-dimensional interactive platform developed in Unity. As aging populations and neurological conditions such as stroke, mild cognitive impairment, and attention-related disorders become increasingly important issues, there is a growing need for cognitive training systems that are interactive, repeatable, and objectively measurable. Most existing digital cognitive training methods rely mainly on visual stimuli displayed on a two-dimensional screen. Although these methods are easy to implement, they often place a high demand on visual processing and lack real tactile feedback. To address this limitation, this project introduces non-contact ultrasonic haptic feedback into a 3D cognitive training environment.

The system consists of two major parts. The first is an ultrasonic haptic module based on a dual-layer phased array structure. The upper and lower ultrasonic arrays are driven by an FPGA, which calculates the required time delay for each channel and controls the emission timing of the transducers. By synchronizing the ultrasonic waves at a designated focal point in mid-air, the system can generate tactile stimulation without requiring the user to wear gloves or hold any device. This provides a more natural, hygienic, and non-contact interaction experience compared with traditional wearable haptic devices.

The second part is the Unity-based cognitive training platform, which is integrated with the Ultraleap Leap Motion Controller 2 for infrared hand tracking. Users can interact with virtual objects directly through natural hand movements. In the training game, multiple balls move randomly in a three-dimensional space. The user must identify red target balls, grasp them, drag them to a transparent target region, and keep them there for a required amount of time. Once the condition is satisfied, the red ball turns back into a white ball, completing one successful operation. This process trains visual search, selective attention, spatial positioning, hand-eye coordination, timing control, and action planning.

The difficulty of the game increases progressively. Higher levels include more balls, faster movement, and longer required holding times, creating a gradually increasing cognitive and motor load. A key feature of the system is the integration of haptic feedback into the task. When the user grasps a red ball, tactile feedback is generated at the finger position.

When the holding condition is completed, the tactile feedback disappears, allowing the user to determine the correct release timing through touch rather than relying only on visual cues.

The platform also records quantitative behavioral data, including the number of completed tasks, the success rate after grasping a target, and the time interval between consecutive operations. These indicators allow the system to evaluate task efficiency, operation accuracy, reaction speed, and task-switching ability. Overall, this project combines FPGA-based ultrasonic haptics, infrared hand tracking, and Unity interaction to build a natural, measurable, and multisensory cognitive training platform with potential applications in rehabilitation, elderly cognitive health, attention training, and human-computer interaction research.

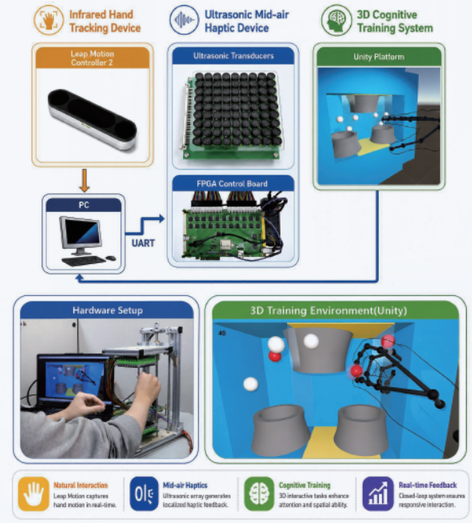


Fig. 2 System structure.