基於空汙智警機器人於情境化空品判讀教學之設計與開發實作

Development and Application of a Smart Air Pollution Warning Robot for Contextualized Air Quality Awareness and Interpretation

李建輝[1]，吳昱靜[2]，邱敏棋[3*]
[1]嶺東科技大學智慧製造科技系
[2]嶺東科技大學資訊科技系
[3]臺中科技大學多媒體設計系
[*]minky413@gmail.com

【摘要】 本研究以系統開發觀點提出並完成「空汙智警機器人」原型，回應空品教育中「學生看得到數值、卻難以理解意涵與轉化決策」之學習落差。系統以台中地區 PM2.5 即時資料為輸入，採「資料取得、判斷引擎、對話／知識回覆、介面與回報」四模組架構，能定時回報地點、時間與濃度，並以閾值規則提供情境化行動建議；同時支援學習者追問 PM 值定義、形成原因與環境／健康影響，透過結構化回覆建構「數值判讀→概念釐清→影響掌握→行動推論」的學習閉環。本文並將系統定位為促進學生由空品現象延伸探討減排、再生能源與儲能之跨域連結。研究亦指出原型仍受限於資料來源代表性、建議語句通用化與知識庫規模，未來可擴充多測站比對、趨勢視覺化與個人化提醒，以提升教學與實務應用價值。

【關鍵字】 空汙智警機器人；PM2.5；情境化空品判讀；對話式學習支援；空氣品質

Abstract: *This study develops a prototype Air Pollution Intelligent Alert Robot from a system development perspective to address a common learning gap in air quality education: learners can access numerical indicators but often struggle to interpret their meaning and apply them to everyday decisions. Using real-time PM2.5 data from the Taichung area, the system adopts a four-module architecture comprising data acquisition, a decision engine, dialogue/knowledge-based responses, and user interface and reporting. It periodically reports location-, time-, and concentration-specific information and applies threshold-based rules to generate contextualized action suggestions for outdoor activities and protective behaviors. Beyond numerical reporting, the robot supports learners' on-demand inquiries about PM concepts, formation mechanisms, and environmental/health impacts. Through structured dialogue-based responses, the system scaffolds a learning loop moving from numerical interpretation and conceptual clarification to impact understanding and action-oriented reasoning. The prototype is positioned as an instructional support tool that helps students extend discussions from air quality phenomena to broader cross-disciplinary topics such as emission reduction, renewable energy, and energy storage. Noted limitations include potential representativeness issues when relying on single-source or single-site monitoring, the generalized nature of advisory messages, and a relatively small rule-based knowledge base. Future enhancements are suggested, including multi-station comparisons, trend visualization, integration of additional air quality indicators (e.g., PM10 and O_3), and personalized alerts, to strengthen both instructional effectiveness and real-world applicability.*

Keywords: Air pollution intelligent alert robot; PM2.5; Contextualized air quality interpretation; Dialogue-based learning support; Air quality

1. 前言

在日常生活中，民眾經常透過空氣品質資訊評估是否適合外出活動，而「PM 值」即為常見的空品指標之一，用以反映空氣中懸浮微粒濃度（其中 PM2.5 因粒徑小、風險較受關注）(Bunds et al., 2019; Engel-Cox et al., 2013)。然而，空品資訊在教學現場常面臨一個落差：學生

雖能接觸到數值與名詞，卻未必能理解其意義、形成原因與對應的生活決策，導致學習停留在「知道」而非「會用」(Carpenter, 2013; Hiebert & Lefevre, 2013; Kanari & Millar, 2004; Mandrikas et al., 2017)。此一現象若從教育理論觀點加以說明，可視為學習者缺乏可供建構新知的情境與支援 (Delen et al., 2014; Narayan et al., 2013; Palincsar, 2012; Wang et al., 2009; Zajda, 2021)。建構主義強調知識並非單向灌輸，而需學習者在既有經驗基礎上透過詮釋與重組逐步形成理解；若課堂只呈現數值與定義，學習者往往僅能記憶而難以遷移應用 (Kintsch, 2009; Larsen-Freeman, 2013; Tan, 2011)。情境學習則指出知識必須嵌入真實情境與任務脈絡，才能促進理解與使用；若能以「台中在地空汙品質」作為真實素材，讓學生在「今天要不要出門、需不需要防護」等情境中判讀數據，將有助於把抽象概念轉化為可操作的判斷 (Arvai et al., 2004; Bell et al., 2013 ; Creighton, 2006; Jacobson & Archodidou, 2000)。另一方面，探究式學習強調以問題驅動理解，學習者透過提問、解釋與推論，逐步建立因果關係與系統思考；因此，若能引導學生追問「PM 值是什麼、為何會有、會造成什麼影響」，並在關鍵處提供鷹架與形成性回饋，便能降低理解門檻，提升概念內化與應用能力 (Duran & Dökme, 2016; Hsu et al., 2015 ; Şimşek & Kabapınar, 2010)。基於上述教學需求，本文以系統開發角度提出「空汙智警機器人」，將「在地空品資訊」與「對話式概念引導」整合為互動式學習支援服務。空汙智警機器人以台中地區 PM2.5 即時資料為輸入，提供監測回報與情境化提示（例如在空品較佳時提醒適合戶外活動），使數據能對應到可理解的行動建議；同時支援學習者追問核心概念並獲得結構化解釋，形成「數值判讀→提出疑問→概念釐清→行動推論」的學習閉環。本文亦將此系統定位作為學生能由空品現象切入，延伸思考再生能源與儲能對減排與空污改善的關聯，強化能源與環境議題的跨域連結與問題意識。

2. PM2.5 與空氣污染的核心概念與影響

PM2.5 係指空氣中粒徑小於等於 2.5 微米之細懸浮微粒，因粒徑極小、可長時間懸浮並隨氣流傳輸，且更容易進入呼吸系統深處，因此常被視為評估空氣污染風險的重要指標 (Feng et al., 2016; Pope III et al., 2018)。就來源而言，PM2.5 既可能來自交通與工業排放、燃燒行為與揚塵等一次排放，也可能由氣態前驅物在大氣中轉化形成二次粒子，使特定季節或氣象條件下濃度明顯升高 (Behera & Sharma, 2010; Cesari et al., 2018; Hao et al., 2020; Yang et al., 2017)。此類細粒子除影響能見度、造成霾害外，更與健康負荷高度相關 (Wang et al., 2019; Liu et al., 2019; Hu et al., 2021)。綜述研究指出，PM2.5 暴露與心肺疾病罹病率與死亡風險上升具一致性證據，可能機制包含發炎反應、氧化壓力與血管功能失衡等，顯示其危害屬於可累積之公共衛生風險 (Fann et al., 2012; Guan et al., 2019; Krittanawong et al., 2023)。此外，美國心臟協會科學聲明亦指出，短期暴露可能觸發心血管事件，長期暴露則提高心血管死亡風險；當污染濃度下降時，健康結果亦可能在較短時間尺度出現改善，突顯降低暴露與即時風險溝通的重要性 (Chen et al., 2018; Hayes et al., 2020; Kloog et al., 2013; Schraufnagel et al., 2019)。PNAS 研究亦以 GEMM 函數推估長期戶外 PM2.5 造成之早逝負荷龐大，且在高濃度地區健康衝擊更顯著，反映其具區域差異且需長期管理 (Zhang et al., 2019)。綜合上述證據，PM2.5 具有健康風險明確、暴露具時間敏感性、改善可帶來效益等特徵。因此，若能以「在地即時」方式呈現空品資訊，並搭配可理解的解釋與行動指引，將更能協助學習者把數據轉化為判斷與決策能力。基於此，本文後續將以空汙智警機器人之系統需求、架構與互動流程為主軸，探討如何整合 PM2.5 即時數據與情境化提示及對話式概念釐清，作為空氣品質判讀與環境素養培育之教學支援工具。

3. 系統需求與整體架構

本章聚焦於「空汙智警機器人」的系統規劃，先界定系統需滿足之核心功能需求，以確保具備在地即時監測、可理解回報與互動能力。接著說明整體系統架構，採模組化與鬆耦合

設計，讓資料取得、判斷規則、問答知識與介面輸出可獨立維護並利於後續擴充。最後以互動流程呈現學習者實際操作路徑，從數據取得到建議提示，再到追問式概念解釋，形成完整的學習支援閉環，如圖 1 系統架構圖。

(1) 功能需求

「空汙智警機器人」以台中地區空氣品質監測與科普互動為目標，其核心功能需求如下：

- 取得台中地區即時 PM2.5 值：系統需能即時取得 PM2.5 資料，資料來源可採(1)環境監測公開資料介接，或(2)部署於場域端之感測器回傳，以確保具備在地化與即時性。
- 顯示/播報監測資訊：系統需同步呈現（或播報）「地點、時間、PM2.5 數值」，讓學習者能掌握資料脈絡與更新時間，避免只看數字而不清楚其時空意義。
- 判斷與建議提示：系統需具備基本判斷邏輯：當 PM 值偏低時，主動提示「今日較適合外出旅遊或戶外活動」；當 PM 值偏高時，則以一句提醒學習者留意防護與活動安排（例如降低戶外劇烈活動）。
- QA 問答支援：系統需提供對話式提問與回覆能力，至少涵蓋三類關鍵問題：「什麼是 PM 值」、「為何會有 PM 值（來源/形成）」、「會造成何種環境污染與影響」，以支援學習者即時釐清概念與建立因果理解。

(2) 系統架構

為兼顧即時監測、判斷決策與教學互動，本研究將空汙智警機器人系統規劃為四個模組，並採鬆耦合方式串接，使資料更新、判斷規則與問答內容可獨立維護與擴充。系統先由「資料取得模組」蒐集台中地區 PM2.5 值，再交由「判斷引擎」依閾值或規則進行空品等級判斷與建議生成；同時「對話/知識回覆模組」負責處理學習者的概念提問（可採規則式或 LLM 結合知識庫），最後由「介面與回報模組」統一輸出為文字、語音或視覺化呈現，完成學習者互動閉環，如圖 2。

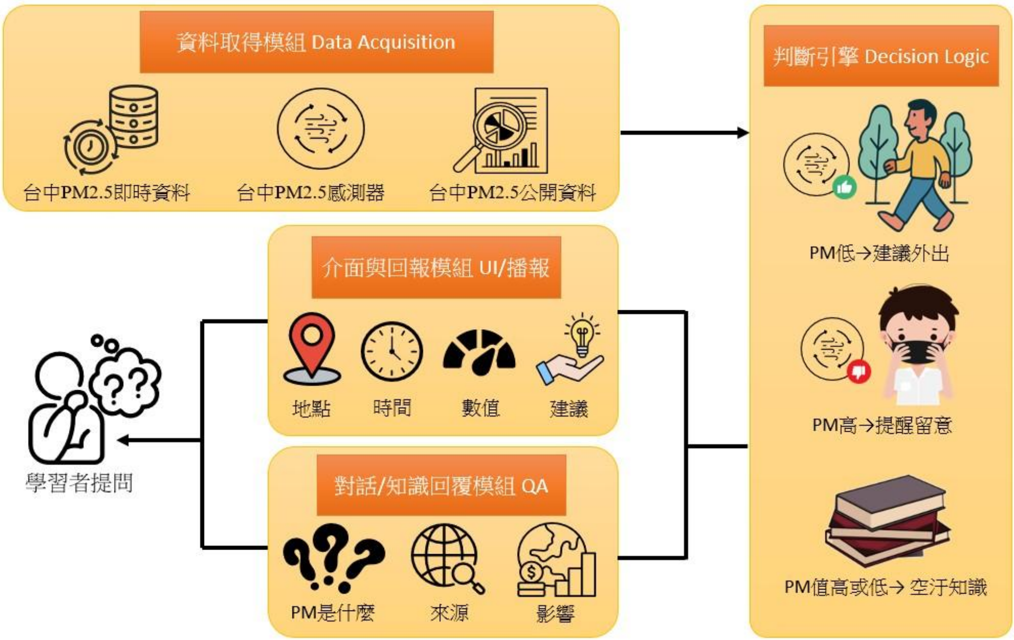

圖 1 系統架構圖

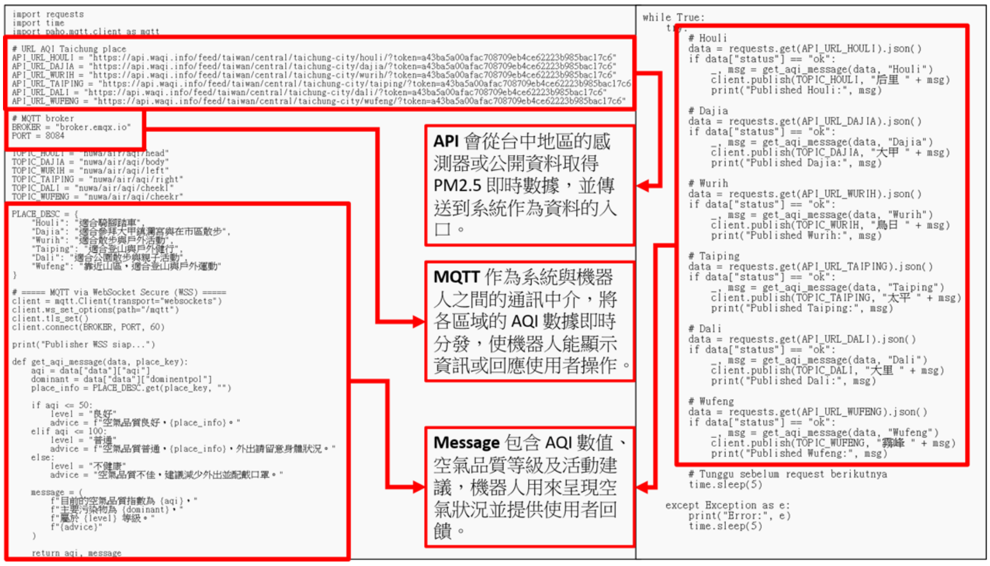

圖 2 PM2.5 系統的圖片教學

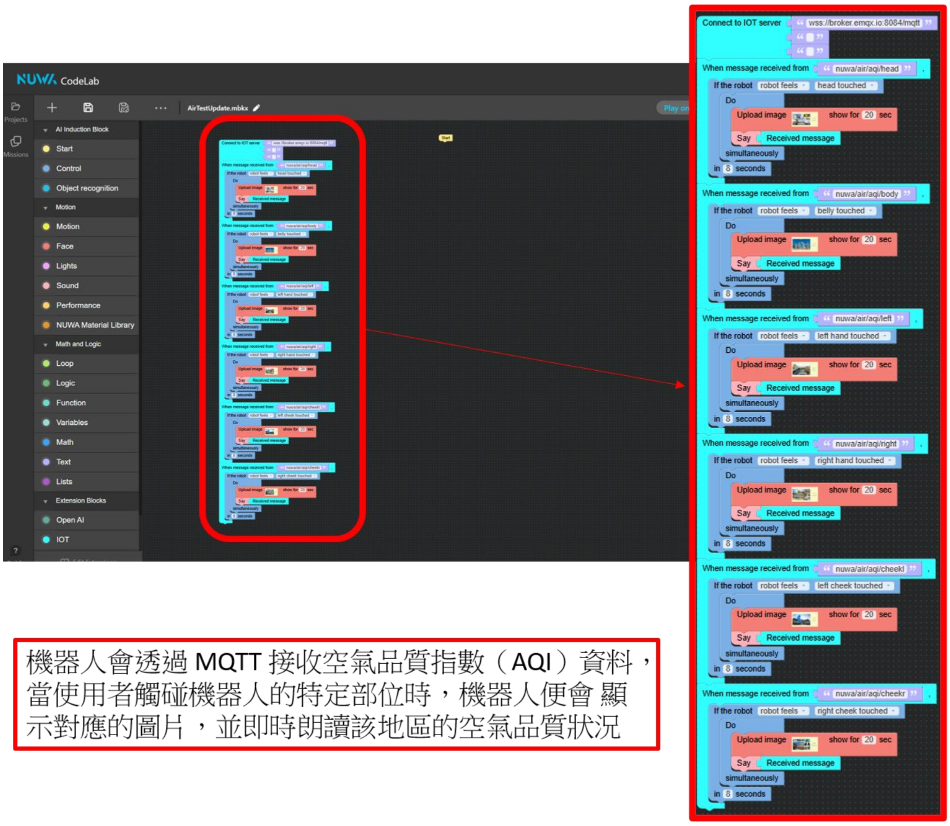

圖 3 PM2.5 系統的圖片教學

(3) 互動流程（用流程敘述）

空汙智警機器人的互動流程以「即時資料驅動」為主軸，並在回報後提供追問式學習支援。系統首先進行偵測/取得：透過感測器量測或介接公開資料取得台中地區當下 PM2.5 值；接著進入回報數值階段，由介面模組輸出地點、時間與 PM2.5 濃度，讓學習者立即掌握空品現況，如圖 3。其後系統執行判斷 PM 高低：判斷引擎依預設閾值或規則將數值轉為簡要狀態，並於下一步給建議：若 PM 偏低則提示適合外出旅遊或戶外活動，若偏高則提醒學習者留意防護與活動調整。最後，學習者可基於回報內容進行追問（例如「PM 值是什麼？」或「為什麼會有 PM？」），系統由對話/知識回覆模組提供概念解釋與原因說明，完成從「數值判讀」到「概念理解」的學習閉環。

4. 實作與成果

本研究完成「空汙智警機器人」之原型實作，並以台中地區 PM2.5 即時資料作為系統運作基礎，驗證其「監測回報、判斷建議、對話解釋」三項核心功能是否能形成完整的互動閉環。在實作上，系統依前述架構分為四個模組：資料取得模組負責定時抓取台中地區 PM2.5 數值並附帶時間戳記與地點資訊；判斷引擎依預設閾值進行空品狀態判讀，生成對應之行動建議；對話/知識回覆模組採規則式問答搭配小型知識庫，能辨識學習者對 PM 概念的三類常見提問（PM 值定義、形成原因、環境與健康影響），並回覆結構化說明；介面與回報模組則以文字為主（可延伸語音播報），將「地點、時間、PM2.5 數值、建議語句」整合輸出，提升資訊可讀性。成果展示以情境化流程驗證為主(如圖 2)：當系統取得 PM2.5 數值後，介面能即時更新並回報目前台中指定區域的濃度；若判斷為偏低，系統會主動提示「今日較適合外出旅遊或戶外活動」，並以簡短提醒補充仍需留意個人健康狀況；若數值偏高，則改以「建議減少戶外劇烈活動並留意防護」作為提示，讓回饋具一致性與安全性。進一步地，學習者在看到回報後可立即追問「什麼是 PM 值？」系統能回覆 PM2.5 的定義與特性；追問「為何會有 PM 值？」則說明交通、工業、燃燒與二次生成等來源；詢問「會造成何種污染影響？」系統可整理能見度下降、霾害與健康風險等重點。整體而言，本原型已達成即時監測到概念解釋的整合，並具備導入能源課程之可行性，後續可再擴充多測站比較、歷史趨勢視覺化與個人化提醒，以提升教學與應用價值。

5. 結論

本研究以系統開發觀點完成「空汙智警機器人」原型，目標將台中地區 PM2.5 空品資訊由被動查詢轉化為「可即時回報、可判斷建議、可對話解釋」之互動式學習支援服務。系統採「資料取得、判斷引擎、對話／知識回覆、介面與回報」四模組：定時擷取台中 PM2.5 數值並呈現地點與時間以確保在地性與可追溯性；以閾值規則將數值轉譯為行動建議，PM 偏低時提示適合外出或戶外活動，偏高時提供簡潔防護提醒與活動調整建議，讓數據更易理解與應用。互動上，除回報數值外，亦支援學習者即時追問「PM 值是什麼、為何產生、造成哪些影響」，並以結構化回覆串接「數值判讀→成因理解→影響掌握→行動建議」的知識鏈，以補足空污教育常見的理解落差。教學應用上，可作為能源課程之媒介，從空品監測延伸討論再生能源與儲能如何降低化石燃料發電需求、減少排放並降低 PM2.5 生成風險，促進能源與環境的跨域連結。惟本研究以原型驗證為主，仍受限於單一來源／單點監測之代表性、閾值與語句偏通用且未納入個人差異，以及知識回覆以規則與小型知識庫為主。未來可加入多測站比對與趨勢視覺化、整合 PM10 與 O_3 等指標，並發展個人化提醒與課堂任務設計，以提升教學效益與實務價值。

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