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Faculteit Industriële Ingenieurswetenschappen

master in de industriële wetenschappen: informatica

Masterthesis

Enhancing Autonomy in Supported Employment: A Configurable DWI with Physical Assembly Assistance

Vinz Roosen

Scriptie ingediend tot het behalen van de graad van master in de industriële wetenschappen: informatica

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Preface

This master's thesis marks the final milestone in my studies in Industrial Engineering at UHasselt and KU Leuven. The journey leading up to this work has been both technically challenging and personally rewarding. Combining software development, embedded systems, and user-centered assistance allowed me to translate my interest in human-focused technology into a tangible and meaningful project.

First and foremost, I would like to express my sincere gratitude to my promoter, **Prof. Dr. Maarten Wijnants**, for his expert guidance, insightful feedback, and the academic freedom he granted throughout the process. His critical yet constructive input was instrumental in shaping both the direction and the quality of this thesis.

I am also deeply thankful to my co-promoter, **Prof. Dr. Davy Vanacken**, and my supervisor, **Raf Menten**. I am grateful to Prof. Vanacken for his clear insights and for consistently setting a high bar that pushed me to deliver my best work. I thank Raf Menten for his support in providing all the hardware necessary to bring this project to life.

A special word of appreciation goes to my external promoter, **Benny Claes**, Innovation & Technology Engineer at Bewel, for his time, support, and facilitating the collaboration from Bewel's side. I also wish to thank the employees at Bewel, and in particular **Kevin Valkenborg**, Customized Employment Coach DISKKOtheek, for their active involvement, openness, and honest feedback during the user tests. Their engagement gave this project a deeply human dimension and served as a constant reminder of its purpose: to develop technology that truly supports.

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Glossary

Term	Definition
Digital Work Instruction	A digital instruction explaining how a task should be completed.
Inclusive Employment	Employment in mainstream settings where people with and without disabilities work together as equals.
Sheltered Workshop	A segregated work environment where people with disabilities perform work tasks, often adapted to their capabilities.
Customized Worker	An employee at a sheltered workshop with cognitive or physical support needs.
Pick-to-Light	A visual guidance system using LEDs to indicate which part to pick.
ESP32	A microcontroller with WiFi and Bluetooth, used in IoT applications.
MQTT	Lightweight messaging protocol for IoT communication.
WebSocket	Real-time, bidirectional communication protocol over a single TCP connection.
JSON	Human-readable data format used for structured data exchange.
Static IP	IP address manually set for a device, remains fixed over time.
Dynamic IP	IP address assigned automatically by a DHCP server, may change.
Language-Agnostic	Applicable across programming languages, not tied to one.
Wear OS	Android-based OS for smartwatches.
UEQ	User Experience Questionnaire. A standardized tool for evaluating user experience.

Abstract

In inclusive manufacturing environments such as Bewel and other sheltered workshops, accessible support systems are essential for empowering workers with diverse needs. While Digital Work Instructions (DWIs) can enhance accuracy and autonomy, existing solutions at Bewel are either limited to screen-based instructions or too complex and costly to configure and implement.

This thesis presents a modular, low-cost, and adaptable DWI system that combines conventional on-screen guidance with real-time visual and haptic cues.

A user study involving nine customized workers demonstrated that the system improves task efficiency and user experience compared to the DWI-only baseline. Visual cues were unanimously perceived as clear and helpful, while haptic feedback received mixed responses. The resulting system offers an inclusive and efficient task support solution suitable for both sheltered and mainstream manufacturing environments.

Abstract in Dutch

In inclusieve productieomgevingen, zoals bij Bewel en andere maatwerkbedrijven, zijn toegankelijke ondersteuningssystemen essentieel om werknemers met diverse noden te versterken. Hoewel Digitale Werk Instructies (DWI's) de nauwkeurigheid en autonomie kunnen verbeteren, zijn de bestaande oplossingen bij Bewel ofwel beperkt tot enkel schermgebaseerde instructies, ofwel te complex en kostelijk om te configureren en implementeren.

Deze thesis stelt een modulaire, kostenefficiënte en aanpasbare DWI-oplossing voor die klassieke schermgebaseerde instructies combineert met realtime visuele en haptische feedback.

Een gebruikersonderzoek met negen maatwerkers toonde aan dat het systeem de taakefficiëntie en gebruikerservaring verbetert ten opzichte van de DWI-only baseline. De visuele aanwijzingen werden unaniem als duidelijk en nuttig ervaren, terwijl de haptische feedback gemengde reacties opriep. Het ontwikkelde systeem biedt een inclusieve en efficiënte ondersteuning voor taken, toepasbaar in zowel maatwerkbedrijven als reguliere productieomgevingen.

Chapter 1

Introduction

1.1 Context

The manufacturing industry is increasingly moving towards digitization and automation to enhance quality and efficiency. Digital work instructions now play a central role as they can significantly shorten the training period for new operators, reduce assembly errors, and enable real-time guidance through step-by-step instructions, photos or videos. Their development and maintenance costs depend largely on the required programming or configuration effort.

Inclusive employment is also gaining importance: companies aim to integrate people with a distance to the labor market into their processes without adding unnecessary complexity. However, academic research on digital assistance tools has so far focused primarily on regular production lines, often overlooking the specific needs of supported workers.

At Bewel, a Belgian sheltered workshop employing individuals with a distance to the labor market [3], the current assembly process relies on non-interactive instructions that are neither step-by-step nor supplemented by external support. To address this, there is a need for a system that allows non-programmers to quickly create digital instructions and provides immediate, cost-effective assistance during assembly with minimal configuration.

1.2 Problem Statement

Bewel currently uses a digital work instruction system to support product assembly. However, this system only provides screen-based written instructions accompanied by photos, rather than integrating with an external support system. A previous attempt to introduce support required extensive customization and frequent updates, which relied on technical configurations that Bewel's non-programming staff could not manage independently, ultimately leading to the system being abandoned.

As a result, customized workers at Bewel often require significant assistance from supervisors. Moreover, workers with more severe cognitive limitations are currently unable to participate in assembly tasks at all.

These challenges stem from three key factors: the absence of a user-friendly interface for creating instructions; the unavailability of an external assistance system that allows for quick and easy configuration; and a lack of targeted research into digital support tools tailored to the needs of sheltered workers. Without addressing these limitations, Bewel risks continued inefficiencies, compromised quality, and barriers to realizing its goals for inclusive employment.

1.3 Objectives

The main objective of this master's thesis is:

> To develop a modular and cost-efficient digital work instruction system that enables the creation of step-by-step instructions and guides customized workers during assembly tasks using cues such as light, vibration, and visual feedback. The solution must be easy to configure by non-technical staff, minimize cognitive load, and offer support comparable to high-end systems, but at lower cost and with more efficient implementation. This thesis also investigates which types of assistance provide the most effective support and aims to ensure that the system is intuitive, effective, and well accepted by customized workers.

To achieve this goal, the following sub-objectives are defined:

- **User-friendly authoring tool:** Develop an application that enables step-by-step digital work instructions to be created and managed easily.
- **Pick-to-light system:** Implement a pick-to-light system with bins that indicate which part needs to be picked.
- **Assembly Assistance:** Implement an assistance system to guide the worker during assembly.
- **Automatic Verification:** Implement a system that verifies whether an instruction has been performed correctly.

These objectives will be evaluated based on effectiveness in real-world scenarios involving customized workers.

1.4 Outlook

This introduction concludes with an overview of the structure of the remainder of the thesis. In the following chapters, each component of the Digital Work Instruction (DWI) and assembly assistance system will be discussed in detail. This includes the step-by-step instruction authoring tool 3.2, the Pick-to-light system 3.4, the Light-based Assembly Assistance 3.5, the Haptic Assembly Assistance 3.6, and hand-tracking verification 3.7.

Additionally, the results of a user study will be presented and analyzed. This study evaluates the performance and usability of the different assembly support systems, with a focus on their effectiveness and usability for customized workers.

Together, these chapters aim to demonstrate how the proposed solution addresses the initial problem and contributes to a more inclusive and efficient work environment. Chapter 2 begins with a discussion of related work.

Chapter 2

Literature review

This literature review provides a foundation for the development of a digital work instruction system by exploring existing solutions and insights relevant to sheltered workshops. It helps identify opportunities, constraints, and design considerations for the chapters that follow.

2.1 Introduction

Digital Work Instructions (DWIs) replace paper-based guides with interactive, context-aware cues to accelerate task execution, reduce errors and boost autonomy in sheltered workshops [4]. Considered DWI technologies span screen displays and projection overlays [1], mixed reality, and light- or HUD-based picking [2, 5]. While these systems demonstrate clear gains in efficiency and user satisfaction, ergonomic issues (e.g. scanner discomfort, head-mounted strain) and the specific needs of sheltered workshop employees remain underexplored. This review synthesizes performance, usability and ergonomic findings to inform tailored DWI solutions for this workforce.

2.2 Results of Literature Review

This section synthesizes findings from prior research on Digital Work Instructions (DWIs), assistive technologies, and cognitive load management in inclusive work environments. Figure 3.1 shows an overview of the studied literature.

2.2.1 Effectiveness of Digital Work Instructions

Couckuyt et al. [4] compare digital and paper-based instructions in sheltered workshops. DWIs improve task speed, autonomy, and training efficiency while reducing errors. However, technical implementation details remain underexplored. Papetti [1] confirms these findings, reporting that projected and screen-based DWIs yield faster task completion and fewer errors than paper or MR-based systems.

2.2.2 Instruction Modalities: Screen, Projection, and Mixed Reality

Papetti [1] evaluated four instruction modalities: paper, screen, projection, and MR. Each modality is shown in Figure 2.1. Projection offered the fastest completion time (10.9s), while screen displays had the fewest errors (1.6). Although MR and screen systems outperformed paper in performance and user experience, MR introduced ergonomic concerns like neck strain and visual fatigue. This highlights a trade-off between performance and comfort.

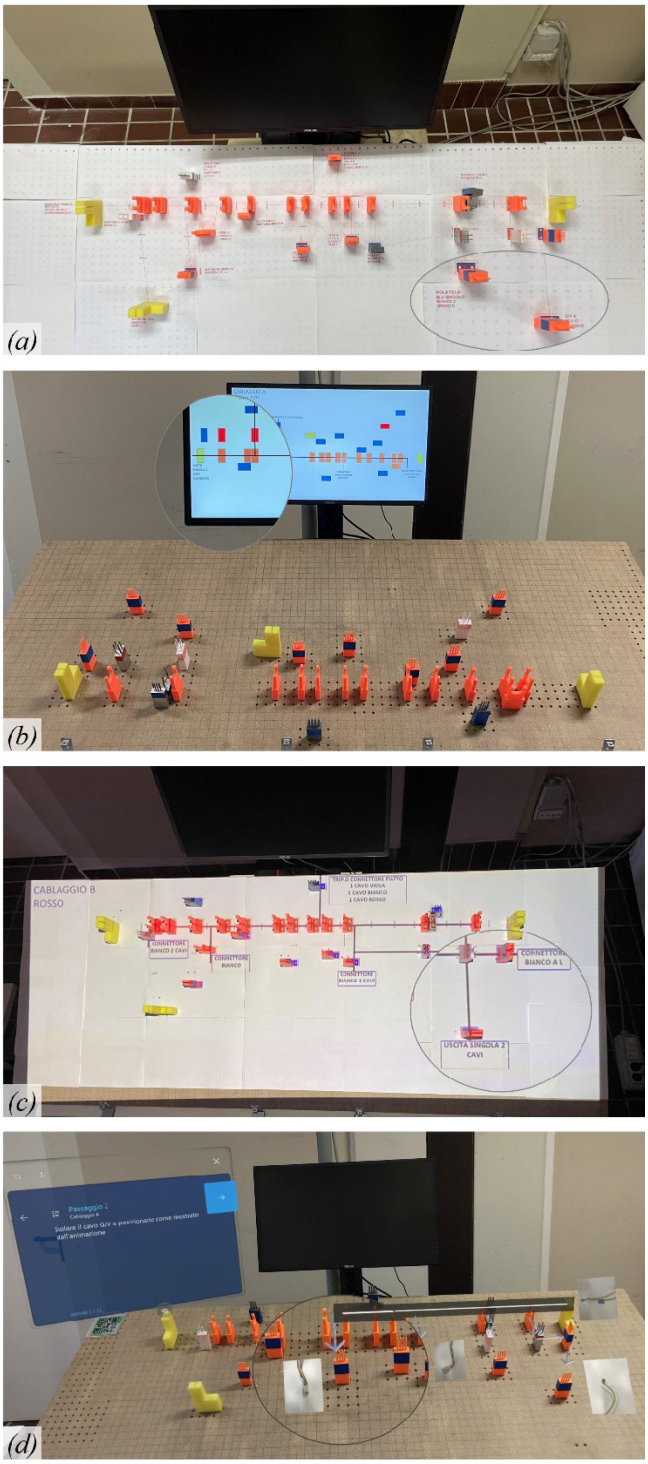


Figure 2.1: Instruction modalities compared by Papetti [1].

2.2.3 Picking Systems: Paper, Light, and Point

Studies by Łopuszyński et al. [2] compare three prominent picking systems: Pick-by-Paper, Pick-by-Light, and Pick-by-Point. These systems are visually summarized in Figure 2.2. The Pick-by-Light system, which uses shelf-mounted LEDs and confirmation buttons, demonstrates improved picking speed over traditional paper-based instructions. However, it still results in a 2.31% error rate. The Pick-by-Point system, which projects a light beam onto the target bin and requires scanner verification, yields greater accuracy (1.18% error rate) and was generally preferred despite some ergonomic drawbacks.

(a) Pick-by-Paper (b) Pick-by-Light (c) Pick-by-Point

Figure 2.2: Comparison of picking systems from Łopuszyński et al. [2]

2.2.4 Light-Based Guidance Systems

Pick-to-light systems highlight the correct bin with LEDs and reduce search time and cognitive load [6]. Advanced versions include color-coding, flashing patterns, and sensor feedback [7]. Projection-based systems directly visualize instructions on the workspace [8], improving comfort and speed but suffering from occlusion and light interference.

2.2.5 Wearables and Tactile Feedback

Wearables like smartwatches provide portable prompts and vibrational cues. Lancioni et al. [9] found high acceptance among cognitively impaired users. Compared to AR headsets, wearables are more affordable and ergonomic. Sigrist et al. [10] highlight their potential in low-distraction, multimodal feedback systems.

2.2.6 Real-Time Verification and Feedback Mechanisms

The ifm mate system [11] uses 2D and 3D vision for real-time hand tracking and task validation, improving independence and reducing supervisory demand. Similar vision-based feedback loops help maintain task accuracy without interrupting the workflow.

2.2.7 No-Code Instruction Authoring

Platforms like Augmentir [12] allow non-technical users to create DWIs using drag-and-drop editors. Academic approaches such as demonstration-based instruction generation [13] enable adaptive, rapid content creation, which is essential in inclusive contexts requiring flexible task support.

2.2.8 Cognitive Load Reduction

Instruction systems should reduce extraneous and intrinsic cognitive load while promoting germane processing. Adaptive feedback, multimodal cues, and chunked content enhance performance [14]. For example, projected guidance in Flanders improved learning speed and preserved autonomy [14].

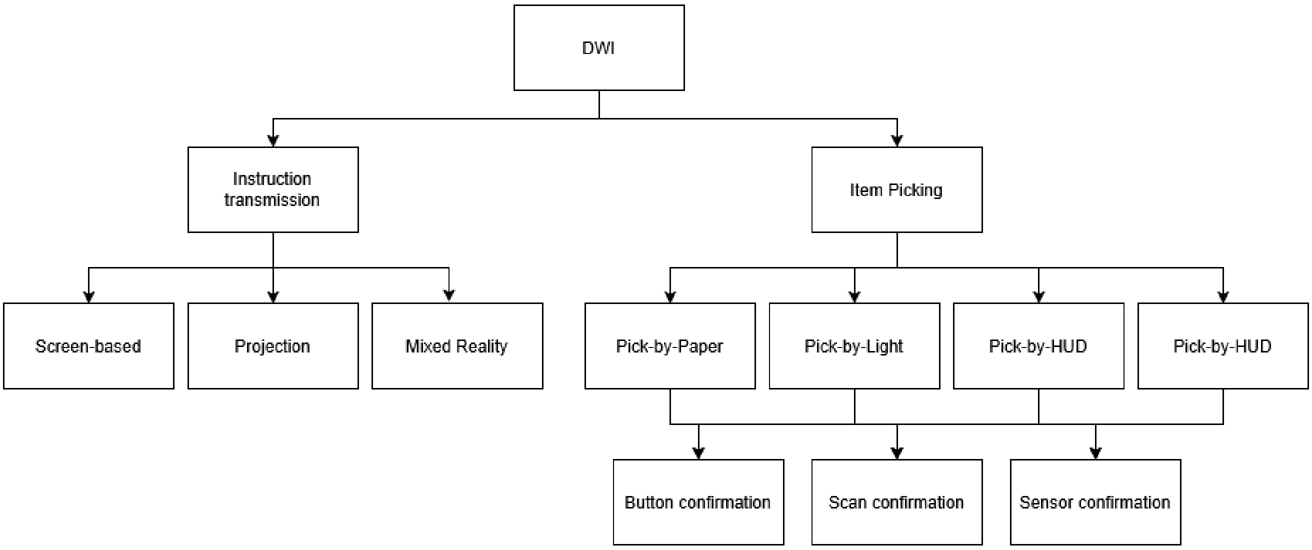
2.2.9 Inclusive Design and Universal Benefits

Inclusive systems using consistent cues, slow pulses, and customizable feedback improve clarity, reduce stress, and enable independent work [15]. Pick-to-light systems and projection-based guidance aid both neurodiverse and neurotypical users by minimizing mental effort and supporting error prevention [16].

2.2.10 Limitations and Research Gaps

Despite promising results, most referenced studies were not conducted with customized workers. As such, their generalizability to sheltered workshops remains limited. Tailored evaluations are needed to understand how assistive technologies interact with specific user needs in inclusive manufacturing.

Figure 2.3: Diagram of studied solutions



2.3 Conclusion

Drawing on the reviewed studies, a hybrid solution that integrates pick-to-light with automated validation, tablet-based instructions and light-guided assembly is ideal for sheltered workshops. Pick-to-light delivers rapid and intuitive cues. Outperforming paper and screen methods, while sensor-based validation reduces errors below those of simple light or paper systems and is more ergonomic and widely applicable than wrist-scanner approaches [2]. Tablet interfaces provide clear, sequential guidance with minimal cognitive load compared to HUD or mixed-reality overlays [4, 1], avoiding the long-term discomfort associated with head-worn displays [5, 17]. Light-guided assembly strikes the optimal balance of simplicity, cost-effectiveness and usability, making it both technically feasible and comfortable for users with diverse abilities. This combination maximizes speed, accuracy and autonomy while meeting the specific ergonomic and cognitive needs of sheltered-workshop employees.

Chapter 3

Implementation

3.1 System Overview

Figure 3.1 provides an overview of the complete Digital Work Instruction (DWI) and Assembly Assistance system. The system is composed of the following components:

- **DWI Application (see Section 3.2):** A software application used to create and display step-by-step digital work instructions.
- **Network Communication (see Section 3.3:** Enables wireless interaction between system components.
- **Picking Bins (see Section 3.4):** Modular bins that each store a specific component. The relevant bin is illuminated when its part is required.
- **Light-based Assembly Assistance (see Section 3.5):** Two LED strips mounted along the x- and y-axes provide visual guidance to the correct assembly position.
- **Haptic Assembly Assistance (see Section 3.6):** A smartwatch delivers vibration feedback that intensifies as the user nears the correct assembly location.

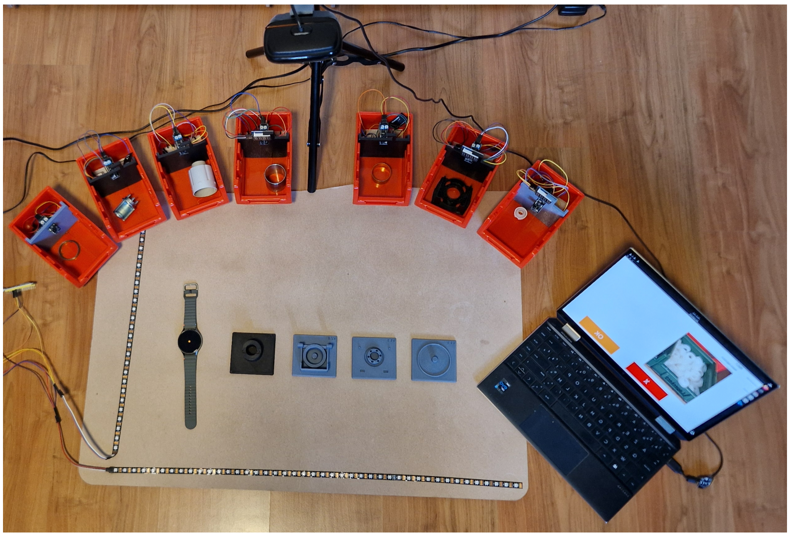


Figure 3.1: Overview of the complete DWI and Assembly Assistance system

3.2 DWI Application

3.2.1 Requirements

The objective of this section is to develop a tool that enables users, specifically employees at Bewel without programming experience, to create and modify instructions easily, without requiring complex configuration or coding knowledge.

3.2.2 Start Page

The start page of the DWI application displays all previously created assemblies. An assembly represents a complete set of instructions for constructing a product composed of multiple parts. The *Assembly Manager* view (see Figure 3.2) presents these assemblies as individual tiles, each with a unique name and color to facilitate easy identification.

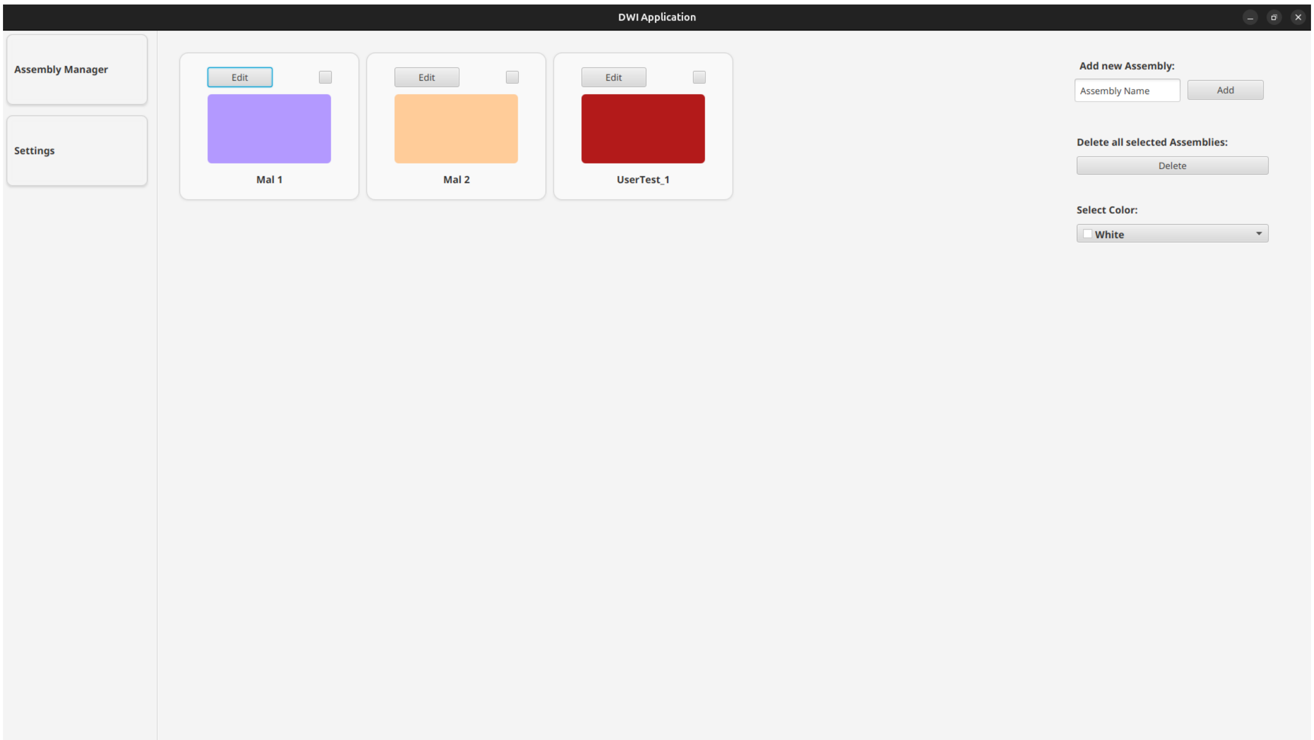
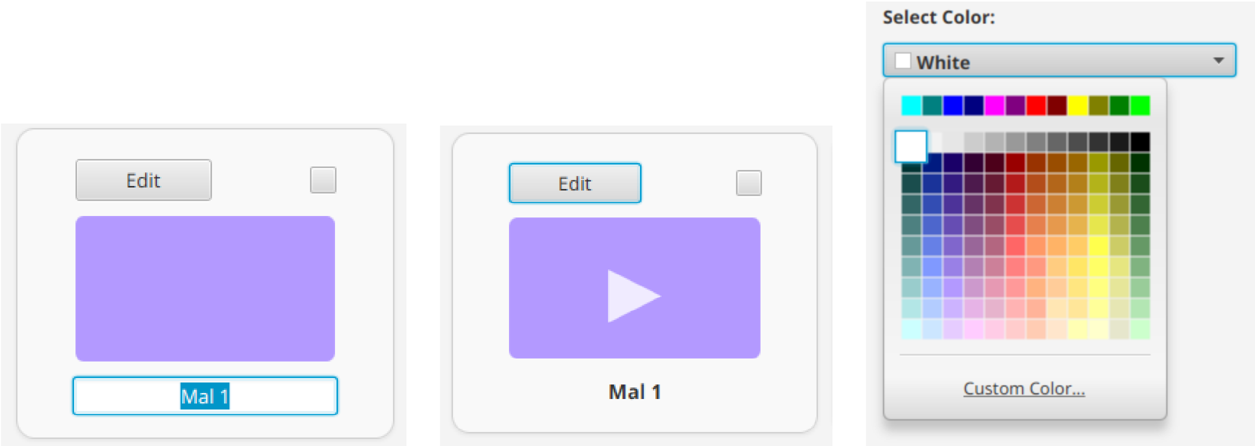


Figure 3.2: Screenshot of the Assembly Manager in the DWI Application

The name of an assembly can be modified by either clicking its label to turn it into an editable text field (shown in Figure 3.3a) or by selecting the tile via the checkbox in its top-right corner and using the settings panel on the right side of the screen (shown in Figure 3.2). The same approach can be used to create a new assembly, change the assembly's color or to delete an assembly. A screenshot of the color picker is shown in Figure 3.3c



(a) Assembly Tile during editing the assembly name

(b) Assembly Tile when hovering over it

(c) Color Picker in the Assembly Manager

Figure 3.3: Visual elements of the Assembly Manager interface

3.2.3 Instructions

Instructions can be divided into two categories: Picking Instructions and Assembly Instructions. This distinction exists because each type requires different user actions and system support. As a result, the DWI Creation tool clearly separates these instruction types.

Picking Instruction: A Picking Instruction specifies the part that needs to be picked, along with the ID of the bin in which the part is located.

Assembly Instruction: An Assembly Instruction consists of a specific assembly position and may include sub-instructions, allowing users to break down complex actions into smaller, sequential steps. Sub-instructions can also be used to simulate a folder-like structure to organize instructions. The assembly position is used later by the Assembly Assistance System and can be defined during instruction creation.

Both Assembly Instructions and Picking Instructions can be modified through the Instruction Manager.

3.2.4 Instruction Manager

The Instruction Manager can be opened by clicking the *Edit* button on an Assembly Tile (Figure 3.3b). A screenshot of the Instruction Manager is shown in Figure 3.4.

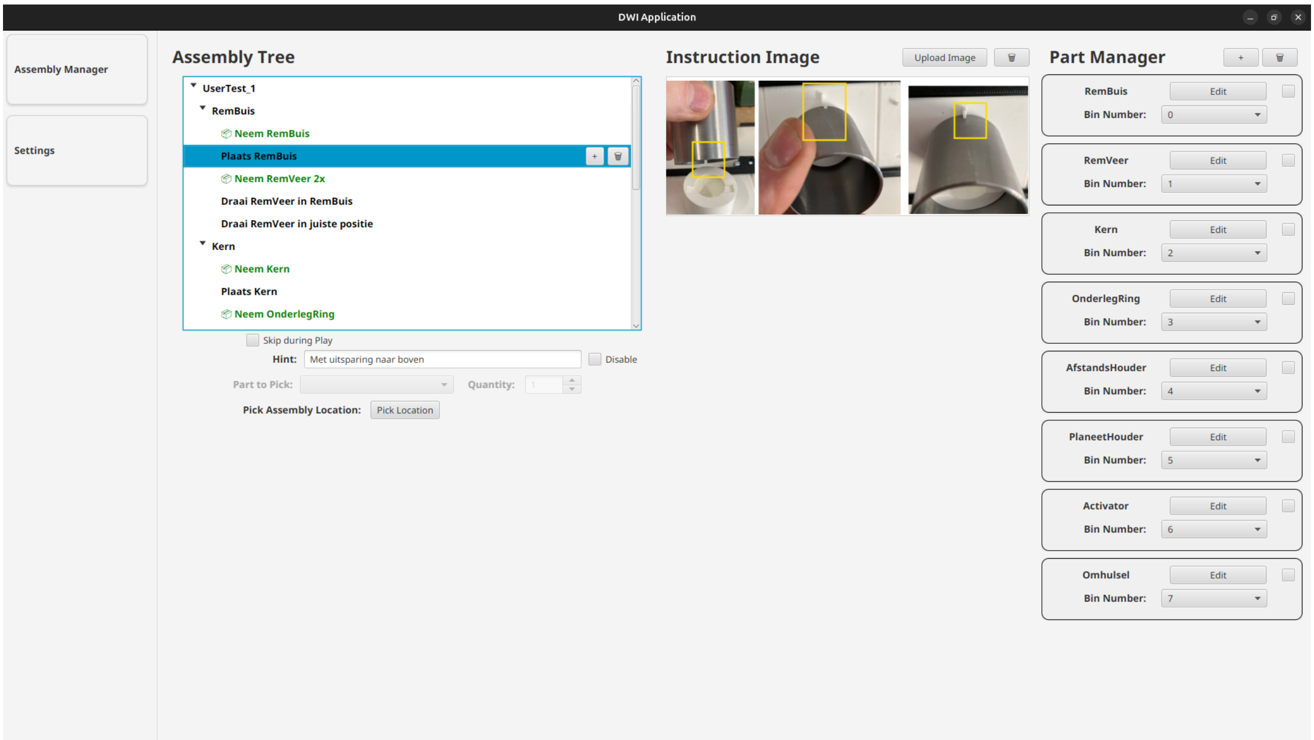


Figure 3.4: Screenshot of the Instruction Manager

The Instruction Manager consists of three main components: the Assembly Tree and Options Panel, the Instruction Image, and the Part Manager.

Assembly Tree The Assembly Tree is the central component of the Instruction Manager. It enables users to create and organize instructions for an assembly. Picking Instructions are visually distinguished from Assembly Instructions by their green color and a box icon at the beginning of the instruction name.

New instructions can be added by clicking the + button next to an existing instruction. This opens a menu that lets the user choose between creating an Assembly Instruction or a Picking Instruction (Figure 3.5).

Instructions with sub-instructions can be collapsed or expanded using a triangle icon, helping users to maintain an overview of the full structure (Figure 3.6).

Options Panel Located beneath the Assembly Tree, the Options Panel allows users to configure the properties of individual instructions. To edit an instruction, it must first be selected in the tree. Users can then modify its properties using various input fields.

The *Skip during Play* checkbox enables users to temporarily exclude an instruction from the playthrough. This is useful for creating folder-like groups or for deactivating steps without deleting them. The *Hint* field allows entering a custom message that will appear when the *NOK* (Not OK) button is pressed. The hint can be temporarily deactivated using the *Disable* checkbox.

For Picking Instructions, a part can be linked using the *Part to Pick* combobox, and the required quantity can be set using the *Quantity* spinner.

For Assembly Instructions, the *Pick Assembly Location* button opens the Location Picker tool, which lets users select spatial positions for later use in the Assembly Assistance System.

Instruction Image The Instruction Image provides visual support during the assembly playthrough (middle section in Figure 3.4). Images can be uploaded by clicking the *Upload Image* button, which opens the system's file explorer to select an image file.

Part Manager The Part Manager (right section of Figure 3.4) is used to create and manage parts involved in the assembly process. Each part is associated with a *Picking Bin*. The loose coupling between parts and bins makes it easy to update the assembly setup quickly and flexibly.

Figure 3.5: Option to choose between a Picking or Assembly Instruction during instruction creation

Figure 3.6: Example of instructions with hidden sub-instructions

3.2.5 Location Picker

One of the objectives of this thesis is to develop an assistance system that is easy to configure. Central to this system is the concept of defining 2D locations on the workspace where assembly actions should occur. For instance, if a bolt needs to be inserted into a screw hole, the precise position of that screw hole can be specified using the location picker interface (see Figure 3.7). This tool is integrated into the Assembly Manager and provides an overlay of a configurable grid on top of a live camera feed of the workspace. The grid aligns with the physical LED strip positioned above the workspace; each grid cell corresponds to a single LED. Therefore, setting the grid size to match the inter-LED distance ensures a one-to-one mapping between selected cells and LED indicators. The grid size can be adjusted via the options panel on the right. Users can select an assembly location by clicking and dragging directly on the image or entering coordinate values. Locations are defined by their top-left and bottom-right grid points, allowing for both single-point and rectangular area selections. This visual method of defining assembly locations makes it easier to assign instructions without requiring complex configuration steps.

Figure 3.7: Screenshot of the Location Picker

3.2.6 Assembly Playthrough

After DWIs have been created, they can be presented by hovering over an Assembly Tile, which causes a white triangle to appear within the tile's colored corner (see Figure 3.3b). This visual cue indicates to the user that the tile can be clicked to initiate the assembly playthrough. A screenshot of the playthrough view is shown in Figure 3.8. This interface represents the main screen that a customized worker interacts with during task execution and forms the core component of the DWI system.

The playthrough interface consists of four main elements. First, the name of the current assembly is displayed at the top and underlined (e.g., *UserTest_1* in Figure 3.8). Directly beneath this, the instruction description is shown (e.g., *Neem Rembuis*), which is the most critical element of the interface. It provides a clear and concise explanation of the specific step the user is required to perform.

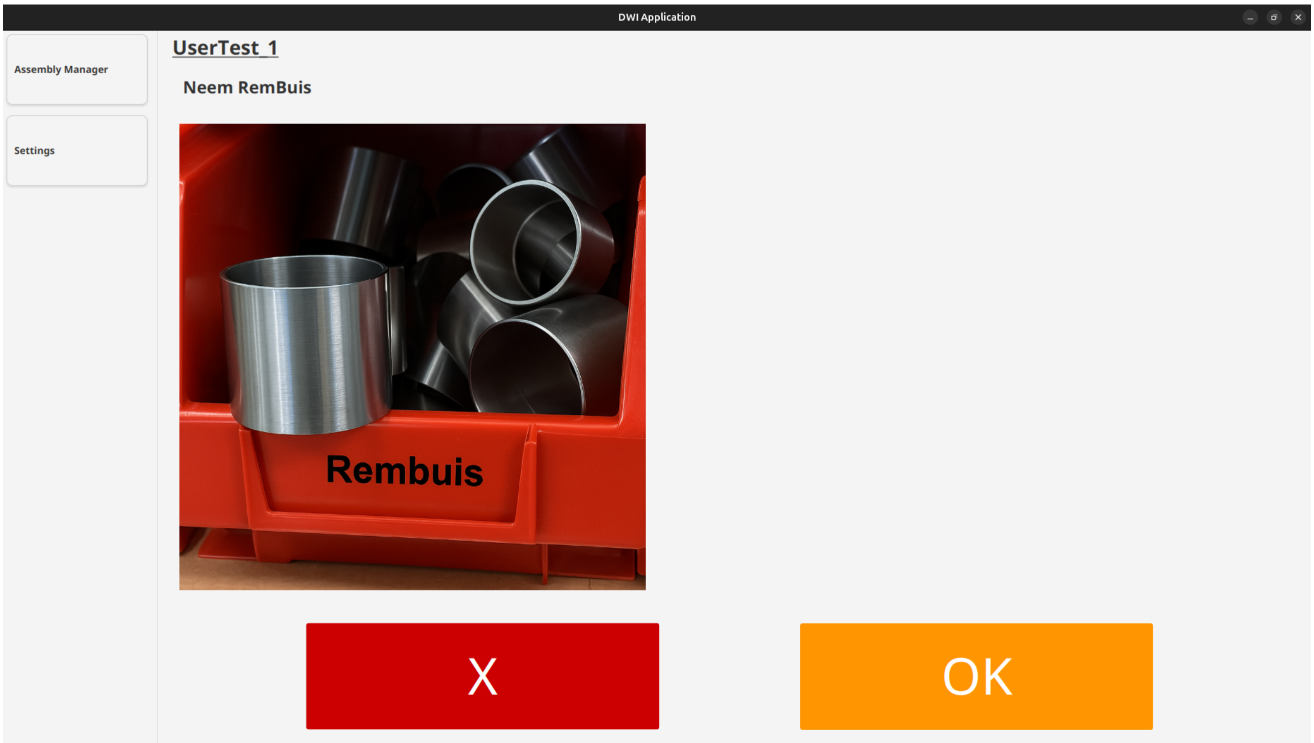


Figure 3.8: Screenshot of the Assembly Playthrough

Below the instruction text, an image is displayed. This image, uploaded during the instruction creation process, offers additional visual context to support the execution of the task. At the bottom of the interface, two buttons are positioned. The left button is labeled *X* (Not OK); when pressed, it indicates that the user was unable to complete the step. If applicable, a hint is then shown on the screen to assist the user (see Figure 3.9). When all instructions are completed, the view in Figure 3.10 is shown to the user.

When an instruction is triggered, the application sends the appropriate message to the corresponding module over the network.

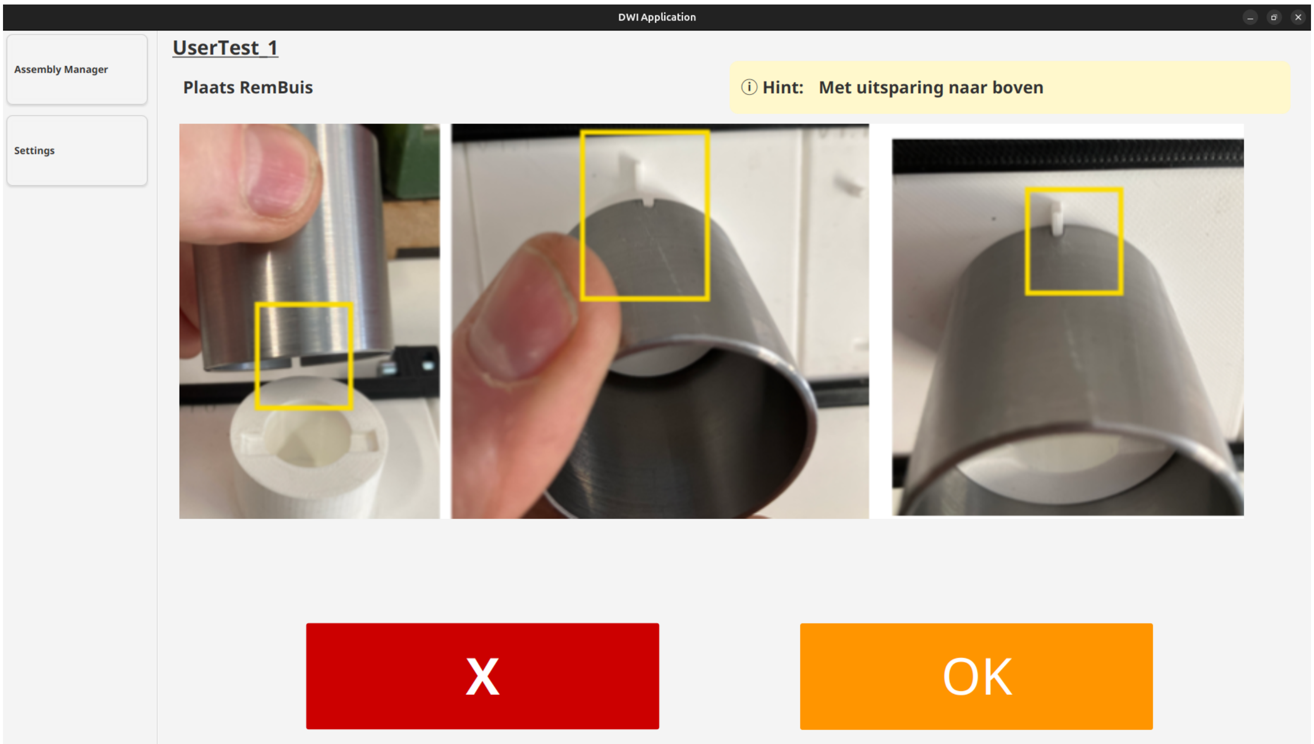


Figure 3.9: Screenshot of an Assembly Step with Hint

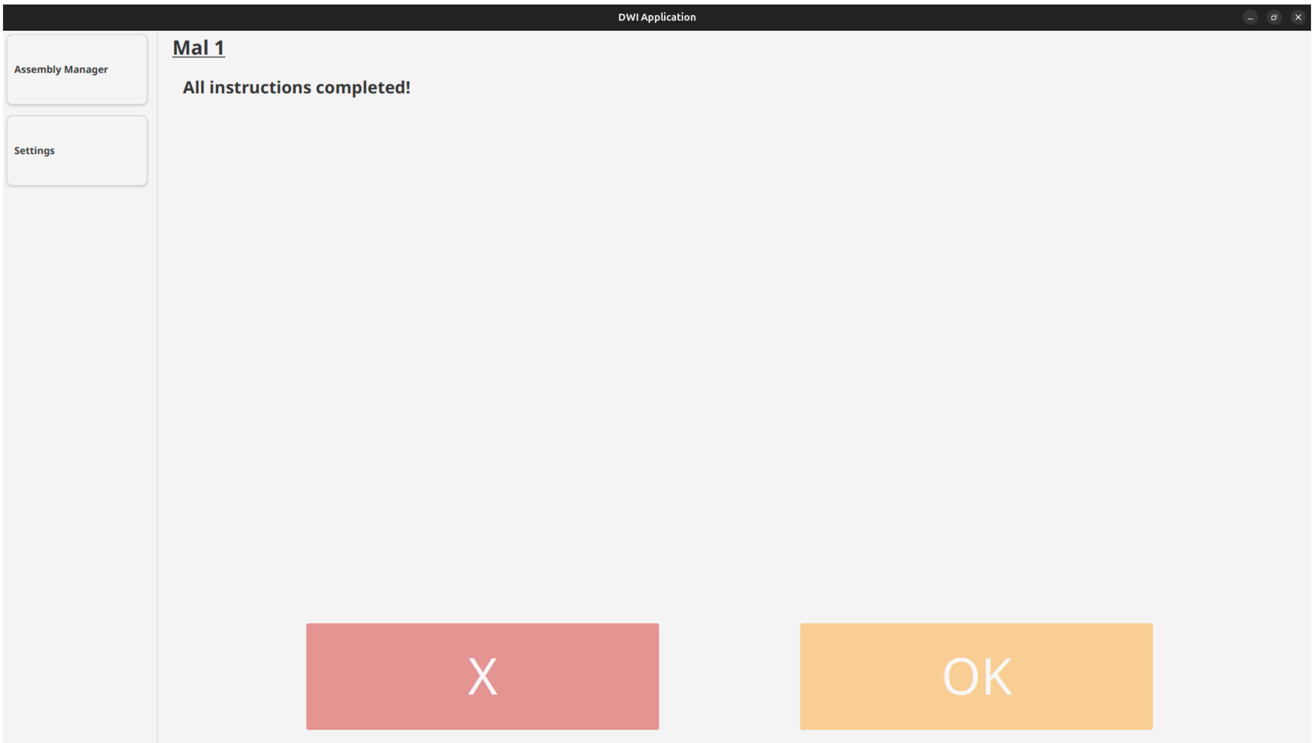


Figure 3.10: Screenshot of a completed Assembly walkthrough

3.3 Network Communication

3.3.1 Introduction

The DWI system with Assembly Assistance is built as a modular architecture, where each module operates independently. To enable seamless wireless interaction between these modules, communication is coordinated through the core DWI Application (see Section 3.2) over a network.

Three communication protocols are used:

- **MQTT** is used for lightweight, general-purpose messaging such as configuration, control commands, and debugging.
- **WebSockets** are used for high-performance, low-latency communication required by time-sensitive features like real-time LED animations and vibration feedback.
- **HTTP (MJPEG stream)** is used to transmit a live video feed of the workplace from the Hand Tracking module to the DWI Application for assembly location configuration.

This combination allows each module to communicate wirelessly while minimizing configuration effort and ensuring responsive interactions across the system.

3.3.2 MQTT

MQTT (Message Queuing Telemetry Transport) is a lightweight publish-subscribe messaging protocol designed for low-bandwidth and high-latency networks. It operates based on a broker model, where clients can publish messages to specific topics, and other clients can subscribe to those topics to receive relevant messages. This decouples senders from receivers, enabling flexible communication between components.

In the DWI system, MQTT is used for basic, non-performance-critical communication between modules. A cloud-based HiveMQ MQTT broker [18] accessible via a DNS hostname with a stable endpoint is used to simplify connectivity (shown with a red arrow in Figure 3.11). Each module can connect automatically without requiring manual IP configuration. This makes the system more robust.

MQTT serves several purposes in the system:

- Distributing the WebSocket IP address to modules.
- Sending control messages, such as which bin should light up.
- Logging and debugging messages, such as JSON parsing errors.

Messages are structured in JSON format, and topics are organized by module and function. Example MQTT messages include:

- `Output/Bin/Display`: {"id": 1, "quantity": 2, "brightness": 255, "status": "on"}
- `Output/Bin/LED`: {"id": 1, "color": {"r": 255, "g": 100, "b": 50}, "brightness": 200}
  (shown with a yellow arrow in Figure 3.11)
- `Output/Bin/Error`: {"error": "Failed to parse JSON"}
  (shown with purple arrows in Figure 3.11)

3.3.3 WebSockets

WebSockets is a full-duplex, bidirectional communication protocol built on top of TCP. Unlike HTTP, which follows a request-response model, WebSockets enable continuous and low-latency communication between a client and a server after an initial handshake. This makes it particularly well-suited for real-time applications such as live feedback, animations, or sensor updates.

In the DWI system, WebSockets are used for time-critical communication that requires high performance and low latency, such as sending real-time vibration and LED instructions or hand-tracking data. While MQTT handles general coordination, WebSockets ensure responsive feedback necessary for the interactive assembly assistance.

Each module connects to a dedicated WebSocket endpoint hosted by the core DWI Application. However, since the IP address of the core application may vary when it connects to the local network, the correct WebSocket IP is distributed via MQTT during system initialization (shown with gray arrows in Figure 3.11).

Each module communicates with its designated WebSocket endpoint. Example endpoints and messages include:

- `ws://172.17.0.1:8080/ws/ledStrip` (shown with a light blue arrow in Figure 3.11):


```
{
  "id": "x",
  "list": [
    {
      "list_indices": [0, 1, 2],
      "color": { "r": 255, "g": 0, "b": 0 },
      "brightness": 100,
      "status": "on"
    },
    {
      "list_indices": [3, 4, 5],
      "status": "off"
    }
  ]
}
```


- `ws://172.17.0.1:8080/ws/hands` (shown with a light red arrow in Figure 3.11): {“label”: “right”, “position”: {“x”: 100, “y”: 0}, “status”: “detected”}

Modules are programmed to automatically reconnect to previously connected WebSocket endpoints and MQTT Topics in the event of a connection loss, ensuring robustness and fault tolerance during operation.

3.3.4 MJPEG Stream

To configure assembly locations, the DWI Application displays a live video feed of the workplace, as detailed in Section 3.2.5. This feed is served as a Motion JPEG (MJPEG) stream, a simple video streaming format where individual video frames are continuously transmitted as a sequence of JPEG images over an HTTP connection [19]. The stream is provided by a lightweight HTTP server implemented with Flask [20] and received by the DWI Application (shown by the blue arrow in Figure 3.11). The server is integrated into the Hand Tracking module (see Section 3.7), which already captures the workplace video stream as part of its core functionality.

3.3.5 Overview

Figure 3.11 shows an overview of the network with examples of data flows.

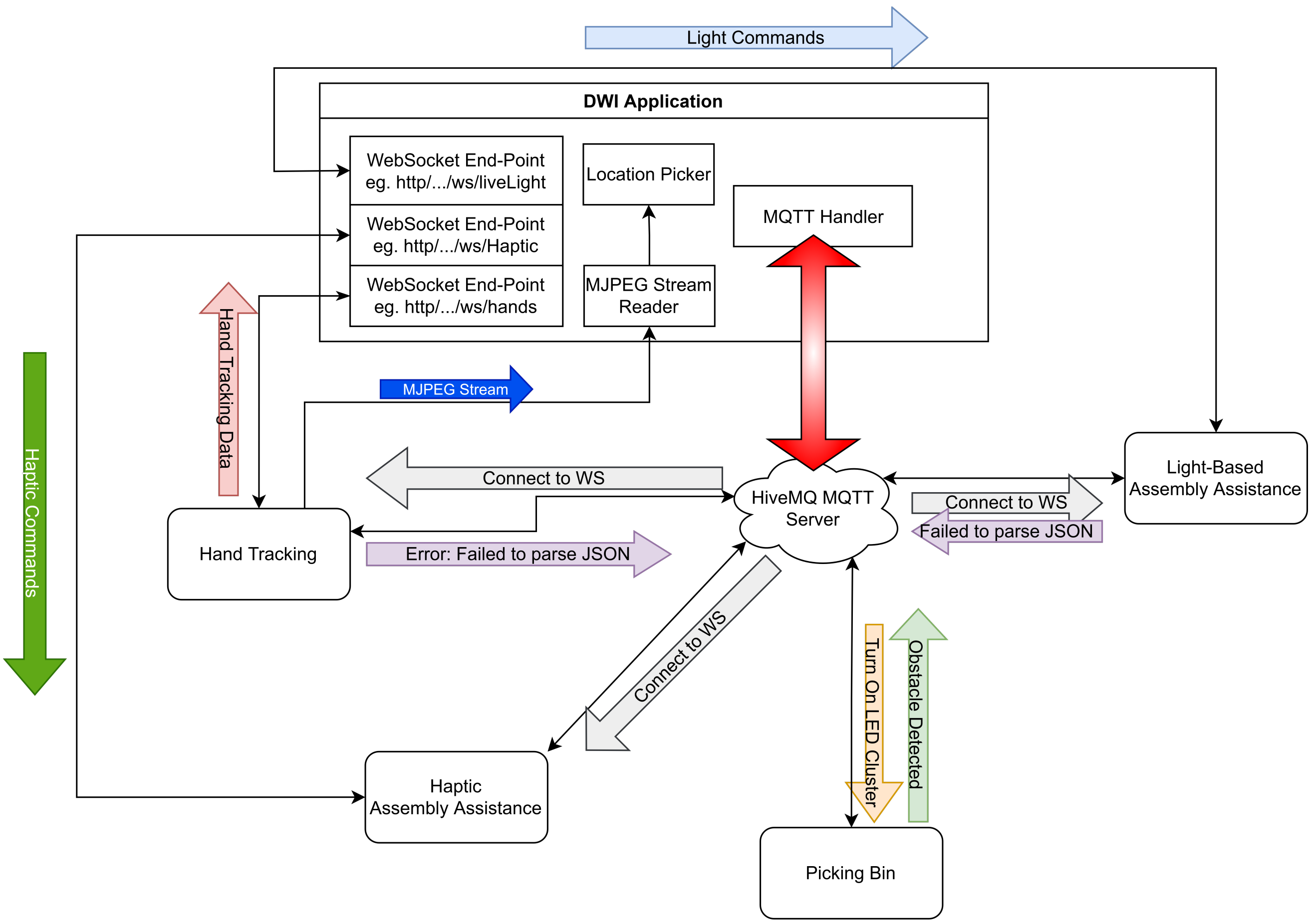
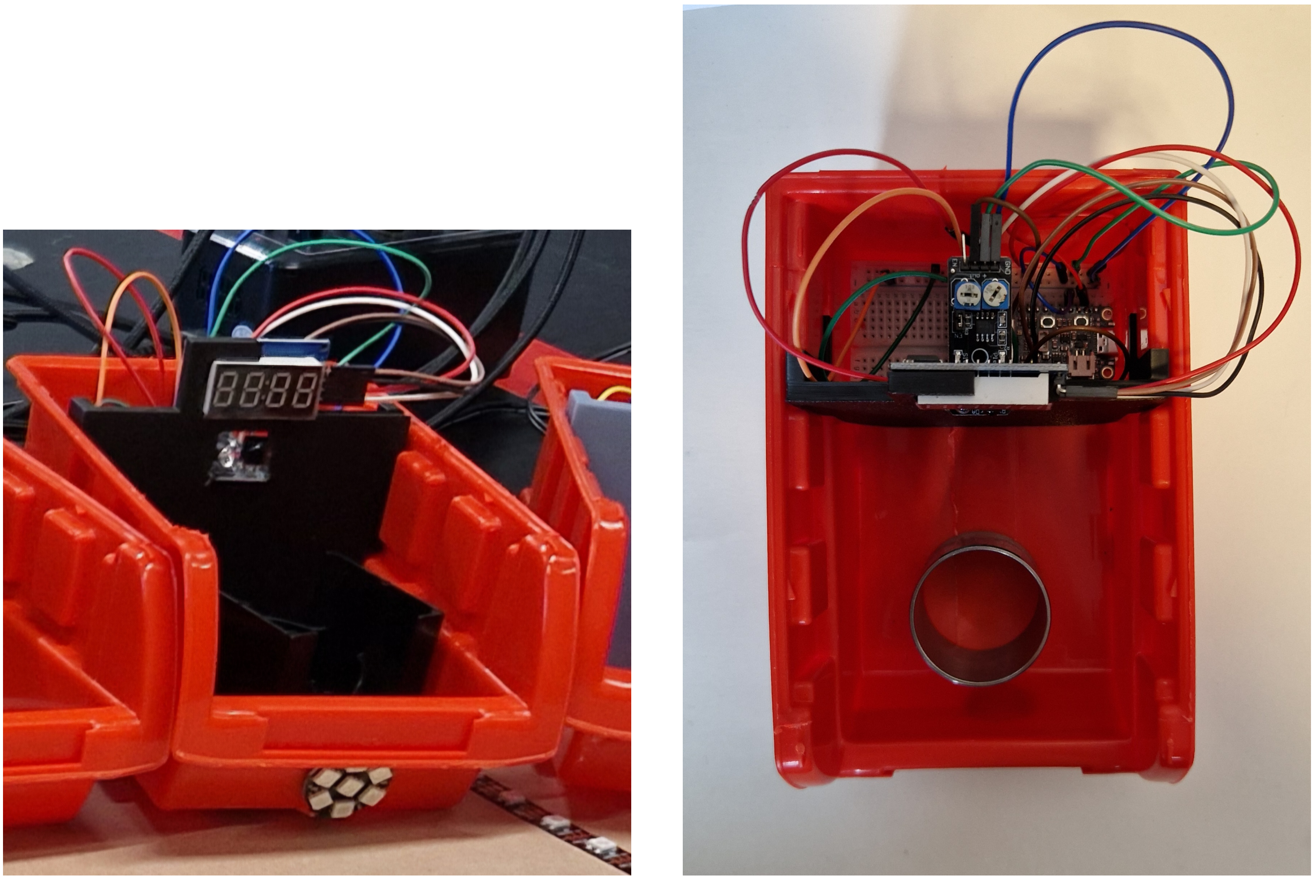


Figure 3.11: Schematic overview of the Network

3.4 Picking Assistance

The Picking Bin (shown in Figure 3.12) serves two main purposes: supporting the pick-to-light functionality by guiding the user during part selection and automatically detecting when a part is picked. Each bin has five key components:

- `Adafruit ESP32 Feather V2` [21]: Serves as the central controller of the picking bin. It features a dual-core Xtensa processor. The built-in WiFi and Bluetooth modules allow for communication with the DWI Application over the network.
- `Separation Wall`: Physically separates the electronics (wiring and ESP32) from the user-facing compartment, concealing internal electronics and improving usability (see Figure 3.13). The separation wall was designed using the free online CAD tool OnShape [22].
- `TM1637 4-digit 7-segment Display` [23]: Displays the quantity of parts to pick.
- `KY-032 Infrared Sensor` [24]: Detects hand movement to infer part picking.
- `WS2812 RGB LED Jewel` [25]: Visually indicates which bin is active.



(a) Picking bin integrated in the assembly setup

(b) Top view of the picking bin

Figure 3.12: Two perspectives of the picking bin

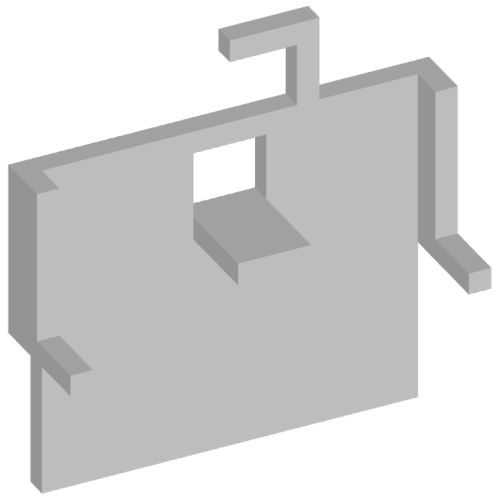


Figure 3.13: 3D render of the bin separation wall

3.4.1 System Architecture

Each picking bin is programmed to operate independently and has its own ESP32 and power via cable to support modularity. The firmware for the ESP32 is built using PlatformIO [26], an open-source ecosystem for embedded development that provides robust tooling, dependency management, and cross-platform support within a Visual Studio Code environment. The ESP32 handles wireless communication, message parsing, feedback control, and sensor monitoring. The key functionalities are as follows:

- **WiFi and MQTT Communication**: Upon startup, the ESP32 connects to a WiFi network and establishes a connection with the HiveMQ MQTT broker [18].
- **MQTT Message Handling**: The ESP32 subscribes to the required MQTT topics. When a message is received, it is parsed as JSON and validated based on the bin's unique `id`. This ensures that only relevant instructions are executed. Messages are then routed to the appropriate module, such as the LED cluster or the display. The picking bin does not use WebSockets, as real-time communication is not required.
- **Visual Feedback**: The LED cluster is used to indicate the active bin through color and flashing effects. The 7-segment display shows the number of parts to be picked, based on instructions received over MQTT.
- **Obstacle Detection and Validation**: The infrared sensor detects when a user's hand enters the bin. This state change is published to the topic `Input/Bin/Obstacle`, allowing the central system to validate picking actions in real-time.
- **Robustness and Error Handling**: If the WiFi or MQTT connection drops, the ESP32 triggers visual error feedback using the LED cluster (e.g., red flashes). The system is

designed to automatically reconnect to the last known MQTT topics and restore communication without user intervention.

Figure 3.14 shows the electronic circuit of the picking bin made using Fritzing [27]. The corresponding pin assignments are summarized in Table 3.1.

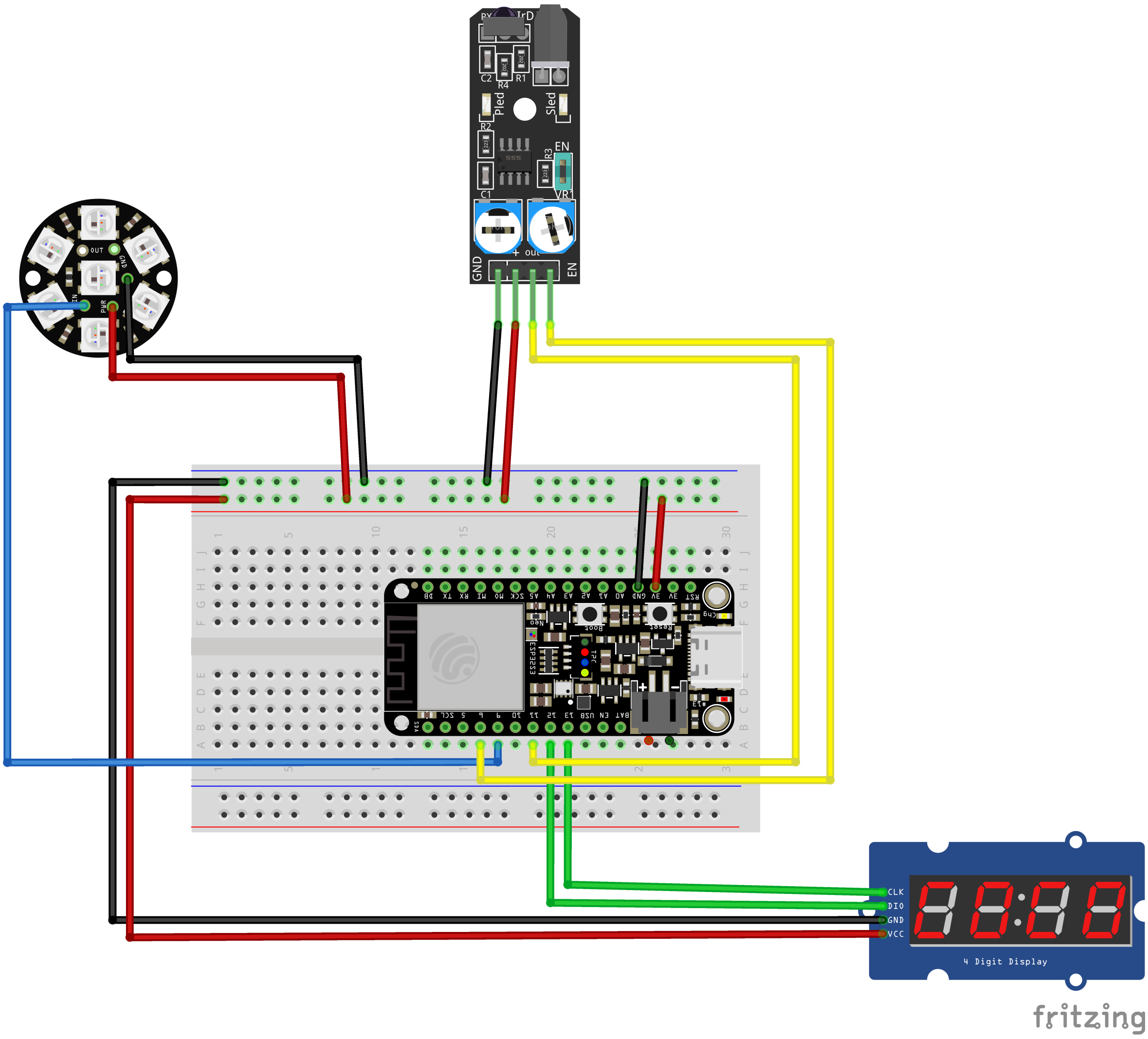


Figure 3.14: Circuit Schema of the picking bin

Table 3.1: Pinout of the picking bin Circuit

Component	**Signal**	**ESP32 Pin**
LED Cluster	Data	D9
	Power	3V3
	Ground	GND
7-Segment Display	CLK	D13
	DIO	D12
	Power (VCC)	3V3
	Ground	GND
IR Sensor	Signal OUT	D11
	Enable In	D6
	Power (VCC)	3V3
	Ground	GND

When the Infrared sensor detects an obstacle, it sends it to the DWI Application via MQTT. The DWI Application verifies if the obstacle is detected and later removed (so a hand goes in the bin, picks the item, and then goes out of the bin) to ensure that a part picking was executed. When the DWI Application is certain that a pick has been executed, it instructs (via MQTT) the bin to turn off the LED cluster and display. Subsequently, the DWI Application updates the color of the OK-button in Figure 3.8 to green (as shown in Figure 3.15) and a sound plays indicating the picking was executed successfully.

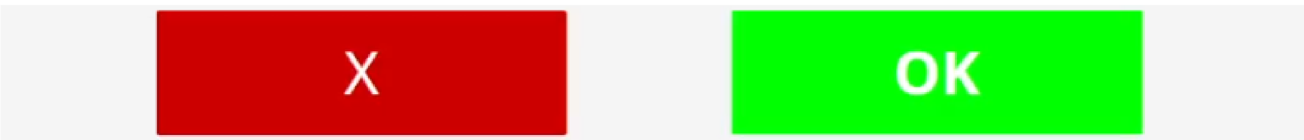


Figure 3.15: Screenshot of the OK-button colored green

Next, the system retrieves and visualizes the subsequent instruction in the assembly sequence. Typically, an assembly instruction follows a picking instruction.

3.5 Light-based Assembly Assistance

The light-based assistance system is built around two RGB WS2812B LED strips, one mounted vertically and one horizontally, as shown in Figure 3.16. Control of the LED strips is managed by the DWI Application (see Section 3.2), which instructs the LED controller (ESP32) to connect to the appropriate WebSocket endpoint (`.../ws/light`) via the existing MQTT connection.

To maintain modularity, the DWI Application sends either the color and brightness for each individual LED or a list of LED indices to be updated. This design centralizes all logic within the DWI Application, ensuring that updates or the integration of new systems only require changes within the core application logic.

Figure 3.16: Assembly Plate with LED strips

Figure 3.17 shows the electronic circuit of the Assembly Assistance. The corresponding pin assignments are summarized in Table 3.2.

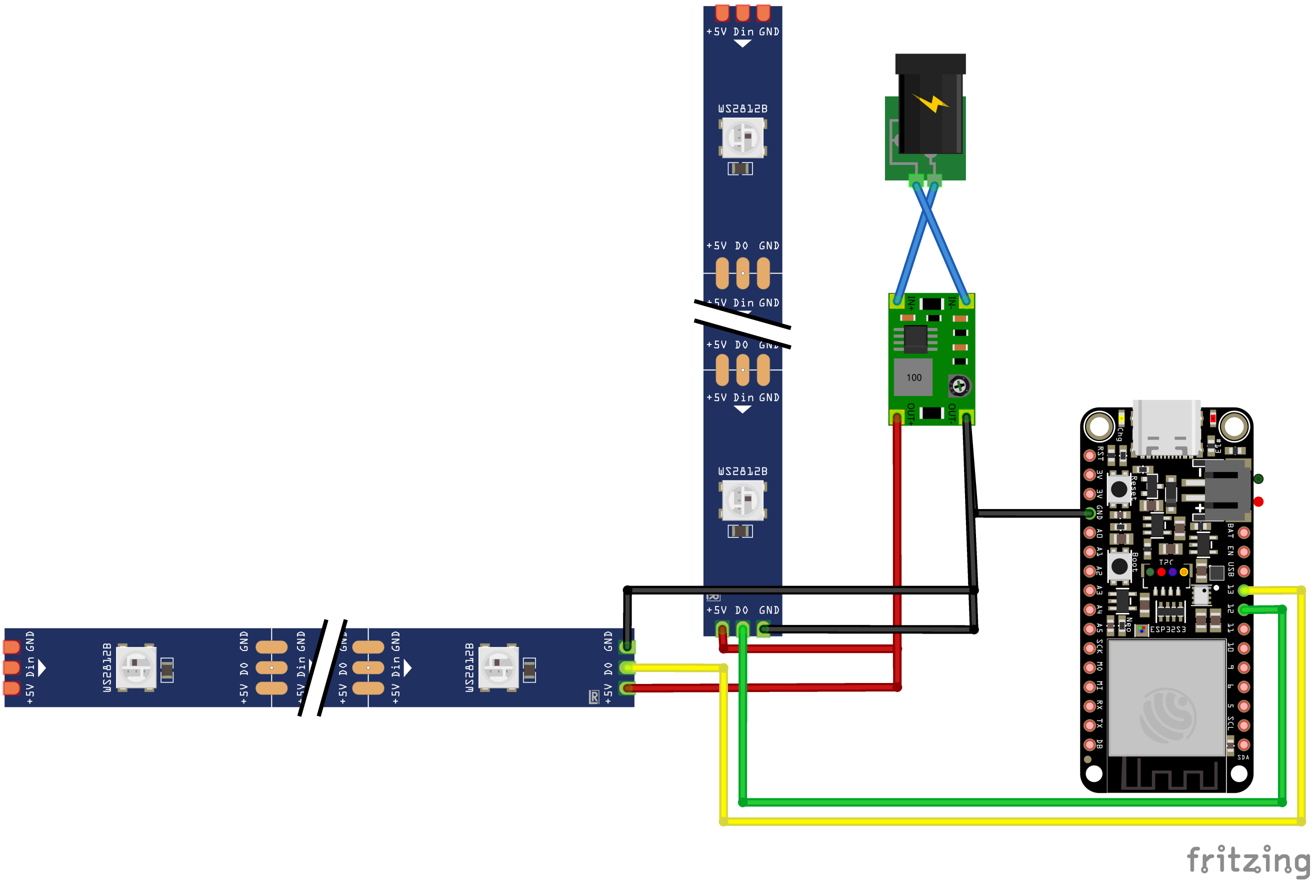


Figure 3.17: Circuit of the Assembly Assistance

Table 3.2: Pinout of the Assembly Assistance Circuit

Component	**Signal**	**ESP32 Pin**
LED Strip X	Data	D13
	Power	5V (via external converter)
	Ground	GND
LED Strip Y	Data	D12
	Power	5V (via external converter)
	Ground	GND

The light-based system implements four distinct LED patterns to guide the user during assembly:

- Static Light
- Live Light
- Flow Light
- Gradient

These patterns will be detailed in the following sections.

3.5.1 Static Light

The Static Light system operates by having the DWI Application (see Section 3.2) calculate the LED indices corresponding to the target location (defined using the Location Picker, see Section 3.2.5). These indices are then transmitted to the LED strip via WebSocket communication (as described in Section 3.3.3).

The corresponding JSON message is structured as follows:


```
{
  "id": "x",
  "color": { "r": 0, "g": 255, "b": 0 },
  "brightness": 50,
  "status": "on",
  "indices": [25, 26, 27, 28, 29]
}
```


Figure 3.18 provides an illustration of the Static Light system, guiding the user to the location of the gray object placed on the assembly table.

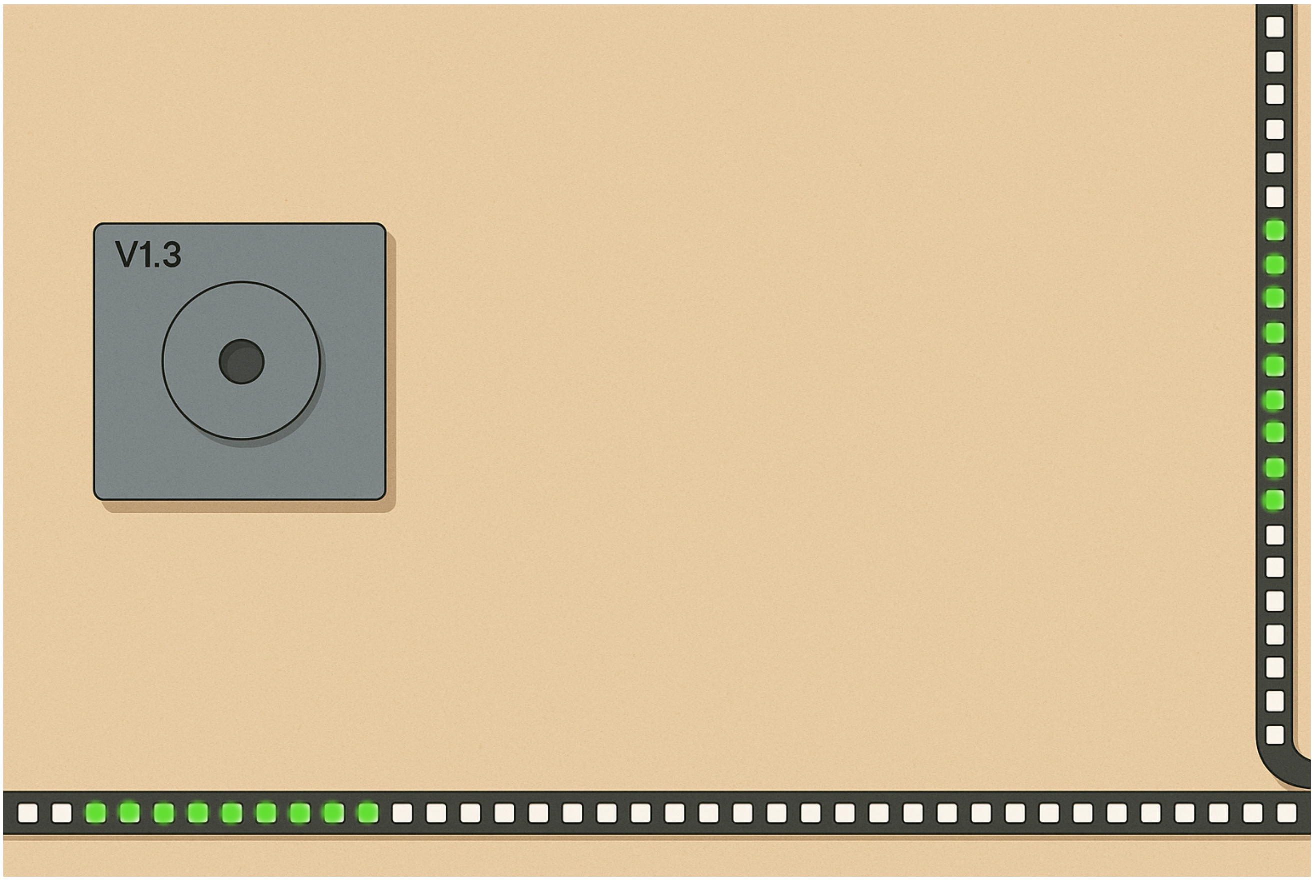


Figure 3.18: Illustration of the Static Light system

3.5.2 Live Light

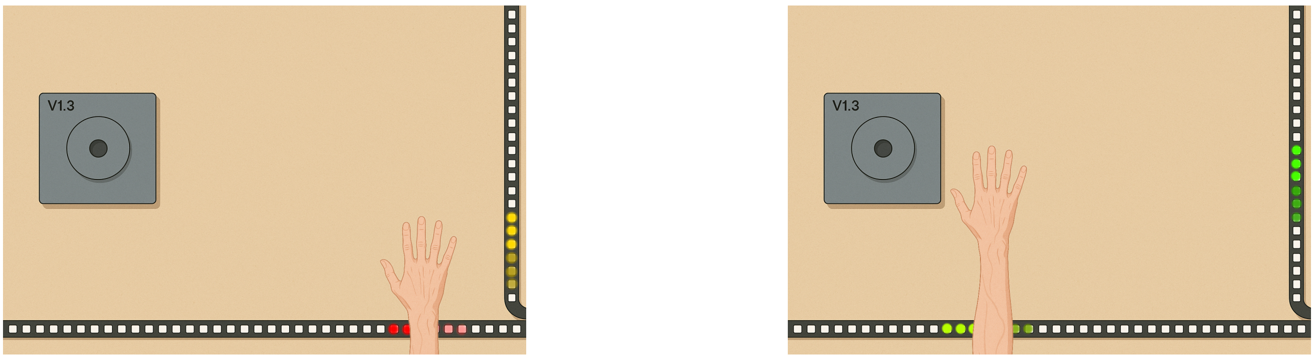
The Live Light system functions by having the DWI Application (see Section 3.2) receive the position of the user's hand through the hand tracking system (see Section 3.7). The DWI Application then calculates the direction vector between the hand position and the target location. This direction vector is projected onto the LED strip as an arrow.

The color of the arrow is determined by the Quality of Work (QoW) , defined as the normalized distance (0–100) between the hand and the target location.

The corresponding abbreviated JSON message is structured as follows:

```
{
  "id": "x",
  "list": [
    {
      "color": { "r": 117, "g": 178, "b": 0 },
      "brightness": 255,
      "status": "on",
      "list_indices": [30]
    },
    ...
    {
      "color": { "r": 117, "g": 178, "b": 0 },
      "brightness": 10,
      "status": "on",
      "list_indices": [33]
    },
    ...
  ]
}
```

Figure 3.19 shows an example of the Live Light system, where the arrow's head is represented by three bright LEDs and its tail by three dimmed LEDs. Figure 3.19a displays a scenario where the user's hand is far from the target: the x-axis LED strip shows a red arrow (indicating a large distance), while the y-axis strip shows an orange arrow (indicating a smaller distance).



(a) User is far from the target location

(b) User is close to the target location

Figure 3.19: Illustration of the Live Light system

3.5.3 Flow Light

The Flow Light system creates a guiding effect by animating a cluster of blue LEDs that move from both edges of each LED strip toward the target location. This dynamic motion helps direct the user's attention to the correct position. The DWI Application manages the entire lighting system by controlling the timing and behavior of the LED clusters. It does so by scheduling tasks that specify which LEDs to turn on and off at defined intervals.

The JSON message follows the same structure as the previously described light systems (see, for example, Section 3.5.1).

Figure 3.20 provides an illustration of the Flow Light system. The blue arrows in the figure are for illustrative purposes only and are not part of the physical implementation.

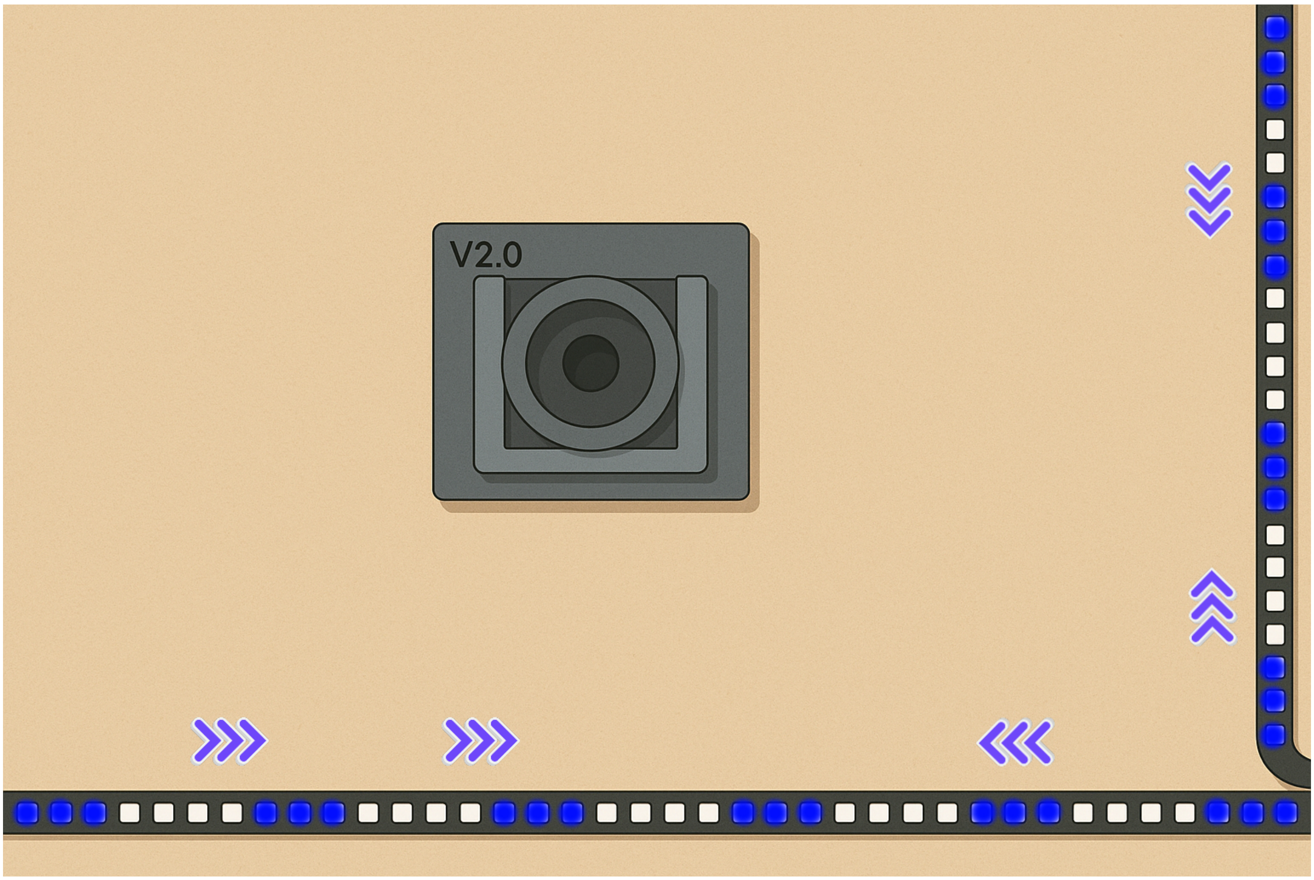


Figure 3.20: Illustration of the Flow Light system

3.5.4 Gradient

The Gradient guidance system visualizes a color transition along the LED strips, moving from red at the edges toward green at the target location. A sharp cut-off ensures that only the LEDs at the exact assembly location are fully green, clearly indicating the intended placement point.

Figure 3.21 illustrates the Gradient Light system.

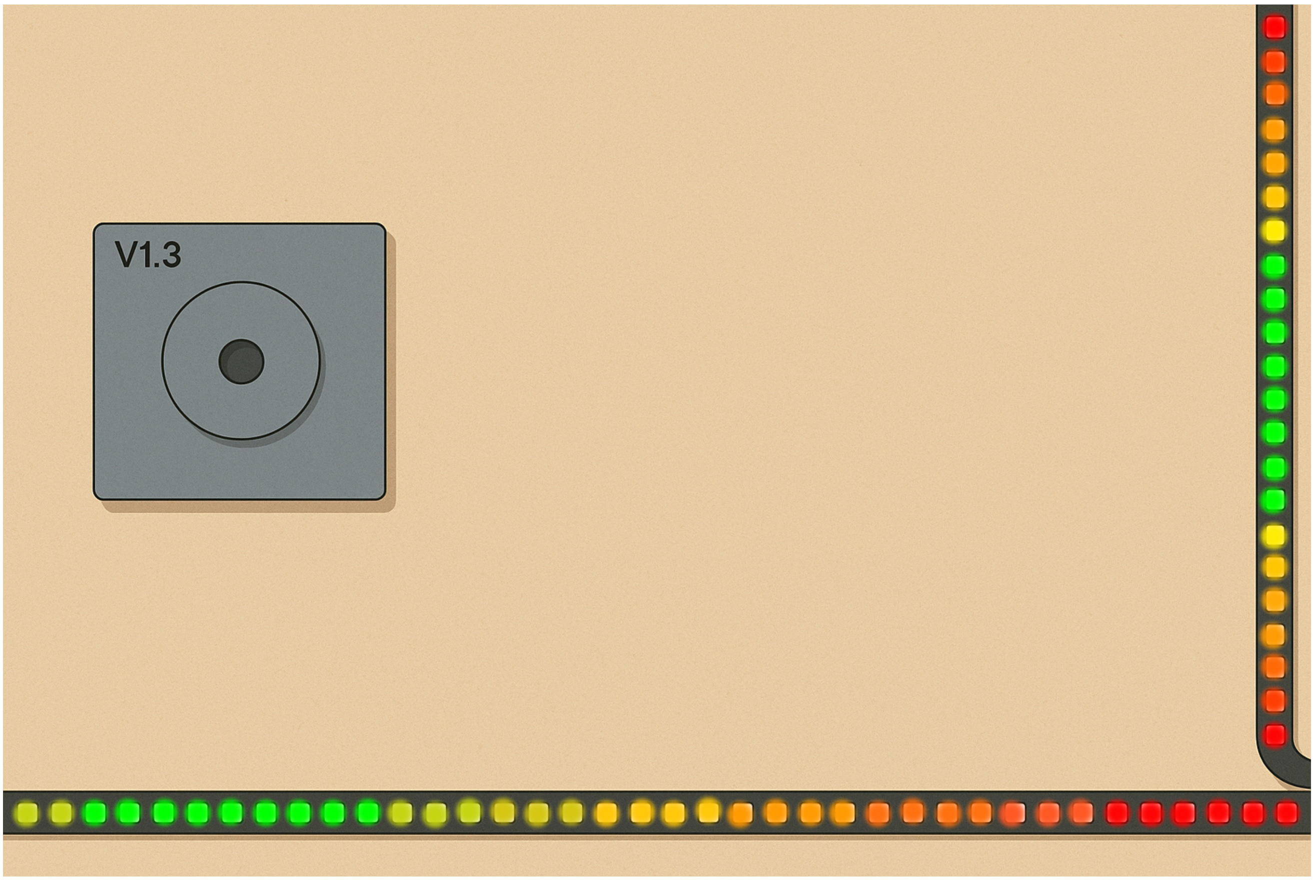


Figure 3.21: Illustration of the Gradient Light system

3.6 Haptic Assembly Assistance

The haptic system is based on a vibrating smartwatch that provides feedback proportional to the QoW score (explained in Section 3.5.2). Figure 3.22 illustrates the Haptic Assembly Assistance. On the left, a user is shown wearing a smartwatch that vibrates strongly, with the watch face displaying a large green circle, indicating close proximity to the target location. On the right, the smartwatch vibrates with lower amplitude and frequency, and the watch face displays a smaller green circle, reflecting the user's greater distance from the target location.

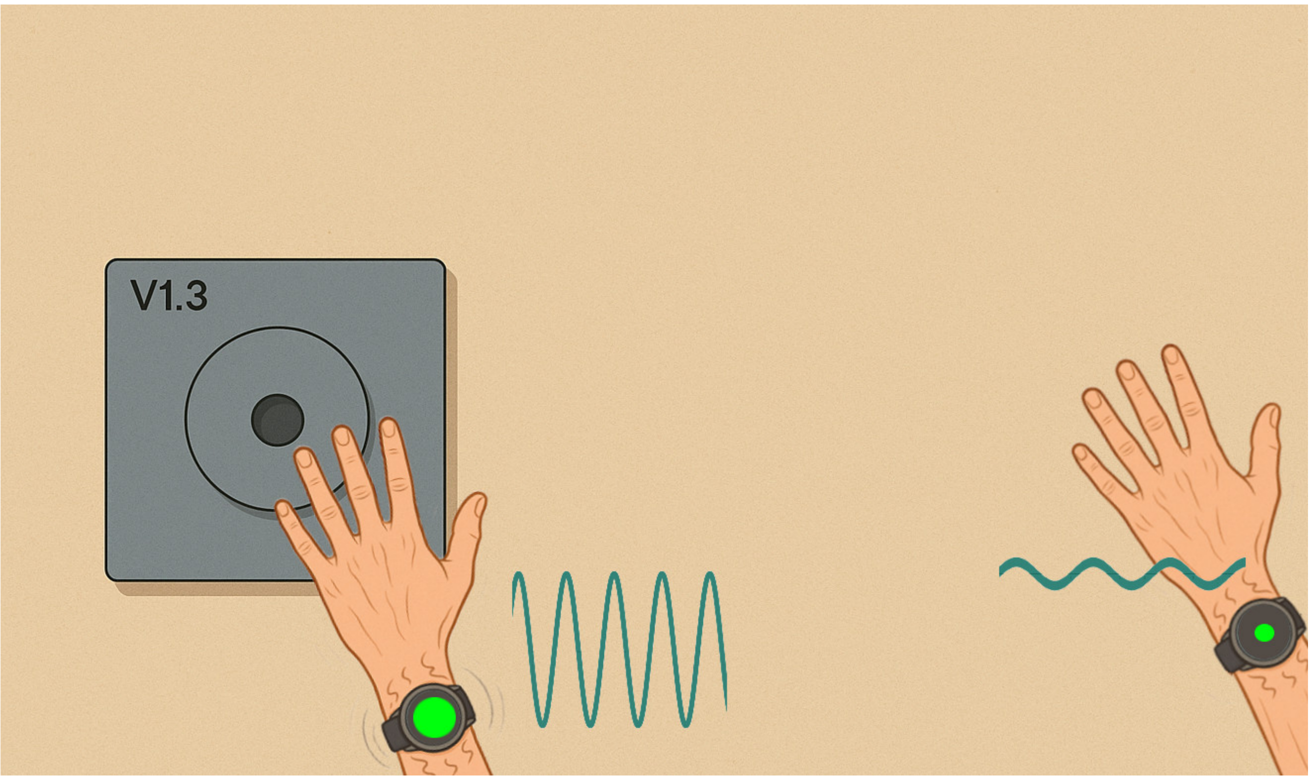


Figure 3.22: Illustration of the Haptic Assembly Assistance

3.6.1 Haptic System Architecture

To achieve low latency and reduce the computational load on the wearable, the system is divided into two modules: an Android companion application and a WearOS watch application both developed using Android Studio. This separation leverages the strengths of each device and supports efficient communication through the Wearable Data Layer.

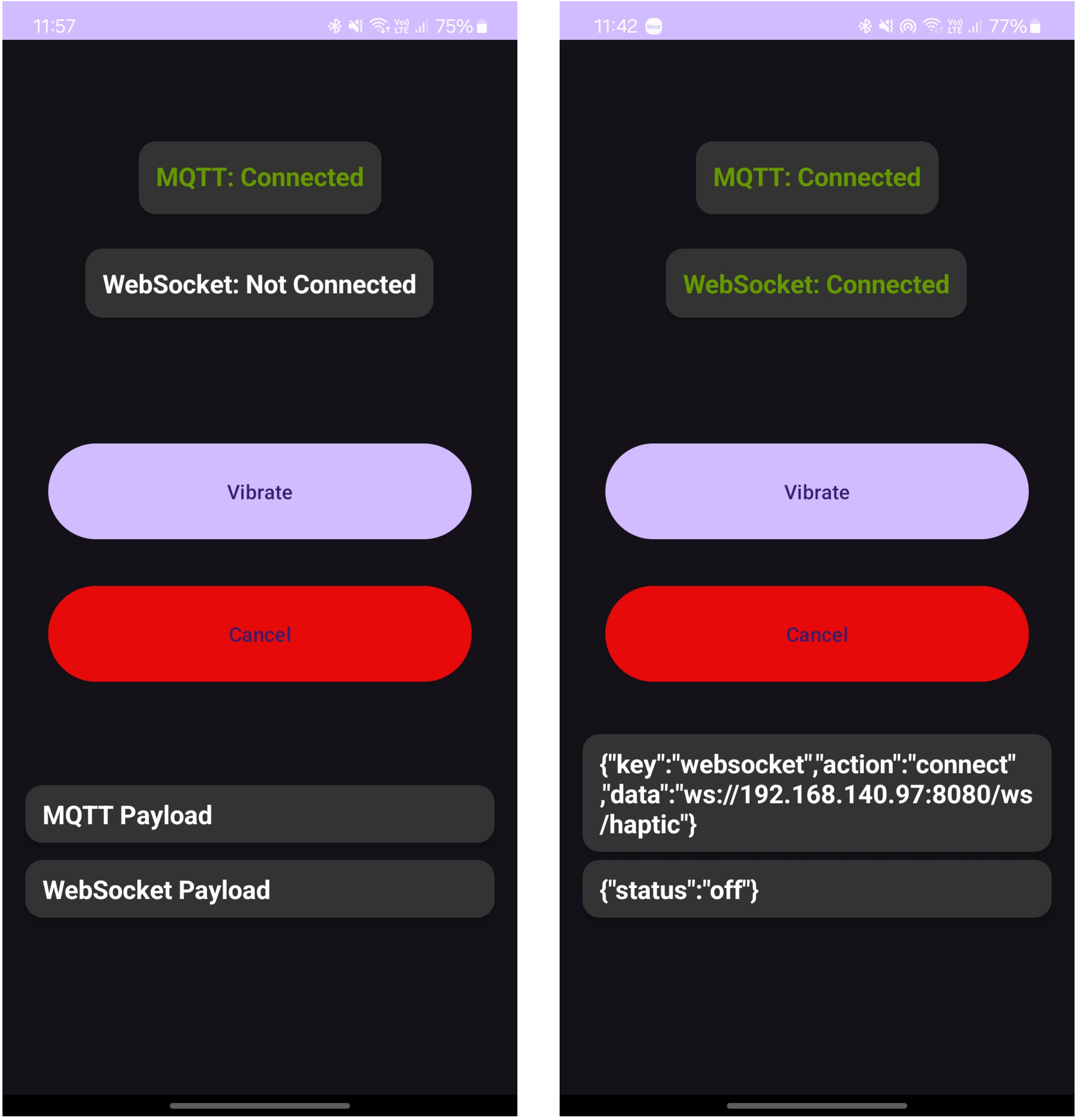
Smartphone Companion Application

The companion app is responsible for all network-intensive operations. It maintains a persistent WebSocket connection with the DWI Application (see Section 3.2), receives vibration instructions in JSON format, and transmits the essential haptic parameters, vibration amplitude (ranging from 0 to 255) and vibration ratio (defined as the proportion of vibration to non-vibration time over a fixed interval, scaled between 0 and 100), to the smartwatch. These parameters are derived from the QoW score (explained in Section 3.5.2).

Communication with the watch is managed via the Wearable Data Layer [28], which abstracts connection handling and message delivery. The companion app performs the following actions:

- Connects to the HiveMQ MQTT server.
- Receives the WebSocket endpoint via MQTT to establish a connection with the DWI Application.
- Discovers available nodes to identify the connected watch.
- Sends received vibration commands over a dedicated path (e.g. `/vibrate`) to the smartwatch.
- Relies on best-effort delivery, with high update frequency ensuring the watch always reflects the most recent state.

Figure 3.23 displays the interface of the companion application. It provides debug information, including the status of the MQTT and WebSocket connections, the received payload, and control buttons for triggering and canceling vibration. This interface is intended for debugging rather than end-user interaction.



(a) Companion app view during setup

(b) Companion app view while running

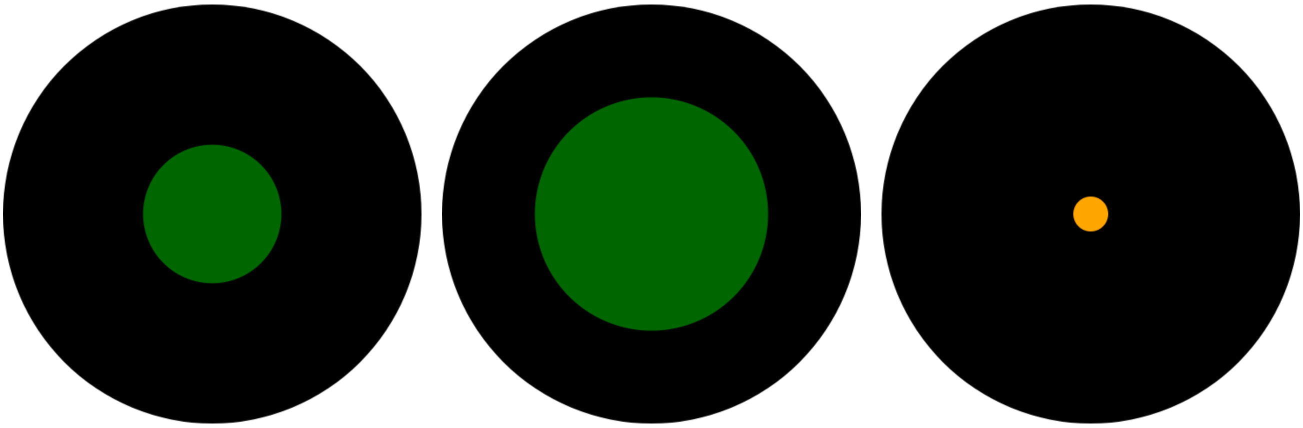
Figure 3.23: Two states of the Haptic Companion Application

WearOS Watch Application

The WearOS application is designed for minimal overhead and real-time responsiveness. It performs two core tasks:

- **Message Reception:** Listens for updates on a predefined Data Layer path (e.g. `/vibrate`) and extracts incoming amplitude and frequency values.
- **Vibration Control:** Uses the built-in `Vibrator` service to emit one-shot pulses at the received amplitude. These pulses repeat at a fixed interval until a new command is received or vibration is canceled.

Figure 3.24 shows the different states of the smartwatch display. Subfigure 3.24a corresponds to the state when the user is far from the target location, similar to the hand on the right side in Figure 3.22. Subfigure 3.24b shows the display when the user is near the target location, similar to the hand on the left side in Figure 3.22. Finally, Subfigure 3.24c presents the display when the haptic assistance is inactive.



(a) Low QoW (b) High QoW (c) Inactive

Figure 3.24: Smartwatch display during different vibration intensities

3.7 Hand Tracking

The Hand Tracking component is responsible for detecting, tracking, and interpreting hand positions in real time using a 720p webcam mounted above the workspace.

3.7.1 Hardware

Figure 3.25 and Figure 3.26 show the hand tracking setup and a render of the 3D printed camera holder, respectively.

Figure 3.25: Illustration of the Hand Tracking setup

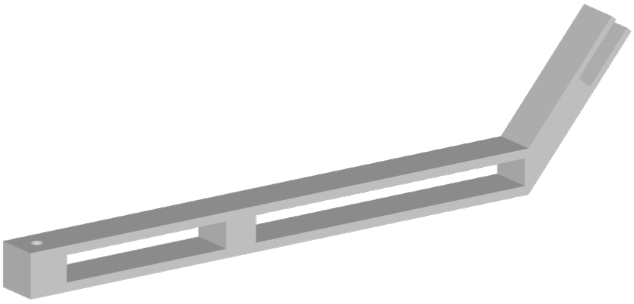


Figure 3.26: 3D render of the custom camera holder

3.7.2 Software

This module uses MediaPipe Hands, an open-source framework developed by Google [29], which leverages machine learning to identify 21 anatomical landmarks per hand and classify them as either “Left” or “Right” (see Figure 3.27). The MediaPipe pipeline is integrated into the system using Python, and OpenCV [30] is used for video input, rendering, and visualization.

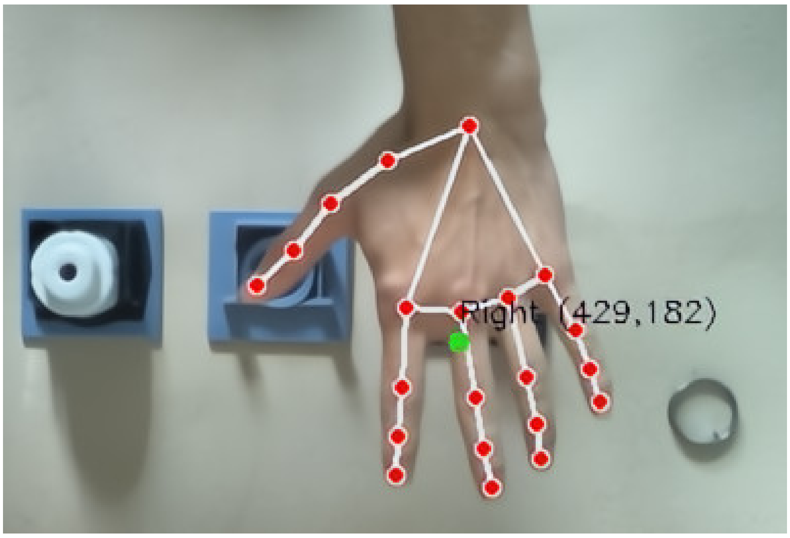


Figure 3.27: Tracked hand with landmarks and average position

The hand tracking pipeline works as follows:

- Initializes the MediaPipe Hands model with confidence thresholds and hand limits.
- Captures frames from the camera input.
- Flips and color-converts frames as required by MediaPipe.
- Extracts hand landmarks and handedness for each detected hand.
- Converts each landmark to pixel coordinates and wraps them in a custom `Position` data class.
- Tracks when a hand was last seen; if a hand has remained undetected longer than a set timeout, it is marked as “unknown”.
- Sends the landmarks’ position to the DWI Application in JSON format via WS.
- Streams captured frames to the DWI Application as an MJPEG stream over HTTP.

To reduce unnecessary communication, updates are only sent when the hand state has meaningfully changed.

For debugging, the landmarks and hand labels are drawn onto the video stream using OpenCV, providing immediate visual verification of the detection results.

3.8 Cost Analysis

As low cost was a requirement for this implementation, Table 3.3 summarizes the cost of each system component. All prices are based on the Manufacturer's Suggested Retail Price (MSRP); actual prices may vary and could be lower in practice.

Table 3.3: System Cost Overview

Item	#	Unit cost	Total
Picking Bin			**47.08**
Obstacle Sensor	1	5,25	5,25
Bin Casing	1	1,49	1,49
LED Cluster	1	4,99	4,99
Display	1	5,29	5,29
Jumper Wires	13	0,06	0,78
ESP32	1	19,95	19,95
Breadboard	1	4,99	4,99
Power Cable	1	3,99	3,99
Separation Wall*	22 g	15,99/kg	0,35
Light-based Assembly Assistance			**88,69**
LED Strip	2	15,99	31,98
ESP32	1	19,95	19,95
Jumper Wires	8	0,06	0,48
ESP Power Cable	1	3,99	3,99
UBEC Buck Converter	1	16,30	16,30
Converter Power Cable	1	15,99	15,99
Hand Tracking			**25,59**
Webcam	1	14,99	14,99
Camera Holder*	38 g	15,99/kg	0,60
Tripod	1	10,00	10,00
Picking Bin	**8**	**47.08**	**376.64**
Light-based Assembly Assistance			**88,69**
Multi USB Charger**	**1**	**21,99**	**21,99**
Hand Tracking			**25,59**
Total***			**512.91**

Notes:

* The 3D-printed parts (Separation Wall and Camera Holder) are calculated by weight, using PLA filament priced at 15.99 €/kg.

** The Multi USB Charger can power up to 10 ESP32 devices. In the current system, 9 ESP32s are used: 8 for the picking bins and 1 for the LED strip.

*** The cost of the computer, Wear OS watch, and Android smartphone used for the DWI application and haptic assembly assistance is not included in this calculation.

3.9 Conclusion

This chapter presented the full implementation of a modular and configurable Digital Work Instruction (DWI) system designed for supported employment environments. Each subsystem was developed with a focus on low cost, ease of configuration, and effective physical guidance.

The **DWI Application** serves as the central platform, allowing non-technical staff to create, edit, and deploy structured, step-by-step instructions. A clear distinction was made between Picking and Assembly Instructions, each with tailored interfaces and functionalities.

The **Network Communication** architecture ensures reliable interaction between modules using MQTT for control and configuration messages and WebSockets for time-sensitive features such as live feedback and real-time LED animations.

The **Picking Assistance**, equipped with ESP32 microcontrollers, LED clusters, displays, and infrared sensors, supports pick-to-light functionality and part picking validation with minimal user input.

The **Light-based Assembly Assistance** utilizes WS2812B LED strips to visually guide users to the correct assembly location using four distinct patterns: Static, Live, Flow, and Gradient. These patterns provide layered feedback, from passive highlighting to active directional guidance.

The **Haptic Assembly Assistance** introduces vibrational feedback through a WearOS smartwatch, with intensity proportional to the user's proximity to the correct location. A companion smartphone app offloads communication and ensures low-latency responsiveness.

Finally, the **Hand Tracking** module, built with MediaPipe and OpenCV, captures and interprets hand position data to support real-time monitoring and enhance spatial feedback during task execution.

Together, these components form a cohesive system that supports accurate, autonomous, and user-friendly task execution for workers with diverse support needs. The implementation prioritizes modularity and accessibility, making it adaptable to a wide range of industrial and inclusive work environments. The following chapter will present the system.

Chapter 4

Experimental Evaluation

4.1 Introduction

To validate and review the system described in Chapter 3, it was deployed at the company site in Bewel, and participants were asked to perform the assembly of the product shown in Figure 4.1. The product consists of eight parts, and the assembly instructions consist of 21 steps: 8 picking instructions and 13 assembly instructions. The instructions were made using the DWI Application.

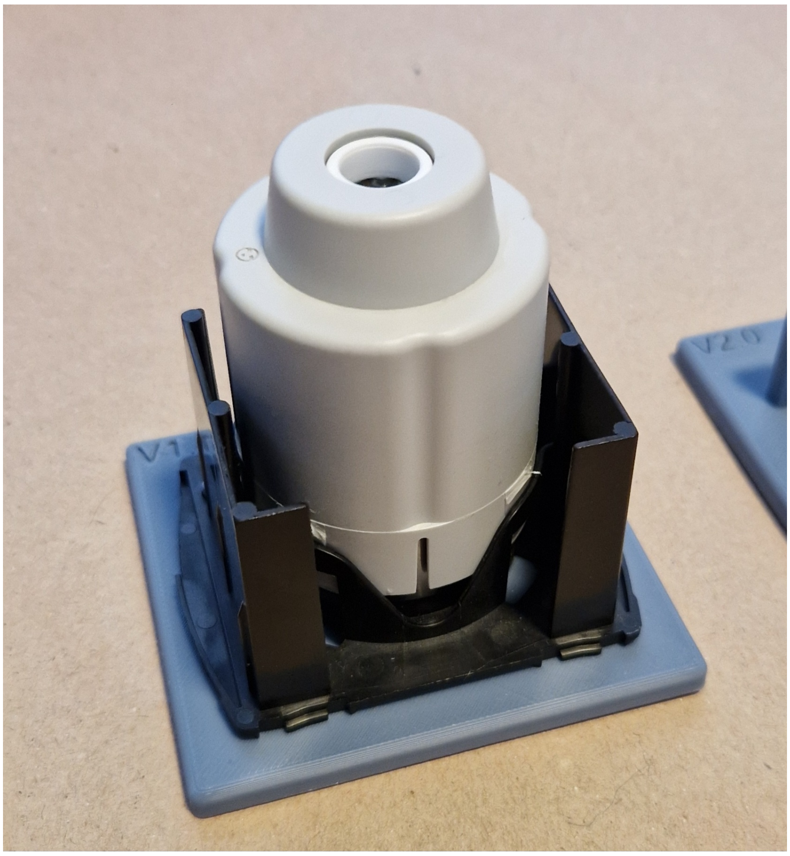


Figure 4.1: Assembled product used for user studies

4.2 Pre-Test: Assistance Mode Selection

To identify user preferences among the five assistance systems (Static Light, Live Light, Flow Light, Gradient, and Haptic), a pre-test was conducted. Customized workers at Bewel were instructed to locate a hidden position on the assembly table using each system and then rank the systems based on their preference. The results, presented in Table 4.1, reveal a preference order (from most to least favored) of: Static Light and Gradient, Haptic, and Live Light. The Flow Light system was explicitly indicated as the least preferred option.

Participant	Haptic	Live	Static	Flow	Gradient
P1	4	5	2	1	3
P2	3	4	5	1	2
P3	4	1	3	2	5
P4	5	1	4	2	3
P5	3	2	4	1	5
P6	4	5	3	2	1
P7	1	4	3	2	5
P8	3	2	5	1	4
P9	2	3	4	1	5
Total	**29**	**27**	**33**	**13**	**33**

Table 4.1: Results from the pre-test

4.3 Procedure

The system was evaluated with nine participants from Bewel. All participants had varying degrees of cognitive or physical support needs. At the start of the session, participants were welcomed and asked for their first name to facilitate communication; names were not recorded. Basic demographic information was collected, including age, gender, whether Dutch was their native language, and the number of years of work experience.

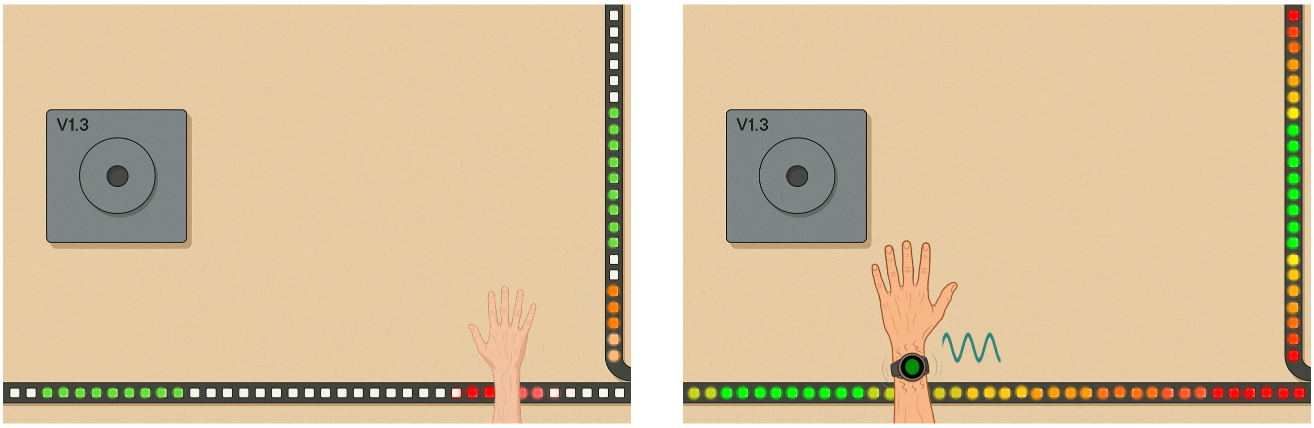
Next, participants were informed about the purpose of the study:

> "Today, we would like to observe how you complete a simple assembly task using digital work instructions. We have developed three different variants of the instruction system, each providing information and guidance in a unique way. We are interested in how you experience these systems and what you think of them. There are no right or wrong answers, and no prior knowledge is required, we are simply observing how you interact with the systems."

Participants completed the previously described assembly task three times, once under each of the following assistance configurations:

- **DWI-only**:
  - Digital Work Instructions (DWI) shown on the display.
  - No additional picking or assembly assistance.
- **Static** (see Figure 4.2a):
  - DWI combined with Picking assistance (see Section 3.4).
  - Static 3.5.1 and Live 3.5.2 Assembly Assistance.
- **Gradient** (see Figure 4.2b):
  - DWI combined with Picking assistance 3.4.
  - Gradient 3.5.4 and Haptic 3.6 Assembly Assistance.

This grouping was informed by the pre-test results (see Section 4.2) and the observation that Static and Live Light work well together, as do the Gradient and Haptic systems.



(a) Static + Live Light Assembly Assistance (b) Gradient + Haptic Assembly Assistance

Figure 4.2: Illustrations of the two Assembly Assistance configurations.

A within-subjects design was used, where each participant experienced all three assistance conditions. To minimize learning and fatigue effects, the order of the conditions was counterbalanced across participants:

- Participants 1–3: DWI → Static → Gradient
- Participants 4–6: Static → Gradient → DWI
- Participants 7–9: Gradient → DWI → Static

For each of the three conditions, the following steps were followed:

1. The video recording was started.
2. The corresponding system was activated.
3. The video recording was stopped after task completion.
4. The participant completed the UEQ+ for that configuration.
5. The time taken to complete the task was recorded.

4.3.1 Data Collection

For each trial, the following metrics were recorded:

- **Task Completion Time**: Measured in seconds from instruction start to task confirmation (automatically captured by the system).
- **UEQ**: User Experience Questionnaire
- **Semi-structured interview**: Qualitative feedback

User Experience Questionnaire

To quantitatively assess user experience across the three different assembly assistance systems, the *User Experience Questionnaire* (UEQ) [31] was administered after each trial. The UEQ captures users' impressions based on six dimensions:

- **Attractiveness**: Overall impression of the product.
- **Perspicuity**: Ease of understanding and becoming familiar with the system.
- **Efficiency**: Ability to perform tasks quickly and without unnecessary effort.
- **Dependability**: Perceived control and predictability of the interaction.
- **Stimulation**: Level of motivation and excitement induced by the system.
- **Novelty**: Perception of innovativeness and creativity.

Participants responded to 26 bipolar items using a 7-point Likert scale [32] ranging from –3 (completely disagree) to +3 (completely agree).

The UEQ was chosen for its validity in evaluating interactive systems. Responses were collected on paper and processed using the official UEQ Data Analysis Tool to generate standardized scores for each of the three tested variants of the assistance system.

Semi-Structured Interview

After the participant had tested all three variations of the assistance system, they were asked a series of semi-structured interview questions to gain deeper insights into their experiences, preferences, and the perceived clarity and effectiveness of each variant. The questions were grouped into thematic categories to facilitate open discussion and allow participants to elaborate on their answers. The applied thematic categories and their composing predefined questions are described below.

Initial Impressions and Clarity

- How did you like working with this system?
- What was the first thing that stood out to you when you saw the system?
- Was it clear to you what you had to do?
- Were there moments when you were unsure if you were acting correctly?
- Was there anything you found confusing?

Independence and Confidence

- Did you feel you could work independently, or did you need extra explanation?
- Did the system make you feel confident in performing your actions?
- What would help you feel more confident while using the system?
- Did you need help at any point?

Support and Guidance

- Did you feel that the system guided you well?
- Did the system ever distract you or feel disruptive?
  (e.g., lights were too bright, unexpected haptic feedback startled you, etc.)

Overall Preferences and Usability

- Which system did you find most pleasant to use? Why?
- Did any of the systems feel faster or easier to use than the others?
- If you could choose, which system would you prefer to work with?

Long-Term Use and Suggestions

- For each of the three tested variants: Can you imagine using this system for a full workday, and over multiple days?
- Would you prefer to use this system only temporarily, for example, just to learn the task initially?
- Do you see other ways to support users through LED or haptic feedback?

Chapter 5

Results

This chapter presents the results of the user evaluation described in Chapter 4, including task performance, user experience scores, and qualitative feedback.

5.1 Task Completion Time

Table 5.1: Average Picking and Assembly Time (seconds) per Participant and System

	Picking			Assembly		
Participant	**DWI**	**Static**	**Gradient**	**DWI**	**Static**	**Gradient**
P1	5.12	2.96	3.05	5.42	3.26	3.55
P2	4.07	2.98	3.79	4.37	3.28	4.29
P3	3.84	3.12	3.08	4.14	3.42	3.58
P4	3.66	3.31	4.12	3.96	3.61	4.62
P5	3.62	4.41	4.26	3.92	4.71	4.76
P6	3.61	3.33	4.18	3.91	3.63	4.68
P7	3.52	2.89	2.99	3.82	3.19	3.49
P8	3.60	5.14	3.23	3.90	5.44	3.73
P9	4.60	3.92	3.23	4.90	4.22	3.73
Average	**3.96**	**3.56**	**3.55**	**4.26**	**3.86**	**4.05**

Table 5.1 presents the average picking and assembly times (in seconds) per participant for the three tested configurations: DWI-only, Static + Live with Picking Assistance, and Gradient + Haptic with Picking Assistance.

Picking times. Picking performance improved with assistance. The average picking time decreased from 3.96 seconds (DWI-only) to 3.56 seconds with Static and 3.55 seconds with Gradient. This demonstrates that both assisted configurations helped participants locate the correct bin more quickly.

Assembly times. Assembly times followed a similar trend. The Static Light configuration yielded the fastest average assembly time (3.86 seconds), followed by Gradient (4.05 seconds), with DWI-only being the slowest (4.26 seconds). These results indicate that visual guidance (Static) was particularly effective in accelerating part placement. The Gradient system also outperformed the unassisted DWI baseline, although it was slightly slower than Static on average.

Since the order of conditions was counterbalanced across participants, ensuring that learning effects are unlikely to have influenced these results.

Interpretation. Both assisted configurations, Static + Live with Picking Assistance and Gradient + Haptic with Picking Assistance, provided measurable efficiency gains over the DWI-only system, particularly in the picking phase. Since both assisted conditions used the same Picking Assistance, this explains why their average picking times are nearly identical. The differences between Static and Gradient arise from the assembly-phase assistance (Static + Live Light vs. Gradient + Haptic), which does not affect picking performance.

The Static configuration produced the most consistent time reductions across both tasks. However, a few participants (e.g., P8) showed longer times with this configuration, even though it was performed last. This suggests that the higher times were unlikely due to learning effects, but may reflect individual interaction challenges or fatigue.

5.2 User Experience Questionnaire (UEQ)

The User Experience Questionnaire (UEQ) was used to evaluate six key dimensions of user experience across the three tested system configurations. Each dimension is scored on a scale from -3 (very negative) to $+3$ (very positive). A score above $+0.8$ is considered a clearly positive evaluation, while scores below -0.8 indicate a clearly negative evaluation [31].

Figure 5.1 presents the average UEQ scores per dimension and configuration.

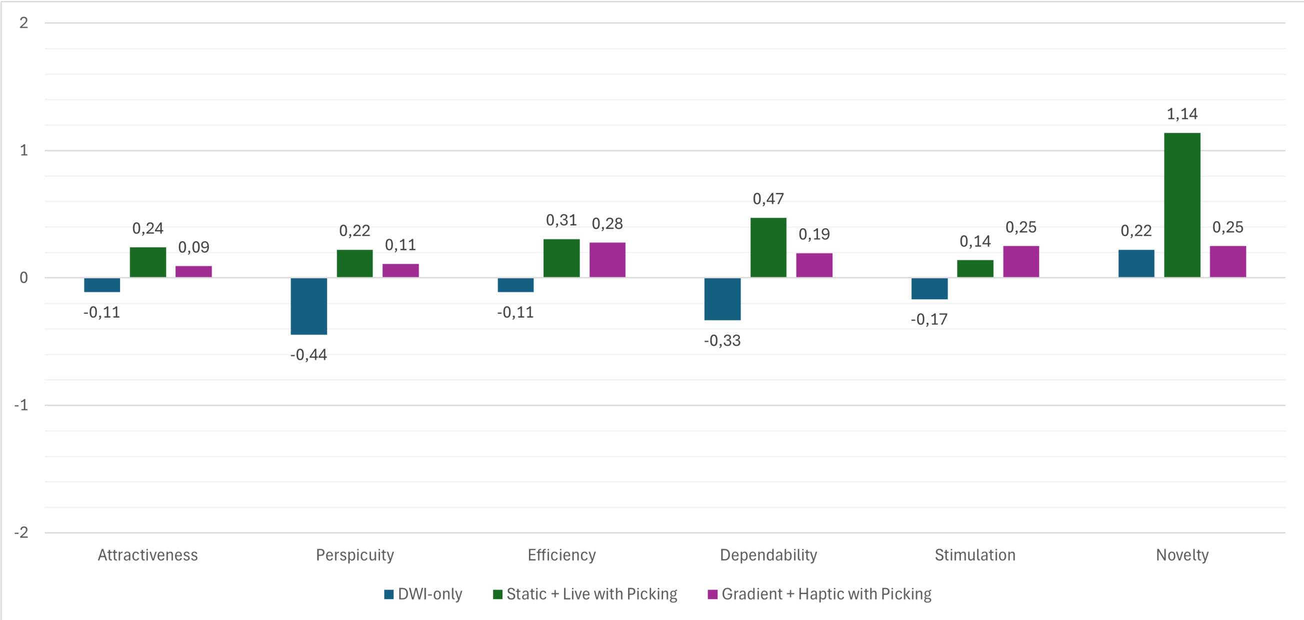


Figure 5.1: Mean UEQ Scores per Dimension for Each System

DWI-only. The DWI-only system received the lowest scores across all dimensions. In particular, *Perspicuity* scored -0.44, indicating that participants found this system difficult to understand or learn. In addition, *Attractiveness* (-0.11), *Efficiency* (-0.11), *Dependability* (-0.33), and *Stimulation* (-0.17) also scored negatively. All dimensions remained well below the $+0.8$ threshold, suggesting a neutral to slightly negative overall user experience.

Static + Live. This configuration received the most favorable evaluations overall. All six dimensions were rated positively, with *Novelty* scoring $+1.14$, surpassing the positive threshold. High scores were also observed for *Dependability* ($+0.47$), *Efficiency* ($+0.31$), and *Attractiveness* ($+0.24$), indicating that users felt more in control and able to complete tasks effectively. The increase in *Perspicuity* ($+0.22$) also suggests improved clarity and ease of use.

Gradient + Haptic. This system achieved strong ratings for *Efficiency* ($+0.28$), reflecting high perceived task effectiveness. *Stimulation* ($+0.25$) and *Novelty* ($+0.25$) were also positively rated, suggesting that the system contributed to an engaging and innovative experience. However, *Attractiveness* ($+0.09$), *Perspicuity* ($+0.11$), and *Dependability* ($+0.19$) scored lower than the Static + Live configuration, indicating slightly reduced clarity (Perspicuity) and predictability (Dependability).

Summary. All assisted configurations outperformed the DWI-only system across all dimensions. Among them, the *Static + Live* configuration achieved the highest ratings across all six dimensions, surpassing the *Gradient + Haptic* configuration. These results confirm that multimodal guidance enhances user experience.

5.3 Qualitative Feedback

Following each session, participants were asked a series of semi-structured interview questions to gain qualitative insights into their experience with the different assistance systems.

DWI without Assembly Assistance. Most participants (8 out of 9) described the DWI-only configuration as confusing and lacking in guidance. There was frequent uncertainty about the correct placement of components, particularly during the initial steps. The system was generally perceived as insufficient for independent work, with several participants (7 out of 9) indicating a need for additional explanation or external assistance. While one participant mentioned that the on-screen images provided some guidance, the overall consensus was that the system alone did not offer enough support. A few participants felt the DWI could be suitable for initial training, but not for sustained daily use.

Picking Assistance. The Picking Assistance was identical in both the Static + Live Light and the Gradient + Haptic configurations, and participant feedback on this component was highly consistent across both conditions. Most participants (7 out of 9) explicitly described the pick-to-light system as helpful, clear, and efficient. Several noted that it enabled them to locate parts more quickly and work more independently compared to the DWI-only condition. No participants reported negative experiences with the picking support.

Static + Live Assembly Assistance. This configuration received near-unanimous praise from participants (8 out of 9). The system was described as clear, calm, and non-distracting. The Static Light instructions alone were generally considered sufficient; the Live Light component was rarely needed or used. Several participants indicated that this configuration allowed them to perform the assembly steps quickly and with high confidence. No participants reported distraction or overload. One participant suggested that mounting the LEDs above the work surface could further improve visibility, as their hand occasionally blocked the light.

Gradient + Haptic Assembly Assistance. Opinions on the Gradient + Haptic configuration were more mixed. The haptic feedback was described as “pleasant” or useful by some participants (3 out of 9), particularly when used as confirmation of correct actions. However, some (2 out of 9) found the vibrations unnecessary or distracting, especially in combination with the visual guidance. The gradient lighting received more critical feedback: some participants (3 out of 9) described it as “too busy” or visually overwhelming. A few participants noted that the gradient could support learning after a short adaptation period, but for extended use, simpler visual guidance was generally preferred.

Chapter 6

Conclusion

This thesis presented the design, development, and empirical evaluation of a modular Digital Work Instruction system with Assembly Assistance designed to provide step-by-step guidance in a low-threshold and accessible manner. The system integrates three key components: a DWI application for creating and displaying instructions, a pick-to-light system with automatic part-picking verification, and an assembly assistance system utilizing light and haptic feedback. Throughout the design, particular attention was given to achieving a cost-effective solution, ensuring that both the overall system remains affordable and practical for deployment in sheltered workshop environments such as Bewel.

The empirical evaluation demonstrated that the pick-to-light system is a highly effective aid in supporting customized workers of sheltered workplaces during the part-picking phase. Its modular design allows it to function as a standalone component, making it equally suitable for order-picking contexts beyond assembly environments (e.g., in warehouses).

The results further suggest that assembly assistance can be valuable, but that excessive support may overwhelm the user. Systems offering minimal yet clear guidance, such as Static Light assistance, were most favorably received. These findings underscore the importance of maintaining clarity without overstimulation of the human senses. While the Haptic system was at times perceived as too intrusive, it proved useful as a confirmation signal, highlighting its potential application in other domains such as order-picking, where discreet feedback can confirm task completion.

Although the Flow Light system was less frequently used due to the adequacy of the Static Light guidance, it opens possibilities for future research. In particular, dynamic directional cues could be extended through augmented reality to provide immersive and continuous spatial guidance.

In conclusion, this thesis contributes a flexible and user-centered approach to digital work instruction, combining low-cost hardware with adaptable software to support assembly workers with varying needs. The results confirm that careful integration of assistance modalities, tailored to the context and user profile, is key to effective and inclusive task support.

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