A Wearable Pick-By-Haptics System to Improve Manual-Picking Tasks in Warehouses

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***Abstract*— This paper presents a novel pick-by-haptics approach to assist workers in manual picking in warehouses. The idea is to equip the worker with a wearable system composed by a vibromotor, a Radio Frequency IDentification (RFID) reader and a microcontroller, all placed on the user's forearm, and exploit it to reveal the correct locations of the items to pick. The system results very intuitive to use as proved by a user study involving 13 subjects that simulated the picking of a list of items. Moreover, the structural setup of the warehouse necessary to implement the pick-by-haptics approach resulted very quick and costly efficient if compared with the current state of the art solutions for workers assistance. The work was motivated by a collaboration with a company that produces controllers for automated plants. The next step of this research will be an experimental campaign in the real warehouse.**

Fig. 1: Real warehouse scenario. Pictures courtesy of GElettric s.r.l. (Siena, Italy).

I. Introduction

Manual picking in warehouses is widely considered to be one of the most physically challenging and economically expensive activity [1]. Due to recent developments in both manufacturing and warehousing, it has become even more imperative to increase efficiency and flexibility in the handling of ordered products. In addition to the potential time-saving benefits, the use of technological support for workers also promises to reduce the number of errors in picking the items. Minimising errors is especially crucial in processes where collected items are later assembled, and the selection of an incorrect component can lead to problems that are difficult to detect. For instance, during the assembly of electric panels, the incorrect choice of a fuse may prove difficult to detect after the full system has been assembled. Additionally, selecting the wrong fuse is a frequent mistake since all fuses have the same shape, a similar product code and are usually stored in a common location of the warehouse.

To address these challenges, new and advanced systems have been developed in recent years, incorporating various technological innovations to support pickers in their work [2] also leading to commercial assistive technologies [3]. The three most commonly utilized solutions fall into three categories: pick-by-voice, pick-by-light, and pick-by-scan. The pick-by-voice system simplify the warehouse picking process by allowing employees to communicate wirelessly with the warehouse management system through a headset. The system initiates the process by assigning a picking task and providing clear, step-by-step guidance, including the location of the items, identification numbers, and required quantities. Throughout the process, the worker is prompted to confirm each step by saying a predefined keyword out loud, thus signalling the completion of one task and the initiation of the next. Although this solution guarantees freedom of motion and few picking errors, it implies a high maintenance overhead and it is too costly for small or very specialized warehouses. An alternative approach to guiding workers is to use light signals displayed on the warehouse racks to indicate the exact items and quantities needed. After the worker has retrieved the specified items, they can confirm completion of the task by pressing a button on the display. This allows the warehouse management system to promptly update the inventory quantity values. The reverse process, known as "pick-by-light", operates similarly, with the worker confirming the placement of items by pressing the button on the display. Combining these two processes can significantly enhance accuracy and efficiency in the warehouse. However, also this solution require a high structuring of the warehouse resulting too costly for small or very specialised warehouse.

Finally in pick-by-scan systems, the picking process is facilitated by using a hand-held device equipped with a 1D or 2D barcode scanner. This mobile device serves as a digital picking list, providing the worker with guidance to the various storage locations. Unlike traditional paper picking lists, the information is captured and stored electronically.

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The data can either be stored locally on the hand-held device or transmitted wirelessly through the network from the warehouse management or enterprise resource planning system in real-time. This enhances efficiency and accuracy in the picking process, but significantly limits the worker mobility. One interesting recently proposed solution merges a pick-by-light solution with a RFID reader resulting in an optimization of the picking process with a reduction of human errors through real-time control and alert features [4], [5]. However, also in this case the setup of the system results complex and not very flexible to possible rearrangements in the items locations. Furthermore, a recent investigation presented in [6] demonstrated that auditory error feedback, although only noticeable when standing at the workstation, significantly violates workers' privacy, suggesting as the best solution a combination of haptic and visual feedback to communicate errors at the workstation while preserving workers' privacy. Finally in [7], the authors demonstrated that in the case of the multilevel picking shelving similar to that of our target real use case (see Fig. 1), the most convenient technology to be used is based on a RFID system.

Based on the aforementioned motivations, we developed a system in order to introduce the novel concept of pick-by-haptics. The idea is to exploit the combination of RFID systems and haptic feedback to assist the workers during manual picking. We tested our solution with 13 individuals in a simulated warehouse environment (see Fig. 3). Initial findings show the user-friendliness of the technology and its positive impact on task completion time and reduction of picking errors.

The rest of the paper is organised as follows. Section II describes our novel device and the rationale which motivated us to choose the system components, in Section III we present our experimental setup and guide the reader through the experimental protocol we followed. In Section IV we describe how we collected and analysed data, and the result of statistical analysis. Finally, in Section V we summarize our findings.

II. Proposed System

To validate the hypothesis detailed in the introduction, we realized a wearable device that fits on the wrist and forearm of the user, as shown in Fig. 2.

The device is a custom bracelet that embeds a liquid crystal display (LCD), a Near Field Communication (NFC)[1] card reader, and a vibromotor. We designed this device to aid users in selecting items from an industrial warehouse. The LCD provides a list of objects that the user has to pick, and the NFC card reader is used to check if the box where the users was inserting their hand corresponds to a container with the desired item in it. The device is equipped with a vibromotor to provide haptic feedback to the user. Its goal is to enhance the user experience and ensure accuracy in item selection.

[1]Near-field communication (NFC) is a set of communication protocols based on existing radio-frequency identification (RFID) standards that enables communication between two electronic devices over a distance of 4 cm.

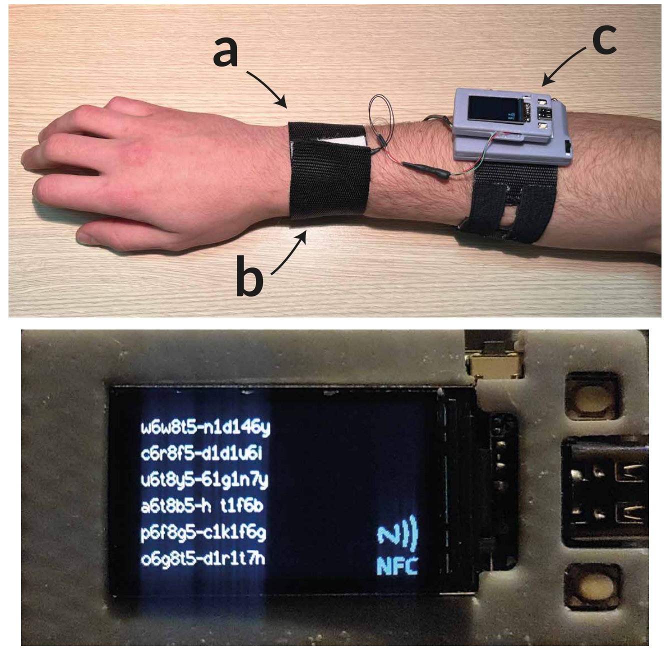

Fig. 2: Detail of the LCD screen and components of the wearable device. a) vibromotor; b) NFC card reader; c) control box with LCD and battery.

This setup allowed for a convenient and efficient method for item selection in industrial warehouses.

The NFC card reader uses the PN532 Near Field Communication controller of NXP semiconductors which communicates via Serial Peripheral Interface (SPI) communication protocol with a TTGO T1 display board that runs on an ESP32 chip as a microcontroller. The reader can scan ISO/IEC 14443 Identification cards called proximity integrated circuit cards (PICC). When in use, the proximity card is positioned near the reader, activating the reader to provide power to the card and establish a communication connection. The card's unique identifier is then transmitted back to the reader, which checks the identifier against a list of authorized cards. Based on the authorization level of the cardholder, the reader either grants or denies access in a matter of seconds, providing a fast and seamless method of access control without the need for physical contact between the card and the reader. We utilized this verification method of proximity to assess whether the user, equipped with our device, inserted their hand into a designated storage bin in whose opening we placed an NFC card. To provide the haptic feedback to operators we used a Pico Vibe Pancake Coin Vibromotor (Precision Microdrives Model No. 310-103.005, 10mm Vibration Motor) driven with a BJT and pulse width modulation (PWM).

Having a system that utilizes passive proximity cards as opposed to traditional light-based systems provides several advantages. With the use of proximity cards, there is no need to install electrical power in each storage bin, making it a more cost-effective solution. The passive nature of the cards also eliminates the need for frequent battery replacements and maintenance, making it a more reliable solution in the

Fig. 3: Laboratory simulated warehouse environment.

Fig. 4: Detail of the standard storage bin with a labeled NFC card.

long run.

Integrating the NFC reader with a high-performance microcontroller such as the ESP32, which has both WiFi and Bluetooth capabilities, enabled the realization of a wearable device with real-time functionality for our application. Additionally, we used the ESP-NOW communication protocol to transmit data from the device to a dongle physically connected to the USB port of a computer, providing robust wireless transfer of information.

The vibrotactile kind of haptic sensory feedback allows for a more discreet and less distracting notification, as there is no need for visual indicators such as lights. When the user's hand goes inside a specific storage bin, the vibromotor will activate, providing a tactile cue to the user, thereby enhancing their awareness of the picking process if this vibration is associated with a specific meaning (e.g., this storage bin is hosting the wrong parts).

We tested the device final specifications and our wearable reader is able to scan a RFID card from $7\,\mathrm{cm}$ and below and the time which elapses from the RFID scan and the feedback actuation in approximately $50\,\mathrm{ms}$, i.e. the time of execution of the main loop of the microcontroller, plus the onset time of the vibromotor which is $40\,\mathrm{ms}$ by datasheet.

III. Experimental setup

To build the experimental setup, we used 12 standard stackable bins to simulate a warehouse environment. As shown in Fig. 3, we arranged those bins forming a grid of three columns and four rows. This configuration allowed for a manageable number of storage bins while providing a representative warehouse setup for testing purposes.

To reproduce the stress situation, which could lead to errors in picking parts, we labeled the storage bins with an alphanumeric string containing 14 characters. The label design, shown in Fig 4, intends to resemble those commonly found in industrial settings and to induce the stress that may lead to picking errors in a real-world scenario.

The labels on the storage bins were designed to be similar but with very subtle variations, such as:

p6f8g5-c1k1f6g

g6r8y5-n1d146g

This design aimed to replicate the typical challenges faced in a real-world warehouse scenario, where the labels may have slight differences but still need to be accurately recognized and differentiated by the user. This labeling pattern allowed for a realistic evaluation of the device's ability to assist the user in correctly identifying the storage bin.

To execute the protocol for the experimental setup, i.e. to control the custom wristband and to collect and analyse the experimental data, we chose LabVIEW 2020. The utilization of LabVIEW facilitated a resilient and versatile approach to protocol implementation, enabling real-time control of the experiment and accurate data acquisition and analysis.

In our experimental protocol, the user is seated in front of a desk with twelve storage bins and a keyboard placed over it. Before the experiment begins, after a brief demonstration on how the device works, the experimenter was given time to test and train the system for 3 minutes to familiarize with the system. Once ready, the experimenter updates the list of six designated storage bins on the device's LCD screen. The user initiates the experiment by pressing a key on the keyboard, which starts a chronometer with a millisecond resolution in LabVIEW. The objective is to pick a small cardboard box from each of the six designated storage bins and place it

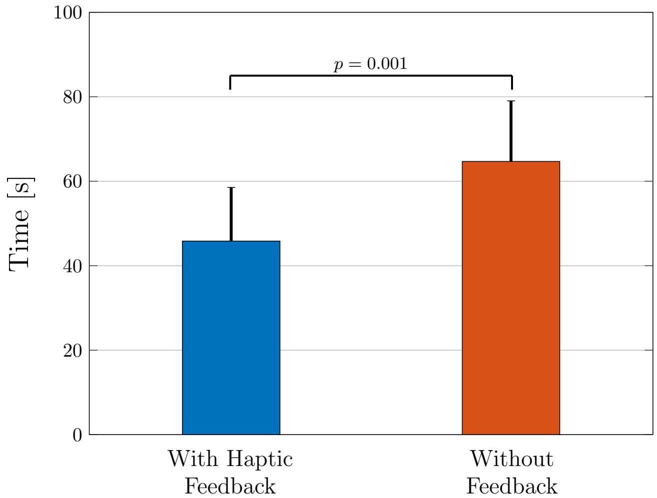

Fig. 5: Comparison of task completion time in haptic feedback-assisted picking versus non-feedback conditions.

User ID	Task completion time (s) With Haptic Feedback	Task completion time (s) Without Feedback	VAS
1	49.01	67.89	7,4
2	48.43	71.67	8,5
3	45.46	68.49	8,1
4	37.35	37.82	7,3
5	36.44	45.95	7,8
6	42.19	88.71	7,9
7	54.13	74.45	8,1
8	31.51	59.95	7,7
9	65.10	84.65	7,9
10	37.11	54.90	7,8
11	75.27	63.86	2,2
12	39.43	53.70	5,9
13	34.48	68.90	6,8

TABLE I: Average task completion time with and without feedback and Visual Analog Scale for each participant.

on the desk. Once all six cardboard boxes are on the desk, the user must press a key on the keyboard to stop the time count and end the experiment. Each participant repeated the experiment six times, with three trials conducted with the help of haptic feedback from the device and three without it. The vibration frequency of the motor was set to 200 Hz since the maximal sensitivity of the human skin is achieved around 200-300 Hz [8] (the human sensitive range is between few Hz to almost 1 kHz). The amplitude, and thus the 200 Hz frequency of the vibration, was determined by properly setting the PWM control signal. Two different patterns were designed to communicate the user if the selected box is the correct one or not. In the case of correct selection, a single burst lasting 400 ms was delivered. Conversely, a pattern consisting in 2 pulses with a duration of 400 ms and an inter pulse interval of 400 ms was selected [9] as a signal for alerting the user of a wrong choice. This condition differentiation allowed us to compare and analyze the task completion time difference between the conditions of haptic feedback-aided picking and the condition of no feedback.

IV. Experimental Evaluation

A. Data Collection

A total of 13 participants (6 females and 7 males, age: 34 ± 6) were recruited for the experimental validation. Each participant gave their written informed consent to participate and was able to discontinue participation at any time during the experiments. The experimental evaluation protocols followed the declaration of Helsinki, and there was no risk of harmful effects on participants' health. Data were recorded in conformity with the European General Data Protection Regulation 2016/679, stored on local repositories with anonymized identities (i.e., User1, User2), and used only for the post processing evaluation procedure. Please note that no sensitive data were recorded.

Users were tasked to read code of the object from the bracelet, pick it from the corresponding box, and place it in the table in front of their. Each subject performed six trials (3 with haptic feedback, 3 without haptic feedback), in a random order. The participant was notified whether the haptic feedback was present or not 10 seconds before the experiment started. At the end of the experiment, an online questionnaire consisting of two questions was proposed. The former question asked the user to evaluate the feedback modality using a Visual Analog Scale. The Visual Analog Scale is a rating method used to measure a subjective experience. In the context of evaluating the feedback modality, the VAS ranging from -10 to 10 is used to assess the participant's preference for feedback. A score of -10 indicates a strong preference for no feedback ("Strongly Prefer No Feedback"), while a score of 10 indicates a strong preference for haptic feedback. A score of 0 means "No preference". The latter question was a text field that allowed users to provide open-ended feedback in their own words, with a maximum of 500 characters. This type of feedback allows for more qualitative descriptive responses and can provide more in-depth insights about the experience or perception of the system being evaluated.

B. Data Analysis

As a first step, we studied how users' performance in correctly completing the task were influenced by the haptic cue.

For each user, we computed the average among trials performed with and without haptic feedback. Resulting times are visually depicted in Figure 5 and reported in Table I, together with VAS scores.

A paired-samples t-test was used to determine whether there was a statistically significant mean difference between the two modalities.

An outlier was detected that were more than 1.5 box-lengths from the edge of the box in a boxplot. Inspection of the value did not reveal it to be extreme and it was kept in the analysis. The assumption of normality was not violated, as assessed by Shapiro-Wilk's test ($p = 0.794$). Participants successfully accomplished the test in minor time when the haptic feedback was provided (45.83 ± 12.74) compared when the user picked the object without tactile cues (64.68 ± 14.35 seconds).

The t-test revealed that the reduction of 18.85 seconds is statistically significant, $t(12) = 4.70$, $p = 0.001$.

Then, scores given by the qualitative questionnaires were analysed. In average the users rated positively the presence of haptic feedback (7.18 ± 1.63). For what concerns answers to the open questions, all the users agree on the ease of use and ease of learn of the system. Three answers pointed out the fact that the mental effort in using the system with the haptic feedback was considerably reduced. Indeed, they may execute the task with less attention to the labels, trusting the system in providing an alert in case the selected box was a wrong one. Similarly, 4 users reported that they learned a strategy to speed up the finding of the correct bin. Without the feedback users have to carefully read the entire label to correctly distinguish similar codes, the haptic feedback allows them to identify only a part of the code (the begin or the end) and proceed with a rapid trial and error approach nearing the hand to the bins and listening for the ack. We also measured the accuracy of the system by evaluating the correct picking from the boxes. When using the pick-by-haptic system the users performed 99% of correct picking, while without the device the accuracy was 93%.

V. Conclusion

In this work, we tested the effectiveness and the accuracy of haptic feedback on task completion time in a warehouse picking scenario. The study found that users perform the find and picking task faster when assisted by haptic feedback with increase of 6 points in the percentage of correct picking score. The average reduction of 18.85 seconds was statistically significant. Users rated positively the presence of haptic feedback reporting a reduction of the mental effort during the task execution that contributed to improve their performance. The study presented in this paper contributes to improving manual picking tasks in different industrial and logistic facilities. Moreover, the use of passive tags instead of lights can also have a positive impact on the environment by reducing energy consumption, whereas the simplicity and cost effectiveness may favour the introduction of pick-by-haptics solutions also in small/medium enterprises with a high dynamic rearrangement of their warehouses. The results of this study provide important insights into how haptic feedback can improve user performance in a task involving picking small objects from stocks of storage bins.

However, this study has also some limitations. One limitation is the study sample size, which consisted of 13 participants. While the results showed a statistically significant difference between the task completion time with and without haptic feedback, future studies with larger sample sizes could provide more robust conclusions.

Another limitation is that the study only evaluated the effects of haptic feedback in a laboratory setting and with a specific task. The possible generalization to different settings has to be demonstrated with further studies. Future research should evaluate the impact of haptic feedback in real-world settings to understand the broader implications of this technology.

In conclusion, this research highlights the importance of considering haptic feedback as a viable and valuable tool to enhance the performance and user satisfaction of manual picking tasks.

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