M.Des Project 2

Evaluating Vibrotactile Guidance and Perception

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Declaration

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19th November 2022

Approval

The M.Des Project 2 entitled "Evaluating Vibrotactile Guidance Systems" by Atish Waghwase, Roll Number 18U130008 is approved, in fulfilment of the Masters in Interaction Degree at IDC School of Design, Indian Institute of Technology Bombay.

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Abstract

We design a tactile guidance system that provides vibrational cues to help the user pick targets out of an array. We evaluate its error rate by varying target size and compare its performance against human visual perception alone in a visual search task that involves absolute judgement of unidimensionally varying stimuli. The system achieves reasonable error rates even at a sub-centimetre target size. Identifying targets is found to be the fastest using perception alone, followed by tactile guidance and perception combined, and guidance alone being the slowest. Conversely, tactile guidance alone is the most accurate, followed by guidance and perception combined and least of all, perception alone.

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Introduction

Locating a specific object in a set of visually similar objects can quickly become time consuming and tedious as the number of objects increases. Common such scenarios include finding a book in a library, a medicine in a warehouse, a specific connection on a large control panel or a particular thread size of screws in a hardware store. These tasks can require a person to carefully inspect each item in the set in order to differentiate them and find the target using their visual perceptual abilities. With an increasing number of objects (Lehtinen et al., 2012) or with decreasing variation between the objects, it can get harder to rely on the accuracy of visual perception. The visual search may become a tedious task of serially analysing each object in the set (Wolfe et al., 2011). Such search and selection tasks can be alleviated by using the help of computerised systems that can locate the target and user in space and communicate the location of the target to the user. While there are many modes of communicating information to the user, tactile modes have the unique ability to be private and non-disruptive of the user's visual engagement with the environment. They are suitable for dexterous tasks if applied directly to the hand due to the natural stimulus-response behaviour of humans. The equipment necessary to deliver tactile stimuli can also be quite small, which makes it a viable choice for wearable devices such as smartwatches.

There are two components to a tactile guidance system — the localization system and the communication system. The localization system is responsible for locating the target and the user in space, whereas the communication system is responsible for conveying the location information to the user. For a given tactile guidance system, there will be a limit to the resolution of the localization system and a distance smaller than which the communication system cannot deliver noticeably distinct stimuli. This limiting distance may be considered the tactile guidance resolution. However, in the real world, humans have the ability to use their visual senses to distinguish between targets that may be much smaller than the tactile guidance resolution.

Our aim is to study this interplay of limiting cases of tactile guidance and visual perception. This paper presents a low-cost localization and tactile guidance system that can guide users to a target in a unidimensional array of objects with reasonable accuracy even at a sub-centimeter level. We provide benchmark data comparing error rate with the size of targets ranging from 30mm to 6mm in size. We also compare the speed and error rate of users using purely visual perceptual target selection to tactile guidance augmented target selection in a target identification task.

Background

A localization system needs to be able to locate the target object as well as in our case, track the user's hands.

Widely used indoor localization and tracking technologies include UltraWide Band (UWB), Bluetooth Low Energy (BLE) as well as optical tracking. UWB and BLE is used in consumer level tracking devices like AirTags alongside GPS to track an object upto a precision of 1 metre anywhere in the world. BLE is also used in indoor localization beacons to track the 3D location of connected devices such as smartphones of hundreds of users in an indoor space with a precision of a few feet. Open source tools like OpenCV use AI based object recognition that can be processed in real time for optical tracking of any given object.

The Meta Quest 2, an industry-leading budget VR headset, includes full hand tracking that uses purely optical tracking. Hand tracking has become extremely accessible using AI and machine learning through Google's open source MediaPipe machine learning pipeline, which allows even a basic webcam to track hands with very reasonably low noise and usable coordinates in the camera's FOV.

Given these technologies, various use cases of tactile guidance have been studied. Vibrational cues have been used to assist visually impaired persons in navigation (Yelamarthi et al., 2014). It has also been used to provide directional cues to improve performance in physical activities like rowing (Ruffaldi et al., 2009), improving standing balance (Ballardini et al., 2020), gait rehabilitation (Ma et al., 2017) and improving touch sensation in stroke victims (Enders et al., 2013) and improving the bowing technique in novice violinists (Linden, 2009).

Directional information cues can be reliably conveyed through the wrist with tactile stimulation (Jin et al., 2014). Wrist worn 2D vibrotactile guidance has been demonstrated to be useful in search and rescue scenarios for human-robot collaboration (Aggravi et al., 2016) and for speeding up visual search tasks (Lehtinen et al., 2012). However, we could not find any work that quantifies the minimum target size or angle that the tactile guidance system can resolve.

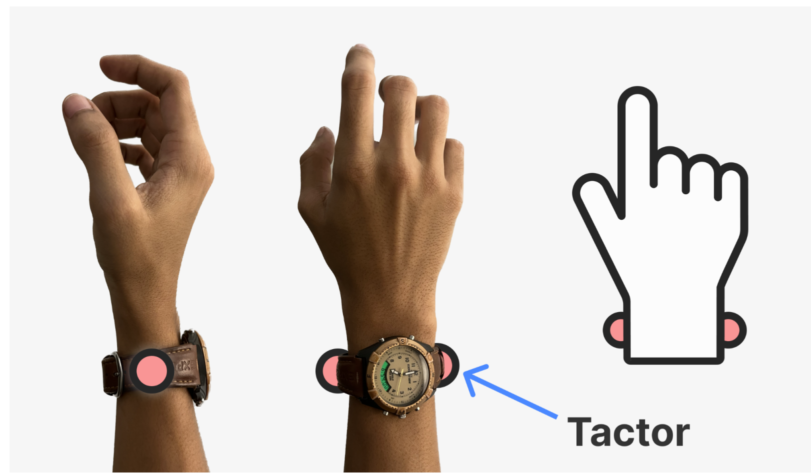
3DOF spatial guidance work includes assistive guidance for visually impaired persons Günther et al. (2018) who were able to successfully guide users to invisible targets in 3D and Tang et al. (2020) who state that they could reliably convey directional feedback in 3D. However, we replicated the apparatus used by Gunther et al. and conducted a pilot study with 16 participants. We found that the error rate of tactile guidance almost doubles with an increase in degrees of freedom (Waghwase et al, 2022). Therefore, to find the best case error rate, we have limited this study to only 1 degree of freedom.

Given that we plan on testing visual perception of objects, we studied the limits of absolute judgement in visual perceptual tasks. The famous Miller, G. (1966) who observed the limit of 7 objects in absolute judgement in unidimensionally varying stimuli by studying examples of auditory and gustatory perception among various other examples, however it has also been verified by Luck & Vogel (1997) in visual tasks. In fact, they found the set size to be around 4 objects for orientation and colour. They also reported that by varying objects in two dimensions instead of one, the set size increased from 4 to 16. It can be concluded that it is the multidimensional variation in objects that lets us recognise and distinguish hundreds of objects. Lehtinen et al. have demonstrated that the effects of set size can effectively be eliminated in visual search tasks with identical distractors and a distinct target when using a vibrotactile spatial guidance device.

Therefore, the goal of this paper is to evaluate the effect of target size on error rate in tactile guidance tasks. We also compare the performance while using a tactile guidance device to purely visual perceptual guidance in a visual target search task. To facilitate this, we also design a tactile guidance system with a smartwatch-like form factor.

Design

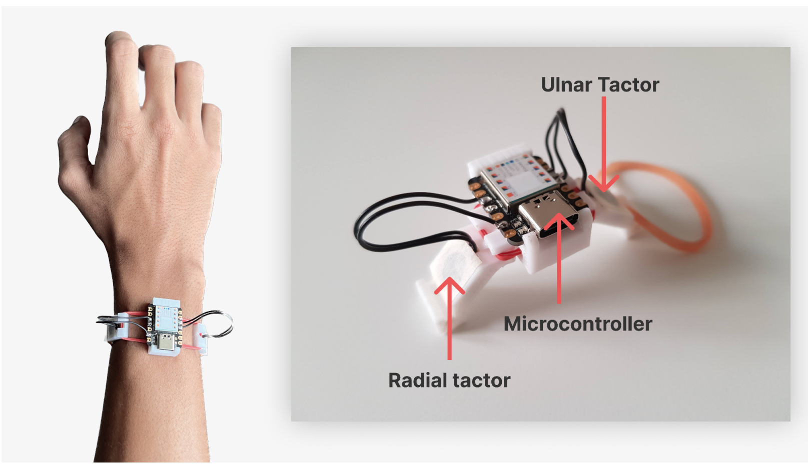
Tactile Guidance System



The intended implementation of our tactile system

Most smartwatches and smart bands come with one tactor, which can only deliver 1 bit of information at once (on/off). 1 bit is enough for alerts, however, even with amplitude or frequency modulation it cannot convey directional information effectively without being encoded.

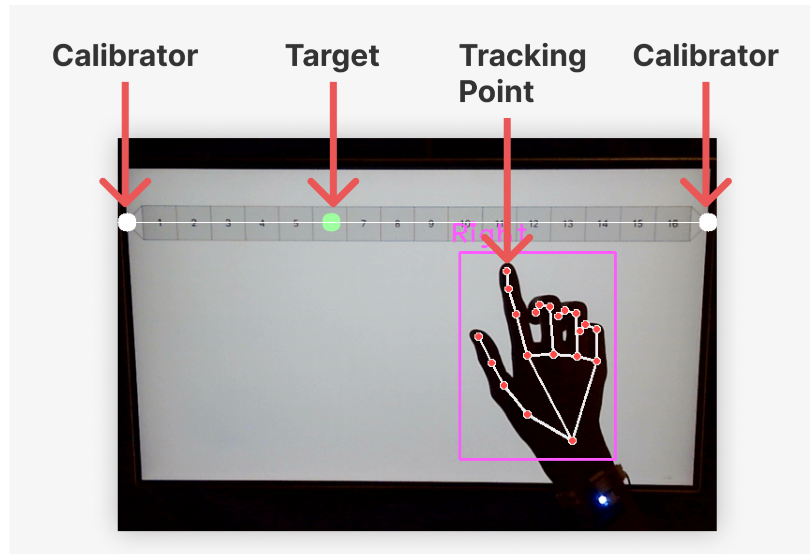
Unidimensional directional feedback would need at least two bits (left-on/left-off, right-on/right-off) in order to intuitively convey direction. We designed our prototype to resemble a smartwatch with just two additional tactors on either side of the wrist — the cost of which should be negligible — that can communicate 2 bits of information simultaneously.



The tactile communication system

Our prototype consists of two wrist mounted tactors — one on the radial side and the other on the ulnar side — and a Seeeduino Xiao microcontroller. This microcontroller was chosen because its miniscule size (21mm x 18mm) allows the prototype to have a smartwatch-like form factor. The tactors are flat 7mm ERM coin motors operating between 1.2V and 3.3V. The three components are held together using two rubber bands that go around the wrist that allow for exact placement of the tactors. Although our prototype was tethered to a laptop for communication and power, it can be made wireless by adding a small battery.

Localization System

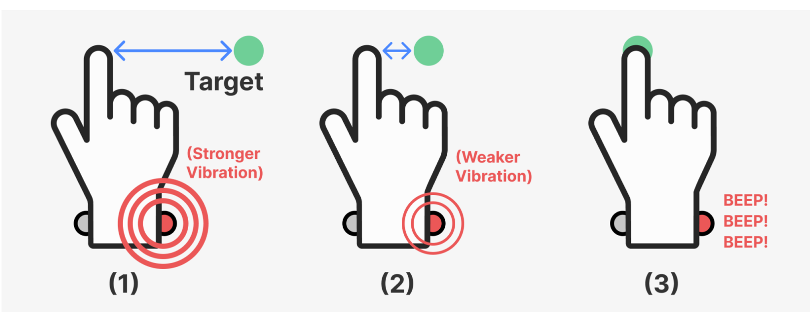


Video feed from the localisation system

Hand tracking was done using a single overhead Logitech C270 webcam with Google's MediaPipe Hands tracking tool. The video feed was being processed at 640x480 pixels at 30fps while tracking the distal segment (fingertip) of the index finger, giving a maximum of 640 discrete possible targets along the x-axis. A 24” 1080p panel was used to display the object arrays containing the target.

The object arrays contain numbered, identical squares along the x-axis without any gap in between. The localization system does not directly track the target — instead, there are two dots at exactly half the distance of the side of the square on either side of the array for calibration. The tracking software draws two calibration points on the video feed from the camera. The two calibration points can be manually aligned with the two dots on either side of the object array. The software then uses a mathematical model to take ‘n’ as an input and set the target on the nth square from the left. This is optimal because this n matches the number on the squares.

Interaction



The Inverse Pull metaphor

Vibration patterns can be used to encode distance into vibration in various ways, referred to as *metaphors*. (Jansson, 1983) conclude that the Pull metaphor — a sensation meant to feel like the target pulling the skin towards it; which activates the tactor closest to the target — is more effective than the Push metaphor which feels like a force is pushing your hand and activates the tactor farthest from the target. We used amplitude modulation and deployed an *Inverted Pull* metaphor for guidance, which means the intensity of vibration gets lower the closer you get to the target. Inverting (providing weaker stimulus as you get closer to the target) the regular Pull metaphor (originally providing stronger stimulus as you get closer to the target) allowed us to include confirmatory clicks such that both tactors beep at maximum amplitude (100ms stimulus bursts with 100ms delay) when the user is at the target and the vibration amplitude would be at its minimum.

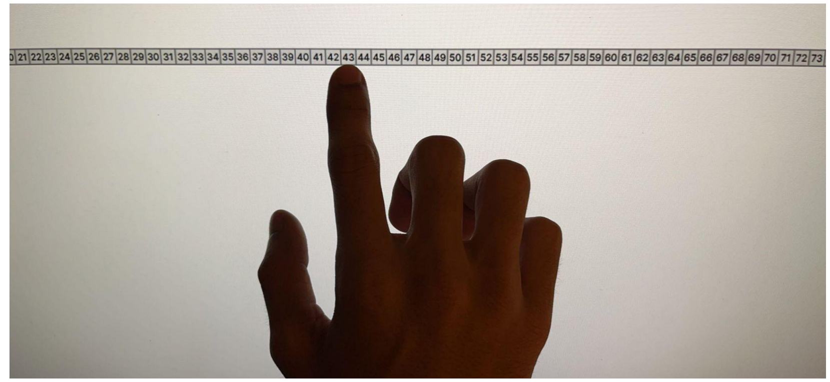
(Lee & Starner, 2010) states that humans are better at distinguishing pulsating vibration actuation than continuous. However, that was in the scenario of alert perception in tactile displays. Our scenario required users to act upon the vibrotactile stimulus to receive updated feedback. We used amplitude modulation because it is theoretically faster to create a JND (just noticeable difference) in continuous actuation, since pulsating actuation by virtue has a delay between pulses.

Evaluation

We conduct two studies to evaluate this tactile guidance system — one to measure the accuracy over varying target sizes and another to evaluate its speed and accuracy compared to purely visual target selection.

Error Rate vs Target Size

The goal of this study was to evaluate the accuracy of the tactile guidance system. We present the participants an array of numbered but dimensionally identical squares, one of which was the target. The sizes of squares are determined by the harmonic progression $f(\lambda)=c\lambda/n$ where λ is the side of the square and c is a constant. We used a harmonic progression because it is easier to identify larger targets, but it gets increasingly difficult as the targets get smaller; using a harmonic progression ensures that there are fewer large targets with large variation and many smaller targets with smaller variation.



Sizes of smaller targets relative to a human finger

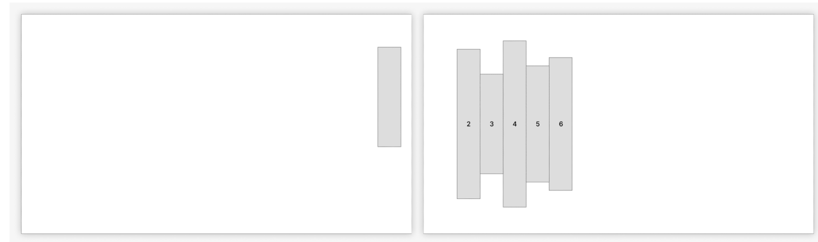
Our hand tracking system tracks the fingertip of the index finger, so we used 15mm as an approximate width of the tip of a human index finger as the base value, with 1 term greater than and 3 terms smaller than 15mm as the sizes for the squares. That gives us $c=3$ with the series being {30, 15, 10, 7.5, 6} mm. Contextually, a minimum size of 6mm covers scenarios with object sets such as magazines in a shelf, a set of allen keys, drill bits, small electronic components, etc. and anything larger.

To sum up, it was a within-subject study with 5 conditions of Target Size (our independent variable) where each participant gets 5 attempts per condition to pick a target.

Perception vs Tactile Guidance

The goal was to compare performance in target identification tasks by human visual perception and by vibrotactile guidance. Our independent variable *Mode* had three conditions — Perception alone, Guidance alone and Combined Guidance-Perception. The type of real life target acquisition tasks we wanted to simulate are as follows — there is a set of distinct objects but comparing them would require close inspection or direct comparison with the intended target. For smaller set sizes it is easy to visually detect and compare small differences but as the set size increases, it becomes harder to accurately tell differences.

It was a within-subject study with *Mode* being one independent variable with 3 conditions (Guidance-only, Perception-only and Combined) and *Set Size* being the other independent variable with 9 conditions (2 to 9). The order of the three conditions was counterbalanced between subjects. *Error Rate* and *Time Taken* were the dependent variables.



Stimulus rectangle (left) and distractor set (right)

We use a set of numbered, monochromatic rectangles varying only in length as our set of target and distractors. The width was kept constant at 3cm, since we observed 100% accuracy of guidance in Test 1 in the first 6 participants. Users had n=9 levels, with the number of rectangles in the set in each level given by (n+1). The stimulus rectangle is displayed on the top-right side of the screen, while the distractor set is centre-aligned and shown on the left side to prevent visual overlap of the stimulus and distractor set. The stimulus is misaligned with the distractor set to prevent using visual alignment cues.

We hypothesise that as the set size increases, the success rate of target identification would drop in case of perception only, whereas it would be indifferent for guidance only and combined modes. We also hypothesise that combined guidance would be faster than guidance only, both of which would be slower than visual perception, for obvious reasons.

Study

1. Error Rate vs. Target Size

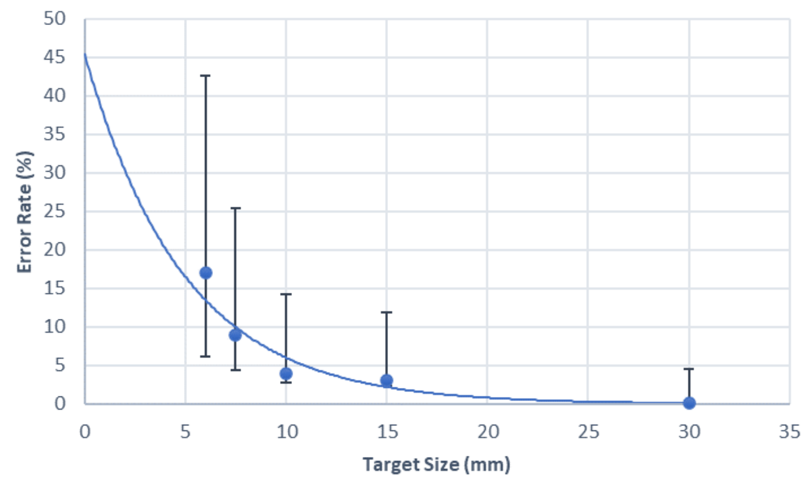
Participants

We recruited a convenience sample of 20 participants (17 male and 3 female) from IDC School of Design aged between 20 to 32 years. Participants were asked to wear the device on their right hand regardless of their handedness.

Method

We present the first target array to the participants. After allowing them to get familiarised with the tactile guidance device, we asked users to locate the target with the help of our guidance system. We used 5 target widths (the independent variable) varying from 30 mm to 6 mm, to determine the average error rate (the dependent variable) for each target width. Each user attempted 5 times with pseudorandom targets. As some of our targets are smaller than the human finger, the squares were numbered. The users were asked to call out its number which was logged as the participant's intended target.

Results



Error rate for the tactile guidance system decreases exponentially with an increase in target size. We predict a trendline using the 5 data points using Target Size as an independent variable and Error as a dependent variable. For the smallest targets that we used ie. 6mm, the error rate was an unusable 17%. Even at 10 mm target size, the error rate is a reasonable 4%. However, it rises quickly to 9% by 7.5mm, which might be reasonable depending on the use case. At 30mm target size, we recorded no errors.

2. Perception vs Tactile Guidance

Participants

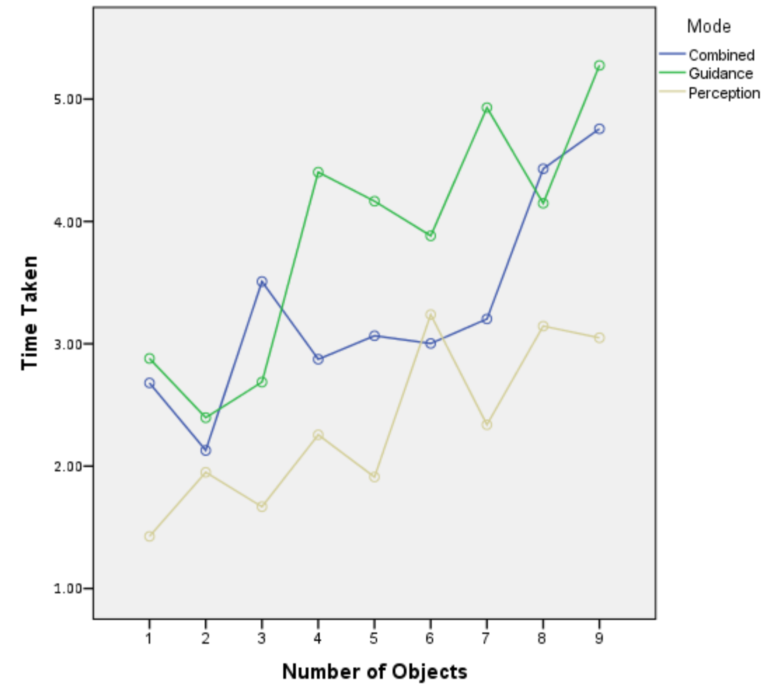
We conducted this study with 14 participants out of the 20 participants of Study 1 (11 male and 3 female, aged 20 to 32). Study 2 was conducted immediately after Study 1, so participants were already well familiar with the tactile guidance system.

Method

We told participants that each attempt would be timed. The screen displayed 'Ready?' before each starting each attempt. During each attempt, participants were shown the target rectangle ie. the visual stimulus for 2 seconds, followed by a blank screen for 1 second, followed by the object set. For the Guidance-only condition, no stimulus was shown; there was a delay for 1 second after the 'Ready?' slide followed by the object set. In all three conditions, the stopwatch started when the object set was revealed and stopped when the participants announced the number corresponding to their selected rectangle.

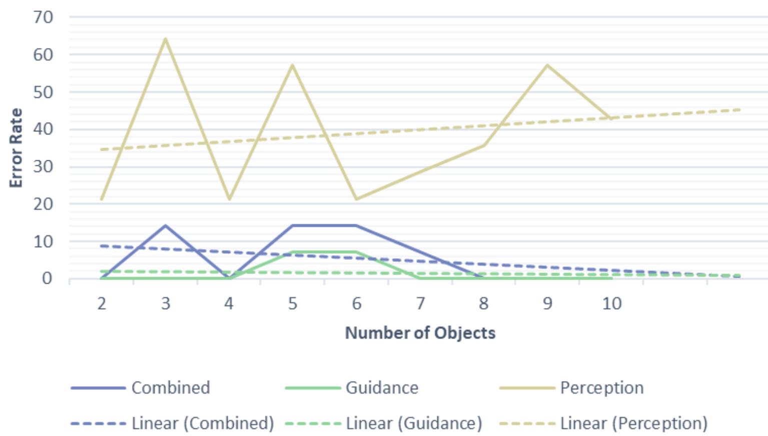
Results

We conducted a two-way analysis of variance with Mode and Set Size as the independent variables and Time as the Dependent variable.



Guidance is the slowest while Perception is the fastest. Even though Combined sometimes takes more time than Guidance and sometimes less time than Perception, there is an overall statistically significant (p-value<0.05) difference in time between each Mode. The average time taken by

Perception was 2.33 seconds whereas for Combined it was 3.29 seconds and for Guidance it was 3.86 seconds.



It is also obvious that Guidance is the most accurate, followed by Combined and Perception. Perception consistently performed worse than both tactile guided Modes with the lowest average error rate being 21%. The maximum error rate for Guidance is 7.1% while that for Combined is 14.3%. The predicted linear trendline for Perception is rising whereas for Guidance and Combined, it is approaching zero.

Discussion

The absence of any errors at a target size of 30mm suggests that this apparatus is fit for implementation in cases where the spacing between the centre points of objects is greater than 30mm. In our originally suggested scenarios, this can be useful for distinguishing between medicines in a warehouse, switches on a wall switchboard or on a circuit breaker or thicker books in a library. Even at 10mm we recorded an acceptable 4% error rate, which implies this system can distinguish between smaller connections or switches on a control panel or medicines in a warehouse or shelf or switches on a switchboard. However, it might be impractical for objects smaller than 7.5mm such as magazines in a shelf or soldering points on a circuit board and will result in frequent errors.

The error rate is greatly dependent on the localization system. Since our localization system was not tracking the targets themselves — but rather using a mathematical model to estimate the location of the target — there were bound to be rounding errors as we had a relatively low resolution webcam. Therefore, the error rate for sub-centimetre targets may be improved by proper calibration and tracking of the targets themselves.

As per our hypothesis, the error rate for Perception only seems to be rising, whereas for Combined and Guidance it seems to hover around zero. The slightly higher error rate error rate in case of Combined might be because of the clashing target wrongly identified through visual perception. Our other hypothesis is also largely true — although there are times when Guidance is faster than Combined or Combined is faster than Perception — overall, Perception is the fastest, followed by Combined and Guidance coming in last. The time taken for all the three modes seem to be increasing with an increase in set size. We did not find any interaction between the conditions of the Mode variable with respect to error rate, which means that Perception will always be less accurate than the other two, regardless of the set size.

Conclusion

We demonstrated that even a low-cost localization and tactile communication system can be used to build a reasonably precise tactile guidance system. After comparing the error rate with the size of the targets, we can conclude that tactile communication is an accurate means of guidance for objects as small as the width of a human finger ie. 15mm. Human perception is faster for identifying targets, but it is also quite inaccurate compared to using a guidance system.

Even though our tactile guidance system is limited to one axis, there can exist an interface which lets the user define the axis of guidance. Thus, it is only limited by the axis currently active. We intentionally created a prototype with a smartwatch-like form factor to validate the usefulness of the tactile guidance interactions for wrist wearable devices. Ultimately, we want this work to inform design decisions in creating interactions for wearable devices and we can conclude that our work demonstrates a feasible way to add tactile guidance to them.

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