"TactiGlove" – A Guidance System to Effectively Find Hidden Spots in 3D Space

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Abstract. Research on vibrotactile navigation and guidance has been a topic of broad interest for the HCI community for quite a while. However, common to most of the presented approaches is a 'map-like' navigation to reach waypoints or targets in two-dimensional contexts. Motivated by the need to simplify and speed up searching tasks in maintenance, training or other everyday situations, a prototype for a three-dimensional guidance system, composed of a glove with integrated 6-DOF positioning sensor technology and vibrotactile actuators, was developed. In opposition to the formerly mentioned systems, the purpose of our "TactiGlove" system is to guide persons to point-shaped, maybe hidden locations in 3D space or annotated digital objects that have been lost. In this paper we present the implemented system in detail, focusing on hardware and software aspects as well as on the different developed tactile feedback models. System evaluation with a lab-based user study based on a Fitt's law experiment for traditional UIs revealed that guidance by the "TactiGlove" was intuitively understood by most of the volunteers, although the system performance varied a lot between the different feedback models. Preliminary results identified much room for improvements and motivates to pursue research on the "TactiGlove".

Keywords: Tactile glove, 3D guidance system, Augmented reality, Improving maintenance/training tasks.

1 Tactile Guidance in 3D Environments

Presenting information using the tactile channel has been an important research topic in the last decade, motivated by reasons such as the possibility to augment or even fully replace information formerly presented using visual and/or auditory channels. This approach would be in particular beneficiary in situations where these senses are either blocked (e. g., in dark or smoky environments where the human eye cannot gather information) or overloaded (for example when maintaining an unknown machine with lots of controls, where the user does not know "where to look" at).

Navigation focusing on tactile feedback only is a well researched topic in this context; the work of van Erp *et al.* is a promising example of such as system developed to support vehicle operators in steering their cars by presenting them

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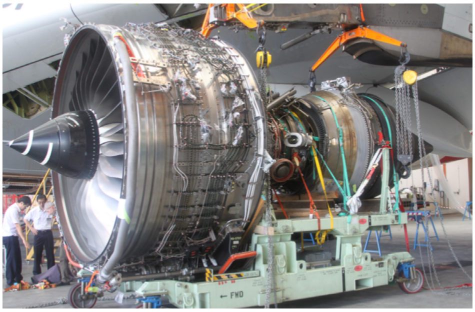

Fig. 1. Tactile guidance could help in improving complex repairing tasks by 'pointing' to the part to change/repair (Image courtesy Australian Transport Safety Bureau, www.atsb.gov.au)

navigational information through the tactile channel [1,2,3]. This enables drivers to keep their eyes and attention on the road and, in addition, to react on recommendations from the navigation system received via tactile messages. Another domain of vibrotactile guidance has emerged in computer aided surgery (CAS). The work of Brell and colleagues [4,5,6] shows impressively how vibrotactile actuators on the hand can guide a surgeon to the area of surgery, even if the patient is thousands of miles away.

The goal of this work is to provide accurate vibrotactile guidance in three-dimensional contexts (such as the one shown in Fig. 1). This is –compared to similar related work– novel as it introduces the advantages of 3D guidance on medium scale (i. e., within reach of the hand or within indoor walking distance). Previously, tactile guidance in 3D was only offered in the large, for example in combination with GPS in aircraft navigation, or at very small scale with pen-shaped interfaces in computer aided surgery. More detailed, the work is motivated by the aim to supply guidance for locating digitally annotated, but hidden, lost or invisible objects. Such a system could enhance maintenance or training tasks, for example on unknown machines, by providing guidance to the object to interact with, and consequently reducing the time to search for the target. Also in everyday situations, for instance if someone has to find an unknown light switch in a dark room, such a system could ease locating it. Considering possible application fields we decided to implement the system as glove, as in most situations the hand would be the extremity responsible for interaction with the object to locate. A further motivation for using the palm as vehicle for our purpose stems from the fact that it offers very low two-point discrimination threshold [7], i. e., allows for a small-sized interface.

1.1 Research Approach

We hypothesize that utilizing vibrotactile guidance provide persons assistance in finding arbitrary locations or annotated objects in three-dimensional space.

Furthermore, we suppose that humans are able to understand and use such signals effectively after a short training phase (on usage of carefully/properly designed signal patterns). The term "effectively" is understood and used here as indication that objects (targets) of different size and distance one to the other are all found in similar temporal behavior.

To evaluate the hypotheses we developed a prototype device that was further on tested in a lab-based user study. The development phase included also the definition of appropriate signal patterns and navigation models. A navigation model in this context describes how position and orientation data of a certain tracking system are transformed and mapped to vibrational patterns presented to the user. With regard to the hardware/software setup, the main requirements were to run the system in real time, implying that both a tracking system with high update rates and fast responding tactile actuators have to be used. Beside the core components, also a reliable wireless network link was required to interconnect the different components without significant delays. For evaluation purpose volunteers had to follow a "virtual" (invisible) route, composed out of predefined, counterbalanced way points of variable size and distance. The measured performance was then evaluated with a metric similar to "Fitt's law" [8] – the standard for traditional interface performance evaluation.

1.2 Outline

The rest of the paper is structured as follows. Section 2 gives an overview of related work and state of the art in vibrotactile guidance systems. Section 3 presents the developed system, section 4 gives insight into the user study and the results of the evaluation. The final section 5 summarizes the findings and achievements and concludes the paper with recommendations for improvements.

2 Related Work

Bosman and others [9] proposed a pedestrian guidance system called GentleGuide. It consists of two vibration units mounted on to the users wrist and provided signals whether a user should turn left, right, moves into the wrong direction, or reached the target. In contrary to our system only map-like 2D guidance to reach waypoints inside a room was provided. Van Erp and colleagues introduced a tactile navigation system mounted on a belt and used that system for finding waypoints on a map in different driving scenarios [2]. Also in this work the navigation task was limited to 2D space. The summary of the research work on tactile navigation systems [3] describes an example of a three-dimensional navigation system. Contrary to our "TactiGlove" system, their proposed 3D navigation device was designed for navigation in a vehicle/aircraft context. The aim of the system was to find outdoor targets using GPS positioning and not to find annotated small objects in an indoor environment. Hein and Brell [4] proposed a tactile guidance system to be used in computer aided surgery (CAS). The system assists a surgeon by navigating his hand, along with the surgical instrument, to the area of interest where it should be used. The tactors 'tell' the surgeon in which direction to

Table 1. The "TactiGlove" is the first tactile 3D guidance system for the hand

System	Integration	Body location			Dimension		Substitution level		Target size		
		Torso	Hand	Wrist	2D	3D	Support	Substitution	Small	Medium	Large
GentleGuide [9]	wristband			X	X			X		X	
Ground-based Waypoint Nav. [2]	belt	X			X			X			X
Helicopter Waypoint Navigation [3]	belt	X				X		X			X
conTACT [4]	glove		X		X		X		X		
Tactile Wayfinder [10]	belt	X			X			X		X	
AR Target finding [11]	cell phone		X		X		X			X	
LifeBelt [12]	belt	X			X		X			X	
CAS Belt [13]	belt	X			X		X		X		
Passive Music Learning [14]	glove		X				X		X		
"TactiGlove" (proposed system)	glove		X			X		X	X	X	

move on the patients surface – this is also a two-dimensional guidance approach (although the system gathers and process three-dimensional data sets). Heuten and others [10] propose a system called tactile wayfinder, which consists of a belt with tactors and a GPS receiver. The difference to the system of Van Erp *et al.* described before is the tactile wayfinder targets pedestrian navigation, thus navigation on much smaller scale (but still outside and in the range of tens to hundreds meters). Ahmaniemi and Lantz [11] proposed to use current Smartphones (all equipped with sensors and actuators) for vibrotactile guidance. They implemented sort of point of interest (POI) navigation by setting off vibration units when the user points at the target (with the phone in the hand). Although no real guidance is provided (the device 'displays' only if the user points in the right direction), it is also said to be a kind of two-dimensional (guidance) system. Ferscha and Zia [12] proposed the 'LifeBelt' - a belt type tactile guidance system similar to the ones of Heuten [10] or van Erp [3], but with more advanced guidance information. They actually incorporate walking trajectories of persons nearby and calculate the best (i. e., most efficient) way to reach a certain target in crowded environments. Another waistbelt system used in a CAS context was presented by Bluteau and others [13]. It signals on a two-dimensional plane whether or not the surgical instrument is moved on the correct trajectory. Huang, Starner and others [14] presented a vibrotactile assistance system integrated into a glove and employed to teach piano scholars to play piano melodies. Vibrators are placed on top of each finger in the glove; activated tactors indicate the finger to be used for playing the next note. While not describing a "guidance system" this device is one example of success for tactile information transmission on the fingers/hand. A summary of the related work with emphasized characteristics and unique features is presented in Table 1. (With regard to the feature 'target size', small stands for targets sized one meter or less, medium targets are 1 to 5 metes large, and big indicated targets larger than five meters.) This overview clearly points out that "TactiGlove" is the first 3D indoor navigation device for the hand. Worth to mention here is the ARMAR (Augmented Reality for Maintenance and Repair) project [15]; although it does not use tactile patterns to provide directional information it features a similar idea as the one used by "TactiGlove" and employs it also for maintenance purposes. ARMAR uses a visual augmented reality overlay of the real world to guide mechanician to find the next task and action to perform.

3 Prototype Development

3.1 System Architecture

The prototype is technically a sensor-actuator system that transforms input data into several output streams. Input comes from a tracking system that measures the position and orientation of the tactile glove. This input data is then processed in the software engine of our prototype to create precise and accurate vibrotactile output for a certain navigation model. In addition, a visualization of the measured situation (i. e., glove movement in the 3D room) is generated. As common 3D engines normally used for scientific simulations, gaming, or complex visualizations have a similar "update and presentation" architecture, and because these engines already feature built-in vector/matrix processing and visualization libraries to efficiently handle 3D data, we selected such an engine (the Microsoft XNA framework) as base for our software implementation and

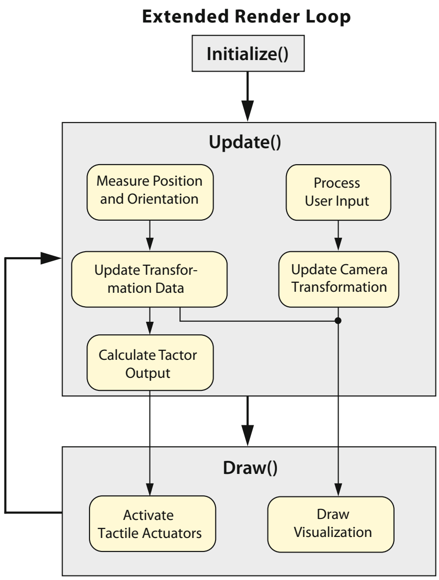

Fig. 2. Render loop with sensor measurements and tactor output

built our system around it. 3D engines normally featuring also real time operation; by extending such an engine the real time requirement of our 3D tactile guidance system was also achieved. The render loop (Fig. 2 shows the control flow) of our 3D engine is structured as follows. First `Initialize()` loads all the necessary data and uploads it to graphics memory. In our case, additionally to initialize the visualization part, all the connections to the tracking system and the controller of the tactile actuators are established in this phase. Then the actual render loop starts with a cyclic repetition of calls of `Update()` and `Draw()` routines. Typically, in `Update()` control signals (e. g., button presses, mouse movements, or time based updates such as animations) are processed, which update the transformations and states of the 3D objects. In our prototype the input is driven by processing data of the tracking system. Updating the internal models also means calculating the current state of our navigation models. In the `Draw()` method the uploaded vertices are transformed using a set of transformation matrices, then rasterized, and finally presented on the screen. Concurrently, the control signals to drive the tactile actuators are forwarded to the tactor control unit (according to the actual navigation model).

3.2 Hardware and Software Setup

To track the position of the "TactiGlove" the Intersense IS-900 motion tracking system was used. This high-precise measurement system is operating based on ultrasonic and inertial signals to provide tracking data with an accuracy of about $2mm$ (position) and with 0.50° rotational resolution (pitch, roll, yaw) at update rates of up to $180Hz$. These specifications as well as the update rate are by far sufficient for our "TactiGlove" system as we wanted to achieve an update rate of about $30fps$ and a "guidance resolution" of at least $25mm$ (i. e., to guide to small objects sized approximately $5cm$). For generating the vibrotactile output C-2 tactors from EAI technologies were used. These tactile actuators are small enough ($30mm$ diameter, $7.9mm$ height) for being integrated into a common glove, and featuring strong, continuous, and clearly recognizable vibration signals at an update rate higher than $30Hz$. The IS-900 system was directly connected to the host computer using USB and the tactor commands were transmitted from the host computer to the tactor control unit (TCU) using a Bluetooth connection. Both the Intersense tracker and the tactor elements were integrated into a glove worn by the user (="TactiGlove"). In order to butt the tactors against the palm skin a tight fit glove typically used by bicyclers was selected as "tactor housing". Tactors were fixed to their defined positions with elastic bands/straps that were sewn on the inside of the glove. The tracker was mounted on the back of the hand using stitched elastic bands. Its position was chosen in a way that the tracker has "good" visual connection to the "SoniStrip" units responsible for receiving and processing ultrasonic wave signals from the tracker all the time. The integration of all the components into the "TactiGlove" prototype is shown in Fig. 3. The software implementation is based on Microsofts .NET 4.0 and XNA frameworks. It integrates the DLLs for interfacing with the IS-900 system and the tactor controller and was developed in a way such that

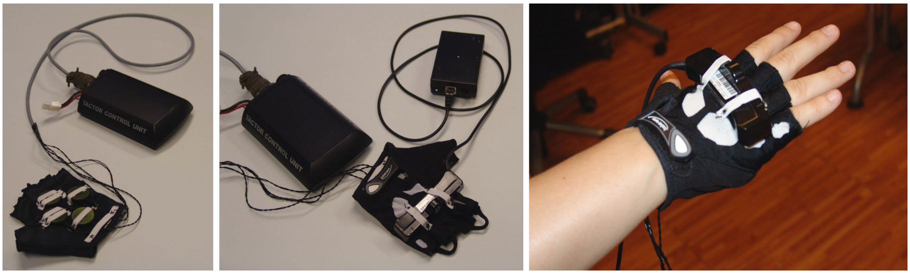

Fig. 3. Four tactors mounted on the palm side of the glove (first row, left); upper side of the glove with the Intersense tracker (first row, right); "TactiGlove" prototype worn by a user and with all the components integrated (second row)

not only signal processing and tactor control is handled by the software, but that also use cases/scenarios for the user study can be configured, monitored, recorded, visualized, and evaluated within the self-contained environment.

3.3 Navigation Models

Navigation models describe how the data received by the tracking system is processed and transformed to tactile stimuli. In this work, a navigation model describes (i) where on the hand the tactors are placed, (ii) which vibration patterns are used to activate them, and (iii) which meaning such a '*Tactogram*' [16] assigned to a specific tactor has. It further includes the algorithm to determine which vibration pattern has to be assigned to the individual tactors on the glove. In our work, Tactograms are only distinguished by variation of the two parameters vibration intensity and frequency. As later shown in the evaluation section, three navigation models were used to study the efficiency and intuitivity of vibrotactile guidance in 3D space. Common to all the 3 models is the need for transformation. Tactor positions are stored as three-component vectors in a coordinate system relative to the origin of a virtual hand model (in computer graphics often referred to as the 'model space'). From the IS-900 tracking system the position and orientation of the tracker is retrieved in its own coordinate system. Its origin is also taken as origin of XNAs world coordinate system, where every model in model space is transformed to in order to form the entire scene. To recapitulate, tactor positions in the model space have to be transformed into world coordinates so that they represent their position in the real space. For that, transformation matrices (for translation and orientation) are generated from the position/orientation data of trackers. The final world space position of a tactor can then be obtained by calculating

$$P_{world} = T \cdot R(yaw, pitch, roll) \cdot P_{model}$$

where P_{world} is the tactors position in world space, T is the translation matrix formed by the position data from the tracking system, $R(yaw, pitch, roll)$ is the rotation matrix formed by the orientation data in Euler angles from the tracking system, and P_{model} is the tactors position in model space. Details on how these matrices are processed can be found, for example, in [17].

'Plane Model'. This model orients itself on the frequently used belt-type navigation systems as indicated for instance in [1,9,10,12]. Four tactors are used to indicate in which direction the target is located. If the target is in the direction the hand of the user is actually pointing to than the front tactor is vibrating, if the target is in opposite direction the back tactor vibrates. The same approach is followed for targets placed left, right or in diagonal directions. The classification of which tactor has to vibrate is done by determining in which angular sector relative to the hand the tactor is located (Fig. 4).

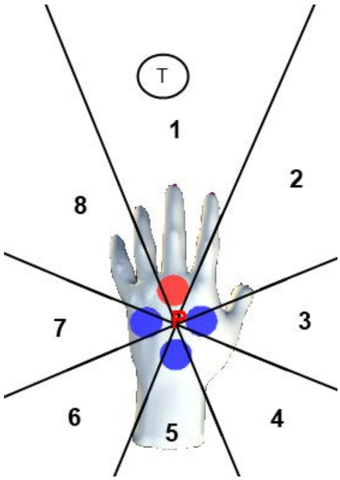

Fig. 4. Plane Model: Fragmentation into sectors to classify the active tactors. If a target 'T' is located within a certain sector the according tactor(s) vibrates. In "TactiGlove" we use eight sectors mapped to four tactors. For the diagonal sectors (2, 4, 6, and 8) the two adjacent tactors are activated. Red tactors are on, blue colored tactors are switched off.

To extend this behavior to the third dimension we used two mechanisms. First, the tactors can indicate if the target is located approximately orthogonal to a plane described by position and orientation of the Intersense tracker. Approximately means in our case if the angle between the normal of our simulated plane and the target is below 45°, and therefore describing a cone around the normal. If the target is located inside the angles described by the cone than all four tactors are activated to signal the "TactiGlove" bearer that the target is orthogonal to its hand. Fig. 5 illustrates this behavior. The second mechanism to incorporate the third dimension simply takes the position and orientation data of the tracker to transform the plane accordingly to the users hand. If the user finds that, for example, the target is above or below the users hand, it is possible to simply tilt the hand so that the target is no longer orthogonal to it, therefore again more detailed direction cues are presented (in the tilted plane). Before calculating the directions (in the case that the target is not inside the sector described by the orthogonal cones) the target has to be projected orthogonally on the virtual plane. This ensures that the vector between the position of the hand and the projected target can be used to compute the directions. To project the target to the virtual plane the plane equation $v_n * X = v_n * P_h$ was used, with v_n corresponding to the normal vector of the plane and P_h representing the position of the hand. This was then combined with the line equation $X = P_t + t * v_n$ that describes a line orthogonal to the plane at the position of target P_t. After inserting the line equation into the plane equation, t can be calculated as shown in the equation $t = (v_n * P_h - v_n * P_t)/(v_n * v_n)$. To calculate the angles necessary for the behavior above we used four vectors v_1 to v_4 assigned to each tactor, each pointing to the direction assigned to the tactors in untransformed model space, therefore $v_f = (0, 0, 1)$, $v_r = (1, 0, 0)$, $v_b = (0, 0, -1)$, and $v_l = (-1, 0, 0)$. In addition, one vector is assigned to the orthogonal plane $v_n = (0, 1, 0)$. These vectors are then transformed using the transformation described before. As next step, the vector $v_{target} = P_t - P_h$ is calculated, with target position P_t and hand position P_h. Using the law of cosines the angle between the five transformed vectors and v_{target} is computed. $\alpha = \arccos((b^2 + c^2 - a^2)/(2bc))$ where $b = P_t - P_h$, $c = (P_h + v) - P_h$ and $a = (P_h + v) - P_t$. To calculate the directional angles, the projected target position is used instead of the real position. After the angles were calculated they are simply compared to threshold angles which specify if the according tactor shall be activated or not. For the directional vectors $v_f v_r v_b v_l$ this angle was set to 67.5°, causing the sectors to overlap so that the overlapping

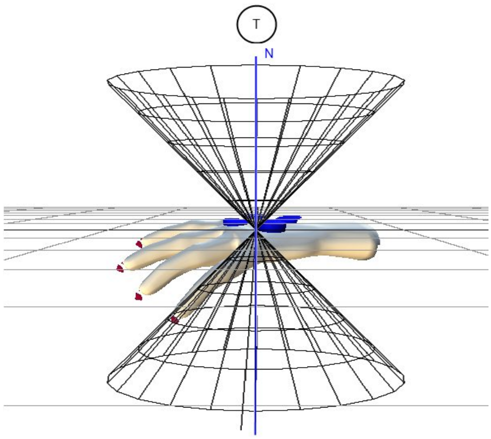

Fig. 5. Plane Model (system extension to 3D space): A target 'T' located inside the cone (as shown in the figure) causes all four tactors to vibrate. This signals the "TactiGlove" user that the target is approximately orthogonal (i. e., above or below) to the plane described by the hand of the subject. A target outside the area described by the cones causes tactor activation according to the description in Fig. 4.

areas represent exactly the diagonal sectors. For the orthogonal vector v_n the angle was set to 45°.

'Yaw-Pitch Model'. The second model orients itself on the idea presented in [11]. Here accelerometers were used to determine the pointing direction of a user, and based on this information a tactor informs the user whether or not the actual pointing direction accords with the direction of the target. In [11] this was only realized for yaw angles, which means that only two-dimensional scenarios were covered. We extended this model by including a second tactor presenting tactile information regarding the pitch direction, i. e., indicating if the user also points towards the target with correct pitch angle. By including up/down directions a "TactiGlove" bearer is now enabled to look for and find targets in three-dimensional space.

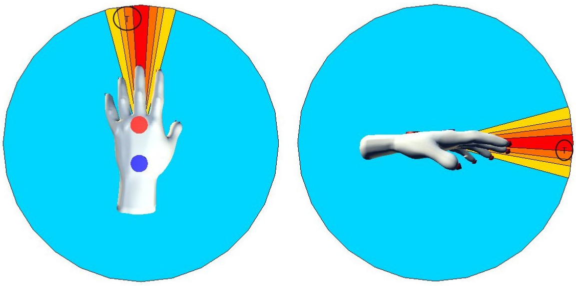

Fig. 6. Yaw-Pitch Model: Angular sectors with color coded vibration strength of the tactors (relative to the yaw and pitch angles by the hand of the bearer). Red color (facing exactly to the front) indicates maximum vibration strengths, blue color stands for no vibration at all. The color grading between red and blue encodes vibration intensities between maximum strength and off. In the left figure, target 'T' causes the front tactor (mapped to yaw angle) to vibrate at second highest gain level, while the back tactor (right figure; pitch angles) vibrates at full strength. In the real system, both yaw and pitch vibrations are overlayed and indicated at the same time.

In the 'yaw-pitch model' we are using different signal strengths to signal if a subject is pointing only roughly or exactly in the right direction. To compute the strengths of the signal the angles between the vector in viewing direction v_{view} and the vector between target and hand v_{target} projected in XZ and YZ planes have to be calculated in order to classify in which angular sector the target falls. The sectors are mapped then to categories of vibration signal strengths, from no vibration (blue area in Fig. 6) to full vibration if the "TactiGlove" bearer exactly points towards the target (red sector). For the mapping between signal strength and pointing angle a Gaussian distribution was used such that the angular sectors are getting more narrow the more precise the user is pointing toward the target. The threshold angles to choose the tactor strength were chosen as follows. If the according angle is below 3.5° the tactor vibrates at full gain, between 3.5° and 7.0° at medium-strong gain, between 7.0° and 10.0° at medium gain, and between 10.0° and 15.0° at weak gain. An angle higher than 15.0° causes the tactor not to vibrate at all. Fig. 6 illustrates the angular sectors with color coded vibration strengths. For calculation of the yaw angles in between we simply project v_{target} and v_{view} against the XZ plane by skipping the Y component. Therefore $v_{targetXZ} = (x_{target}, 0, z_{target})$ and $v_{viewXZ} = (x_{view}, 0, z_{view})$, where v_{view} is the transformed direction of the hand and $v_{target} = P_t - P_h$. The viewing direction is calculated from a vector that is by default $(0, 0, 1)$ and is then transformed by the matrices constructed from the data received by the Intersense position/orientation tracker with P_t being the position of the target and P_h the position of the hand. The angle Δyaw between v_{viewXZ} and $v_{targetXZ}$ is calculated as angle between two vectors $\Delta yaw = \arccos \frac{v_{viewXZ} * v_{targetXZ}}{|v_{viewXZ}| * |v_{targetXZ}|}$. The pitch angle difference is calculated as the (absolute) difference between the height angle of the target relative to the hands position and the given pitch angle from the tracking system. The height angle α is calculated from the law of sines $\alpha = \arcsin \frac{b * \sin 90}{|v_{target}|}$ where $b = P_t.Y - P_h.Y$. α is later referred to as Δ_{pitch}. Δ_{pitch} is taken as $\Delta_{pitch} = 360° - \Delta_{pitch}$ if the angle was above 180°. This case can occur if the Intersense tracker faces downward and therefore the palm of the user is facing, by mistake, upward.

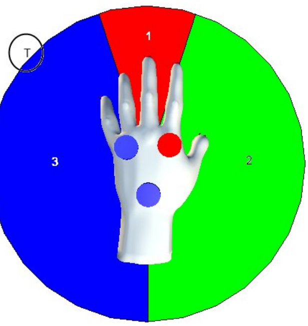

Fig. 7. Yaw-Altitude Model (top view) with angular sectors of yaw angle. If a target is residing in sector 1 (red) both "angular tactors" vibrates, if it is in sector 2 (green) only the left tactor vibrates, if it is in sector 3 (blue) the right tactor vibrates. Target 'T' in the figure causes the right tactor to vibrate, signaling the "TactiGlove" bearer to turn to the right. This is sort of inverse model and the same paradigm is followed for the altitude (one tactor mounted above, one below the hand).

'Yaw-Altitude Model'. The third model mixes cues of pointing and instruction directions and can be somehow seen as "inverse model". It 'tells' the "TactiGlove" bearer if he/she is pointing in the right yaw direction and furthermore if the height position of the hand is in the right altitude or if the hand has to be moved upwards or downwards. In contrast to the 'yaw-pitch model' above, two tactile actuators instead of only one tactor are used to present the yaw angle and/or the altitude of the hand. This means that the "TactiGlove" bearer is not only informed if he/she is pointing in the right direction, but also if he/she should turn left or right. The same paradigm is used for indicating whether or not the plane of the hand is in correct altitude to reach the target.

Calculation of Δ_{yaw} is done analogous to the 'yaw-pitch model' with the exception that the angle is signed whether the user has to turn left or right or not. To check the turning direction $v_{targetXZ}$ and v_{viewXZ} are used. v_{viewXZ} is then transformed using a rotation matrix given from the determined yaw angle to $v_{viewXZangle}$. If $|v_{viewXZangle} - v_{targetXZ}| = 0$ then $\Delta_{yaw} = \Delta_{yaw}$, otherwise $\Delta_{yaw} = -\Delta_{yaw}$. If the angle between view $v_{viewXZangle}$ and $v_{targetXZ}$ is negative then rotating v_{viewXZ} using Δ_{yaw} exactly matches $v_{targetXZ}$, and therefore the vector in between has a length of zero; in any other case there is vector in between. If the calculated $|\Delta_{yaw}|$ is smaller than 18° (10% of 180°) then both angle tactors vibrate, signaling the user that he points in the right direction. If Δ_{yaw} has a negative sign then the user has to turn right until the direction matches, if Δ_{yaw} is positive, than the user has to turn left. Fig. 7 illustrates this approach.

Altitude signals are calculated straight forward. A target 'T' has additionally to its position a top and bottom border, which can be computed easily from the targets spheres radius. We then have only to check if the Y coordinate of P_{hand} rests below the bottom of the target, above the top of the target, or in between (=correct altitude; no vibration).

4 Evaluation

To evaluate our "TactiGlove" prototype a lab-based user study was conducted; this section presents the procedure and summarizes the results obtained.

4.1 Experiments

To evaluate the behavior of the system all test subjects (see below for details) had to perform movements from predefined starting points to sphere shaped virtual targets. Both (intermediate) start position and target points (objects) were not visible in reality, but were represented as position vectors in our evaluation software. This ensures that searching tasks for invisible objects are correctly simulated. The first starting position was visually marked in the laboratory room, after reaching one of the targets, the user received a short acoustic notification signal. The experiment was designed in a way that the test subjects had to follow a path with explicit direction changes consisting of multiple targets (different distances, different sizes; all parameters counterbalanced). After reaching a target (and receiving notification), this target immediately becomes the starting point for the next search task (see Fig. 8 for explanation). The target spheres had different sizes to represent multiple difficulty levels. Although Fitt's law [8] is not directly applicable as it is normally used to evaluate the performance of movements with input devices (such as keyboard, joystick, or mouse) instead of movements driven by a guidance system, we found it a useful performance metric also to evaluate the performance of the (different models of the) "TactiGlove"

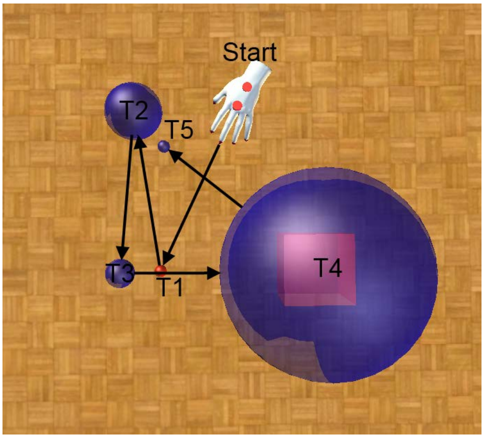

Fig. 8. A path is formed by multiple targets. The first target to reach is T1, then T2, T3, and so on.

system (same variation elements). A participant had to move from a given starting position to a target position, passing a distance or amplitude A. The targets all had different sizes W. This provides us to choose difficulties accordingly to $ID = \log_2(A/W+1)$ (ID...index of difficulties). We chose A to be fixed at 2 meters, resulting in values of W for each ID as given in Table 2. The fixed distance should not have influenced the behavior of our test subjects, as they haven't been informed about this prior to the study. During initial experimentation it turned out that small spheres with a radius of only about three centimeters (ID 5, 0.0645 m diameter) were very hard to find and took a long time, so they were skipped for the final user study.

One test run had to be accomplished by each test subject per each navigation model, which results in three runs per test subject. One test run contained twelve targets with three instances of each ID. We expected learning effects for each navigation models, but also among them. To compensate, test subjects were given a short training phase per trial where they could get familiar with the navigation model. In a training phase five targets with ID 2 were presented

Table 2. Index of difficulty (ID), target amplitudes (A), and target widths (W) as used in our experiments

ID [bits]	A [m]	W [m]
1	2.00 m	2.00 m
2	2.00 m	0.67 m
3	2.00 m	0.29 m
4	2.00 m	0.13 m
(5)	(2.00 m)	(0.06 m)

and had to be found. A training cycle could be repeated as often the user wants. We counterbalanced the order of navigation models within-subject to cope with learning effects among the different models. There was a time limit of 15 minutes for each trial, but no time limit on a single target. If technical problems occurred or the target was not reachable for the person (e. g., the test subject was too small) the corresponding items were skipped. For each experiment a trace together with temporal data was recorded. These traces allow for visual inspection in order to reason about specifics how the user moved or the time (on a per item basis) can be extracted and used for further evaluation. An example of such a trace is given in Fig. 9. Theoretically, the moved distance could also be derived from such a trace, but jittering and random failures of the tracking system have made these data in the given experiments unreliable.

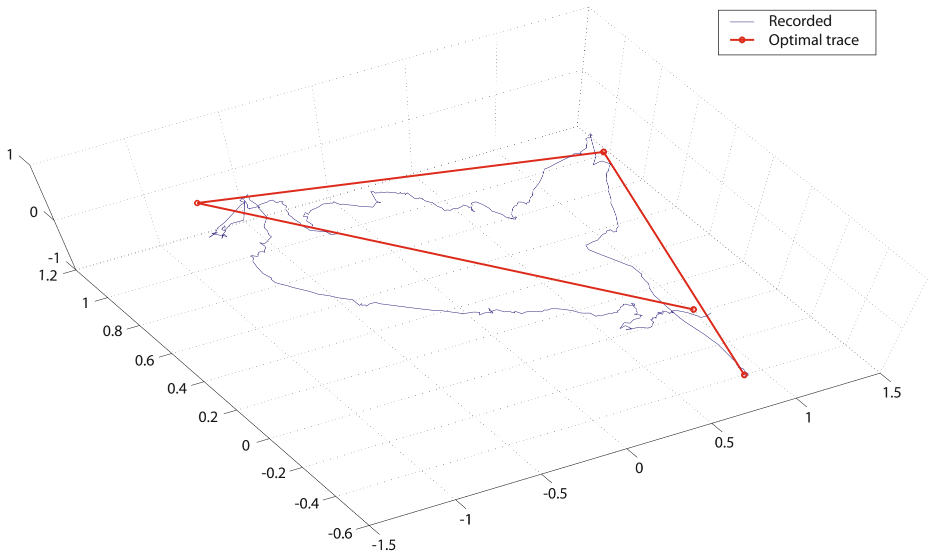

Fig. 9. 3D plot of a recorded trace. The blue line represents a recorded trace, the red line the optimal path between starting point and two targets.

4.2 Results

We tested the prototype system with 17 test subjects (13 males, 4 females; age $\bar{x} = 27 \pm SD = 5.84$). The complete test would have generated a total sample size of 51 measurements for each of the 4 IDs and 3 navigation models (612 samples). However, not all measurements could be used for our evaluation – some of the target traces had to be removed later because of time lapse, while others were skipped due to technical problems with the tracking system (indicated in detail below). An examination of the problems is one aim of this section, another is the performance investigation as well as a comparison for the three different navigation models using a metric similar to Fitt's index of performance (IP).

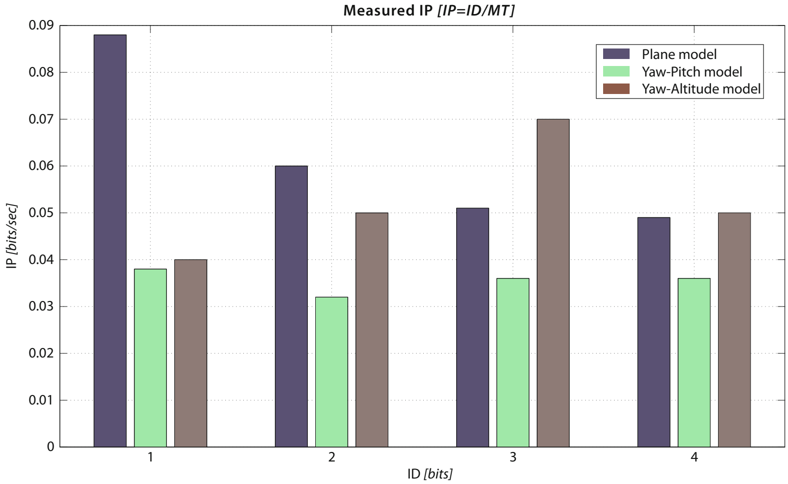

Fig. 10. Performance (IP) for all the three models and different task difficulties (IDs)

In the evaluation for the 'plane model' 16 targets (or 7.8%) had to be removed because of tracking system problems, 18 (8.8%) targets because of time lapse, and additionally 12 (5.9%) due to problems with the glove (slipping/moving during the experiment). These skipped measurements have not been used for the final evaluation presented later. In the remaining 158 correct measurement points only 2 (1.27%) were erroneous, finally resulting in a target completion rate of 98.73%. For the 'yaw-pitch model' 11 measurement points (5.4%) had to be withdrawn due to problems with the tracking system, 32 (11.3%) because of time lapse, and 12 (5.9%) because of glove problems. In the remaining 147 measurements 2 (1.36%) were faulty (target completion rate of 98.64%). In the last series evaluating the performance of the 'yaw-altitude model' 18 targets (8.8%) had to be skipped because of problems with the tracking system, 48 (23.6%) because of time lapse, and 12 (5.9%) due to problems with the glove. These skipped measurements are again not taken into account for the final evaluation. In the remaining 126 measurements only 1 (0.79%) was indicated erroneous, leading to a target completion rate of 99.2%.

It can be observed that most of the skipped targets (about 21% of all measurements) were skipped due to time constraints or problems with the "TactiGlove" (size, slipping during the experiment), another 7% were skipped due to technical problems. This indicates that in scheduling possible future experiments more time should be reserved for each test subject. Nevertheless, the low skip rate caused by technical problems and the high overall completion rate of the actual used measurements let us feel quite positive that the system will operate at ever higher accuracy and without faults in the near future – as it has shown that it works already in its current stage of development very well.

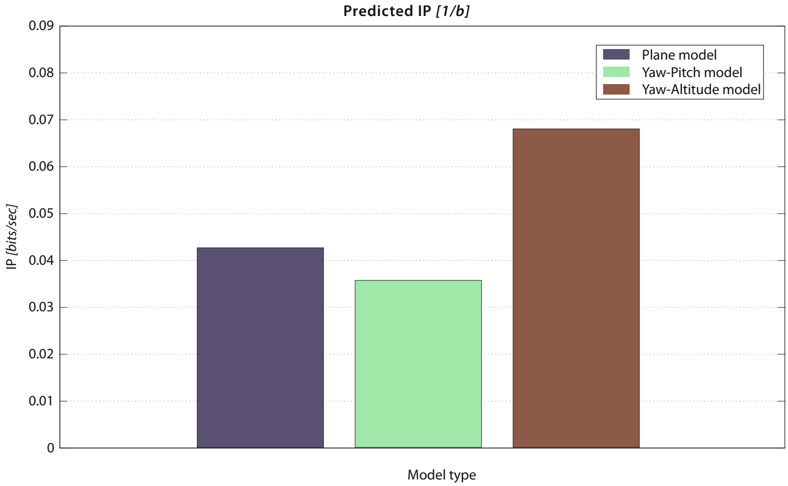

Fig. 11. Predicted performances (IPs) for the three models

To compare the performance of each navigation model against each other the mean values of the measured times for each model and for each ID were taken to build the prediction model $MT = a + b * ID$ (according to Fitt's law [8]). The correlation of measured and predicted MT gives an indication how good the prediction fits the measured data. For the 'plane model' a prediction model of $a = -12.335sec.$, $b = 23.372sec.$ was derived; $MT = -12.335 + 23.372 * ID$, $r^2 = 0.9993$. For the 'yaw-pitch model' the prediction model is specified by $a = 1.215sec.$, $b = 27.826sec.$ and $MT = 1.215 + 27.826 * ID$. The correlation coefficient was calculated at $r^2 = 0.9892$. For the 'yaw-altitude model' finally a prediction model of $a = 1.215sec.$, $b = 27.826sec.$ and $MT = 9.475 + 14.662 * ID$ was derived ($r^2 = 0.8633$). The index of performance per model and ID (Fig. 10) allows the following conclusions. The 'yaw-pitch model' performs worse (it has the lowest IP for all IDs, the 'plane model' performs in our experimental series best for targets with low IDs while the 'yaw-altitude model' performs best for targets with higher IDs.

Finally the performance of a model can be quantified by only one value by taking the reciprocal values of the regression line's slopes into account to derive the value for IP [8, p. 97]. The higher the bit rate the better is the performance of the model. The runs using the 'plane model' achieved an IP of 0.0428, while the 'yaw-pitch model' achieved IP=0.0359 and the 'yaw-altitude model' attained a IP of 0.0682 (=model perceived and performed best in the experiments). The performance of the different models (reciprocal IPs) is shown in Fig. 11.

To complete the evaluation, Fig. 12 shows the regression lines for each model in a single plot to better indicate the differences between the three models used.

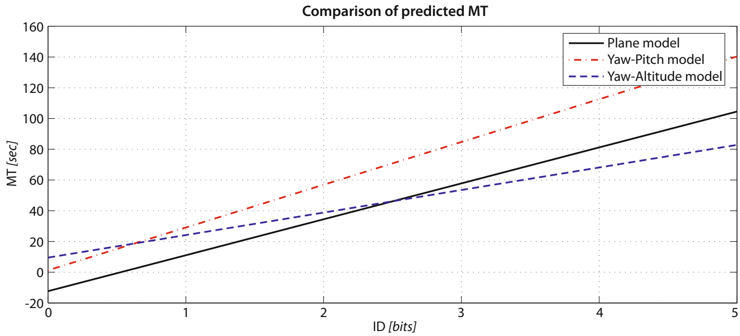

Fig. 12. Predicted movement times (MTs) for the 3 navigation models

4.3 Discussion

The most crucial points to discuss are whether the stated research hypotheses are supported by the executed study and its evaluation. The **first hypothesis** states that **vibrotactile guidance cues allows persons to find arbitrary locations or annotated objects in 3D space** by using vibrotactile signals only. For this hypothesis our test subjects had to complete a series of trials with different difficulties for each model. As shown completion rates of 98.7% for the navigation using the 'plane model' as well as the 'yaw-pitch model' and 99.3% for the 'yaw-altitude model' gives support for this hypothesis. However, a sample size of 17 subjects with each 12 trials per navigation model is fairly small, nevertheless, we tried to diversify the backgrounds of the subjects and used not only people with deep technical knowledge.

Along with the evaluation of the this hypothesis a performance comparison of the proposed model was performed. The comparison revealed that in general the 'yaw-altitude model' achieved the highest bit rate of 0.07 bits/sec. (=index of performance) and therefore worked best. However, the bit rate is quite low compared to other experiments using Fitt's law – mouse input, for example, achieved IP values of up to 4.35 bits/sec. [18]. Nevertheless, the intention of our experiments was not to compare the "TactiGlove" against mouse, touch, trackball, joystick, or other similar input devices, but to give us the possibility for comparing these initial results with prototypes and navigation models developed in the future.

The **second hypothesis** posed was that **test subjects would be able to understand and use such signals effectively after a short training phase** if properly designed signal patterns were used. Every user had a short training phase before executing the actual experiment. The high completion rate could be an indication for the acceptance of this hypothesis, but it does not evaluate how effectively the actually have been used. To answer the question, test participants had to complete a questionnaire after the experiment. Its examination showed that the three navigation models were clear each to everyone; nevertheless, some of the subjects had problems with distinguishing the tactors from each other, especially after using the system for a while. This is a clear advice that the system has to be further improved in making the tactors better distinguishable and the tactile patterns better perceptible. The majority of the users reported that they have understood the navigation models and could distinguish the signals. Along with the high completion rates the second hypothesis is supported. Many users reported that they had problems with finding the targets, but this more reflects that they had to deeply concentrate on the task. If this problem could be reduced with more training has not been evaluated in the current study. Additionally, we have also shown which one(s) of the proposed navigation models worked best, and which one(s) should be skipped from further investigation.

One weakness of the presented study is that the proposed models were not compared against alternative guidance systems using alternative modalities, such as visual or acoustic guidance. It is expected that looking for known entities using visual search (e. g., by marking a target with an augmented reality overlay) would be much faster than guiding the hand to a target using vibrotactile feedback only; but this is also not directly comparable as the proposed guidance system was designed to augment or replace visual searching. For acoustic guidance different results depending on the situation and scenario could be achieved; this might one issue to include for investigation in studies in the future.

To conclude, the evaluation of the proposed system showed that in principle it works already quite well in terms of locating targets by only using the vibrotactile signal. However, there is still much room for improvements, especially in tactor placement, signal processing, and message encoding. It was shown that subjects had problems with distinguishing the tactors, particularly after the system has been used for a while. The measured times were also quite high, which limits the system to be used only in situations where the visual sense is restricted. Weaknesses can be found in the evaluation itself. The problems here consists of small sample size, no differentiation between age group or gender. After improving the system based on the findings of the current user study, all (at least some) of the identified issues should have been eliminated in future studies.

5 Conclusion

In this paper we presented the "TactiGlove", a prototypic vibrotactile position finding system for 3D environments integrated into a glove. Our main motivation was to guide persons, for example in training or maintenance tasks, to point-shaped maybe hidden spots in 3D space or to provide assistance in finding and locating invisible, digitally annotated objects. System evaluation was performed in a lab-based user study based on a Fitt's law experiment, where subjects had to follow virtual, invisible paths (defined by targets of different size and distances) in 3D space similar to a "click & point" interaction with a common computer mouse. The evaluation revealed a completion rate of 98.7 % for both the 'projection on plane' and the 'yaw pitch pointing' models and 99.3 % for the 'yaw and altitude' navigation model. Furthermore, the guidance by the "TactiGlove" was intuitively understood by most of the volunteers, although the system performance varied a lot between the different feedback models and subjects. Another finding that might be of help for other researchers is that all the data processing and calculations in 3D space could be easily integrated into a common 3D engine normally used in the gaming, simulation, or virtual reality domains. The three-dimensional data which needs to be processed to drive the "TactiGlove" is very similar to calculations typically carried out in such engines; with our work we have shown that the built-in functions of a 3D engine can be used for efficient sensor data processing and actuator control (e. g., for feedback generation).

5.1 Further Work

Initial experiments with the "TactiGlove" revealed that the prototype basically works well and could be used in the aimed situations, but still offers great potential for further improvements. First, the navigation models, especially the placement of the tactors could be reassessed as many users reported that they were not at all able to distinguish the tactors clearly and really had to put hard effort to concentrate on the task to finally reach the target. From improvements in the placement we also expect increased speed for reaching the targets. Second, the aim of the current study was to test the feasibility of the "TactiGlove". In future experiments the focus should rely more on the reachable performance as compared to other common approaches such as visual search of objects on unknown positions in 3D space or acoustic guidance. Furthermore, future experiments should also feature a bigger sample of subjects with equal distribution of males and females.

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