Follow the Force: Steering the Index Finger towards Targets using EMS

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Author Keywords
Guidance; haptic feedback; electrical muscle stimulation

ACM Classification Keywords
H.5.2. Information interfaces and presentation: User Interfaces – haptic I/O, input devices and strategies

CHI'16 Extended Abstracts, May 07-12, 2016, San Jose, CA, USA
ACM 978-1-4503-4082-3/16/05.
http://dx.doi.org/10.1145/2851581.2892352

Figure 1: A user is guided to a point of interest. An EMS-actuated mid-air gesture, whose shape corresponds to the shape of the object, disambiguates the target.

Abstract
In mobile contexts guidance towards objects is usually done through the visual channel. Sometimes this channel is overloaded or not appropriate. A practicable form of haptic feedback is challenging. Electrical muscle stimulation (EMS) can generate mobile force feedback but has a number of drawbacks. For complex movements several muscles need to be actuated in concert and a feedback loop is necessary to control movements. We present an approach that only requires the actuation of six muscles with four pairs of electrodes to guide the index finger to a 2D point and let the user perform mid-air disambiguation gestures. In our user study participants found invisible, static

Electrical muscle stimulation

Using EMS means sending ~50 μs impulses at around 100 Hz with 10 – 40 mA through electrodes on a user's skin. This leads to a contraction of muscles between the electrodes.

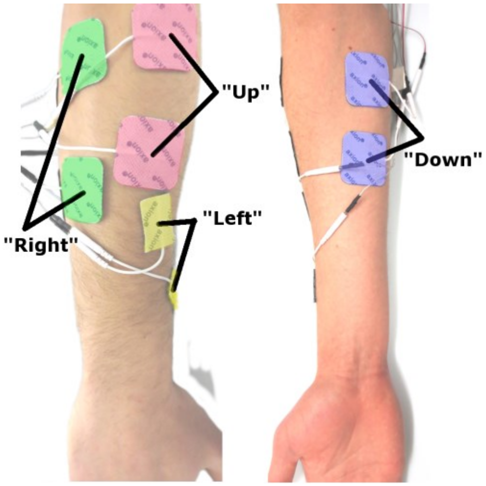

Figure 2: Electrode pad positioning on the forearm with marked and colored muscle groups.

target positions on top of a physical box with a mean 2D deviation of 1.44 cm from the intended target.

Introduction

Guidance in mobile contexts primarily uses visual feedback [2]. However, visual feedback is problematic in mobile situations if the visual sense is already occupied. Mobile force feedback would be helpful, but force feedback technologies are usually confined to the lab or very specific environments [5]. They cannot easily be applied in mobile situations, because of large mechanical parts and considerable power consumption. EMS offers potential as a force feedback technology. It has already been shown that EMS can be used for enhancing 3D environments with additional properties [7,9], for gaming in public space [8], and in mobile contexts to guide pedestrians [6]. Lopes et al. described affordances of physical objects with EMS-based gestures[4]. Tamaki et al. showed that it is possible to move some of the hand's joints individually and proposed navigation use cases in their work "PossessedHand" [10]. On the topic of haptic feedback for visual search tasks, Lehtinen et al. presented a system featuring four vibrotactile actuators mounted on the hand [3]. Yamaoka et al. developed a system to teach users drawing skills by moving the tip of a ballpoint pen with an underlying magnet [11].

We envision a system that guides users towards a certain static or moving target. Once found, the target can additionally be disambiguated in case of multiple candidate targets in the pointing direction by guidance shapes (i.e. finger follows the contour of a shape) that visually describe the target. Figure 1 shows this approach: The finger is directed towards the target, the user consciously follows with his body, and the system lets the finger follow the contour of the target. This outlining of the target helps the user to recognize the intended target.

In this work we investigate EMS as a force feedback technology for search tasks. We present a system that uses EMS to guide users to specific points in space or on physical objects. The system uses a PID control loop to actuate four muscle groups of the lower arm to guide the index finger to a specific target. We did a user study on searching invisible, static targets. We found that users can be guided on top of a physical 3D box to a target with an average error of 14.37 mm (SD of 20.38 mm). Dynamic targets (i.e. guidance shapes) are investigated in an explorative study. We report on several challenges we faced such as EMS calibration for individual users and the choice of PID parameters for actuating the four muscle groups.

Concept

Humans use their index finger as a pointing device in order to communicate a particular direction to other people. Using EMS the user's index finger and hand can be forced to point in a particular direction. We use this as a natural way to communicate a point of attraction. The hands and fingers cannot be bent beyond a certain degree, so the user may naturally follow his finger by turning the body until pointing straight ahead. Resisting the force will leave the hand and finger in an uncomfortable position.

We implement a feedback loop with PID controllers whose input parameters are the current position and orientation of the index finger and the desired target position. As output the system generates the required EMS signals for the electrodes.

Figure 3: System components and their interactions.

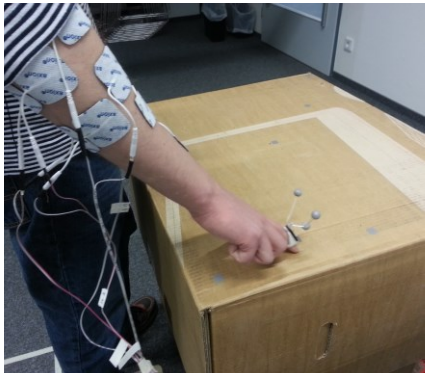

Figure 4: User trying to find an invisible target on a physical box. The box is also tracked through reflective markers.

Chosen muscles
When trying to do two-dimensional movements with the index finger through EMS, electrode pad positions have to be carefully chosen in order to cause only desired movements. For our purposes, we actuate some muscles which move the index finger but also other muscles that move the whole hand (including the index finger). Four muscle groups are relevant as shown in Figure 2.

- “Up” refers to a finger extension movement, using *musculus extensor digitorum.*
- “Down” refers to a finger flexion movement, using *musculus palmaris longus*.
- “Left” for right-handers refers to a hand movement towards the thumb, also referred to as “radial abduction”. Here, *musculus abductor pollicis longus* and the adjacent *musuculus extensor pollicis brevis* are used in order to pull the thumb and hand in the direction of the thumb.
- “Right” for right-handers refers to a hand movement towards the small finger, also referred to as “ulnar abduction”. This is done by stimulating *musculus flexor carpi ulnaris* and the adjacent *musculus extensor carpi ulnaris*.

Overall, we use four pairs of electrodes, one for each muscle group. Due to the adjacency of muscles for a similar movement, four pairs are enough to stimulate the six targeted muscles.

The pads for the “Left” muscle group are smaller (1.5x3 cm) than the others (4x4 cm), because stimulating the *musculus flexor pollicis longus* on the inside must be avoided since it bends the thumb instead of extending it.

Prototype

We built a prototype to guide the user’s index finger towards a target as conceptually shown in Figure 3. The prototype consists of two Sanitas SEM 43 EMS devices, two Arduino Nano boards with WiFly modules, and custom attenuation boards for controlling the EMS intensity, powered by 9V batteries. A tracking system (OptiTrack with 10 Flex13 cameras and a custom finger tracker with three Ø10mm spheres) is used for tracking the finger position and orientation. An Android phone implements the PID controllers and provides a user interface for the experimenter.

On the software side, the Android app includes two PID controllers in order to control both movement axes (up-down and left-right). The prototype takes a static (i.e., stationary) or dynamic (i.e., moving) target in the coordinate system of the OptiTrack tracking system as an input and maps it to EMS intensities. Dynamic targets for disambiguation gestures are defined in their own local coordinate system that gets mapped onto the global coordinate system when starting the experiment.

User Study

As a first step, we conducted a user study to investigate how well users are able to locate static targets with an emphasis on final precision rather than completion time.

Participants got the task to find invisible targets on the top of a physical 3D box (surface area: 69.0x58.5 cm) shown in Figure 4. We defined 16 targets on the surface in a 4x4 square. Each user had to locate all

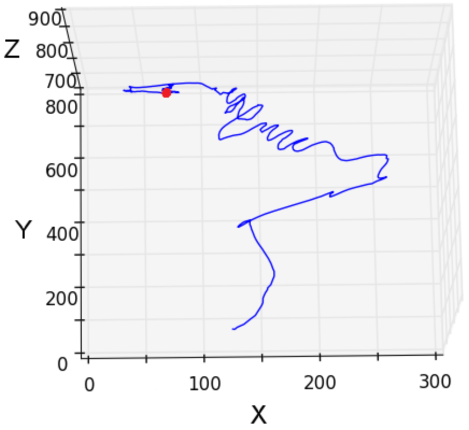

Figure 5: Typical trajectory of one of the faster trials (user 7, 21.5s trial time). Trajectory in blue, target in red. Participant's point of view, dimensions in mm, shrunk to trial area (not physical box dimensions).

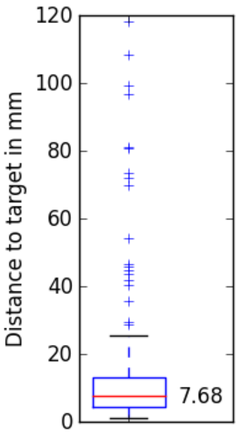

Figure 6: Boxplot containing final distances to target for all 169 viable trials.

targets in random order. Participants did not know about the symmetrical 4x4 square.

Before starting the study the tracking system was calibrated for the index finger and participants themselves slowly increased EMS intensity for each muscle group until they reached the limits of comfortable signal strengths. The PID controllers got fixed parameters determined by experimentation in a small pre-study in order to keep the calibration time at an acceptable level. Before doing actual trials, participants familiarized themselves with the system by doing three training trials. Pre- and post-study questionnaires gathered qualitative feedback.

We invited 11 participants (two female, age between 21 and 32 years, mean=24.4 y, SD=3.6 y). For each trial, a participant begins in a starting area in front of the physical box with the arm slightly stretched out. Participants were instructed to follow the index finger until it is on the target and then say "stop" (Figure 4). There was no time limit on the task but users were made aware of the fact that the longer they take, the worse the system would perform due to increasing insensitivity of the muscles to EMS signals and muscle fatigue induced by EMS (see [1,12]). After each trial, participants were asked to take a small pause in order to regain muscle sensitivity.

Results

Figure 5 shows a typical trajectory for a single, rather fast trial, looking from the top (participant's perspective, XY is the horizontal plane). The participant started on the bottom and made a quick lift of his arm towards the top-right. From there, he goes straight towards the target, with his finger alternating between all axes because the target was directly in front. After overshooting a bit, the participant moves back for fine correction and stops the trial. The alternation between the axes is explained in the discussion section.

Out of the 11*16 total trials conducted, one was manually excluded due to a measurement error trail and another 6 were excluded due to outliers (outside of mean ±3σ range, 3.4% of total trials). The mean distance to targets for all 169 remaining trials is 14.37 mm (SD=20.38 mm) and median is 7.68 mm (MAD=4.01 mm) showing in Figure 6. The mean time to search a target is 60.6 s (SD=35.7 s).

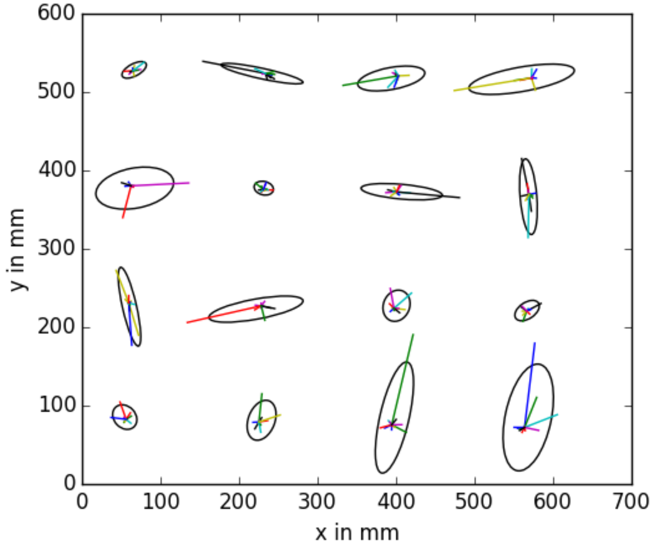

Figure 7: Final 2D deviation to target for all users (169 trials, one color per user). Mean error ellipses at 2σ.

The corresponding errors for each target are shown in Figure 7. Large errors of the trials are clearly visible as

Identified variables with an influence on real-time EMS systems using a control loop:

- type, placement, and size of electrodes used
- intensity, pulse and period duration, pulse form
- skin type, thickness, comfort level, subcutaneous fat tissue, hairiness
- muscle size, power, and muscle power over time
- side effects of other muscles
- effects of muscles moving under the skin, leading to different electrode positioning in different postures and oscillation
- effects of gravity in different body postures
- whether the user thinks about movements and tries to “help”
- whether the user relaxes his muscles or, on the other hand, cramps them

Figure 9: Identified variables with an influence on real-time EMS systems using a control loop

all small errors are so close to the targets that they visually disappear. Note that most high error trials are either horizontally *or* vertically off the target.

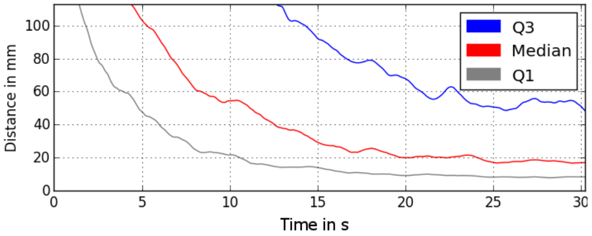

Figure 8: How fast users approach defined target points. Smoothed by a moving average with a ±500 ms time window.

Even though the mean trial time is 60.6 s, users get close to targets much faster as shown in Figure 8. The average time to get within 10 cm is about 6 s and less than 13 s to get within 4 cm of the target.

Qualitative results

Qualitative results were gathered on a 1-5 Likert scale. Participants disagreed about consciously taking control of their hand (mean 1, MAD=0.5) but they were very mixed about concentrating strongly on the EMS signals (mean 3, MAD=1.5). They agreed that the feeling of current weakened over time (mean 4, MAD=1). Participants were mixed about feeling equal intensity in all directions (mean 3, MAD=1) and two participants explicitly mentioned the “Left” movement being too weak compared to the others.

Discussion

The quick alternation between the axes for trials such as the one in Figure 5 is not caused by users manually trying different directions but is caused by the PID controllers overshooting / being a bit too fast to react to changes in the direction of the finger and could be improved by a better PID controller calibration individually for each user in future work.

The boxplot in Figure 6 shows that the average trial was close to the target with a deviation of 7.7 mm. The mean however, is much higher at 14.4 mm which leads to the conclusion that there were many high-error trials. Figure 7 indicates that most of those high-error trials were caused by one axis not providing enough muscle strength which means the EMS intensity was too low for that particular muscle group (up & down *or* left & right). The error ellipses visually appear to have a high variance between targets. This is caused by having only 11 individual trials per target and due to single large errors having a high influence on mean error ellipses.

There is a large variance between participants on how well they were able to find targets. For the best three participants, the system worked well with a mean precision of 5.8 mm (SD=1.68 mm) within a mean time of 40.5 s (SD=5.5 s) per target. The worst three participants on the other hand struggled finding targets with a mean deviation of 28.3 mm (SD=8.6 mm) within a mean time of 76.5 s (SD=25.7 s). There seems to be a correlation between precision and search time. The reason for this appears to be that muscles are becoming more and more insensitive to EMS signals over time, which was observed and mentioned by participants with high search times. The longer a trial takes the less of an impact the same EMS intensity has on a muscle. Thus, the harder it is to find the target precisely and the higher is also the chance of one muscle group responding so weakly to EMS that the user no longer sees or feels any displacement of the

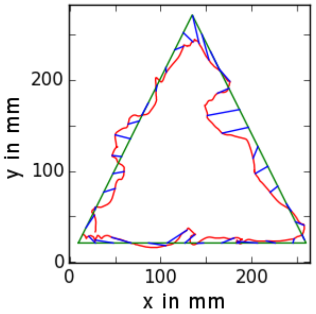

Figure 10: Isosceles triangle, guided clockwise in 16.5s. Mean deviation to moving target: 14.7mm (SD=8mm)

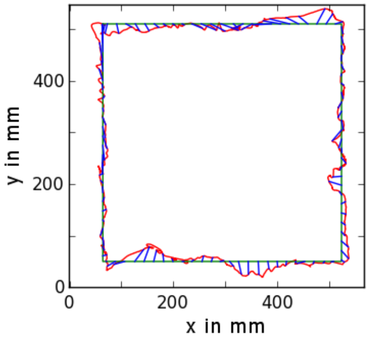

Figure 11: Square, guided counter-clockwise in 44s, mean deviation to moving target: 15.5mm (SD=9.7mm)

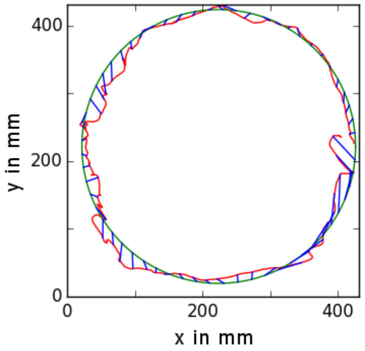

Figure 12: Circle, guided counter-clockwise in 26s, mean deviation to moving target: 17.8mm (SD=12.8mm)

index finger. These specific trials resulted in the highest-error deviations.

However, when taking box dimensions of 69.0x58.5 cm into account, even trials with a larger error were still somewhat close to real targets. Figure 8 shows that users were also able to close in on a target within a short time. If the system is used to guide users to targets without a lot of visual clutter the achieved precision and speed would likely be sufficient.

As usual with systems utilizing EMS on humans, every user has a different comfort level and reaction to EMS intensities. We confirmed this in our user study and resulting qualitative feedback. This is another reason for the large variance in performance between users, as some did not turn EMS intensities high enough to have a sufficiently strong muscle response. For some users it was also hard to find the right muscles, which made the calibration phase of the user study last up to an hour.

Through testing our prototype and from user feedback we identified several variables that have an influence on systems utilizing EMS in a real-time scenario with a control loop as shown in Figure 9. Such parameters need to be taken into account when designing systems with EMS. A more sophisticated PID controller should be used in order to reach decent stability in a system. This PID controller should be auto-calibrated for each user individually as all the other variables also have an influence on how the PID controller has to react.

As a second step, we implemented an extension to our prototype in case the achieved precision from simple pointing is not high enough or there are multiple possible targets. In this case, a disambiguation approach based on dynamic targets should help users find the correct target.

Dynamic Targets

Our approach supports dynamic targets (i.e. the target is constantly moving with the time over a pre-defined shape) for disambiguation of targets with a lot of visual clutter. In order to reach a stable-enough system for dynamic targets, PID controllers have to be calibrated on a per-user-per-session basis. As a first step, we calibrated one experienced EMS user and did a small, *purely explorative* study on dynamic targets as shown in Figures 10-12. The user did not know which shape was currently active but knew about the possible shapes. The figures show single, exemplary trials where the system worked well. We measured the deviation (blue) from the baseline (green) to the current finger position (red) on the mid-air 2D plane of the dynamic target. This invisible 2D plane is projected in front of the user's finger right when the dynamic target execution is started and is aligned with the finger's orientation at that point in time.

Of course, this evaluation is purely explorative and cannot be generalized. Future work should do a large-scale user study on this subject.

Future Work

This is a first step towards developing a real-time EMS guidance and disambiguation system for the index finger in two dimensions. Several challenges regarding real-time feasibility of EMS-based systems surfaced. These challenges, specifically regarding EMS calibration and PID controller calibration will be addressed in future work.

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