Touch for spatial and motion representation: mathematical modelling and applications for advanced human-machine interaction.

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***Abstract*—The sense of touch plays an important role to build a perceptual representation of motion and space. This aspect deserves specific attention since it can guide the technological development of devices that can encode relevant information related to touch-related spatial information processing, as it is the case of Braille displays, and shed light on the neuroscientific mechanisms underpinning motion control and execution. In this paper, we report on the design an validation of an electromagnetic single-cell refreshable Braille display, named *Readable*. We also analyse and model the role of touch in guiding hand movement. To this aim, we performed experiments where we asked blindfolded participants to slide the fingertip on a ridged plate. We found that the orientation of the ridges produced a bias in hand motion direction. This is due to the fact that the tactile cues induced the illusion of bending towards a perpendicular direction with respect to the ridge orientation and this triggered a correction of the movement in the opposite direction. We modelled the integration of touch with classical muscular-skeletal proprioception using a Kalman filter model.**

***Index Terms*—Tactile feedback, Braille code, Tactile motion**

I. Introduction

The sense of touch contributes to the perception of spatial features. At the same time, it is well known that tactile cues contribute to human proprioception and motion perception [1]. The study of these aspects is extremely important: indeed, on one side, it can provide guidelines for the design and control of mechatronic devices, such as Braille displays, which specifically target the encoding of spatial features tailored on optimized exploration modes. On the other side, the investigation of the role of touch in controlling human motion could offer interesting insights on the neural bases of kinesiology and provide inspiration for the development of tactile feedback systems. In this paper, we report on the design and validation of a refreshable single cell Braille display and on the modelling of the integration of touch and classical muscular-skeletal proprioception. Regarding the first point, we presented a new low-cost electromagnetic refreshable single Braille cell, named *Readable*, presented in [2].

The device was tested by blind expert Braille code readers who showed their appreciation of the system through objective metrics and subjective quantitative evaluation. The readers also suggested applications of the *Readable* in every-day life. Then, in the second part, we reported on an experiment designed to show the importance of touch in guiding hand movements. To measure the contribution of touch in guiding reaching actions, it is necassary to dissociate it from the somatosensory cues from the musculoskeletal system (i.e. extracutaneous proprioceptive cues). Here, we used the tactile phenomenon, presented in [3], to decouple the two motion estimates. We have asked blindfolded participants to move their index fingertip on a ridged static plate [3], trying to move the hand along a straight ahead direction. If touch operates as a cue for proprioception, then the orientation of the ridges should produce a systematic error in hand trajectory because the subject would take into account the biased tactile signal, which is perpendicular to the ridge orientation [3], for motion estimation. If it were the case, coherently with [5], it is reasonable to hypothesise that subjects integrated the cues from touch and the ones provided by the musculoskeletal system in a Bayesian way. To test this hypothesis, we developed a Kalman filter model, and its outcomes were compared with our participants' trajectories.

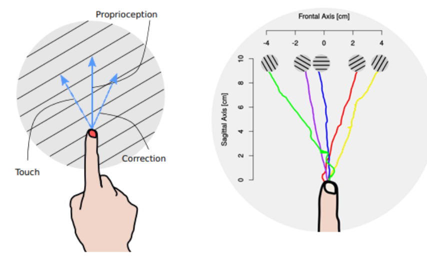

Fig. 1. Left: We assumed that, during the task, cues from muscular-skeletal proprioception provided an accurate measurement of the direction of motion (proprioception). Instead, the tactile feedback produced the illusion of bending towards a direction that is perpendicular to the ridge orientation (touch) [3]. This led to an adjustment of the motion towards the direction of "correction" (e.g the direction opposite to the one provided by touch). Right: Example of trajectories obtained for the different ridge orientation. Data for single participant. Plate orientations were -60, -30, 0, 30, 60°(cc by [4])

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Fig. 2. A blindfolded user using the *Readable device*

II. Readable Device

The *Readable* device (Fig.2) is a new low cost electromagnetic refreshable single Braille cell. The system is able to control independently six dots whose spacing is comparable with the standard Braille coding [6]. Each dot is attached to a ferromagnetic bar, and when a current i flows into the coils, the bar is attracted inside the hall of the solenoid and the dot goes down with respect to (w.r.t.) the reading surface. When the current stops flowing the bar is released, and the dot goes above the reading surface. The mechanism of attraction and relaxation of the bar is allowed thanks to the use of a spring, wrapped around the bar. (for more details refers to [2]). The device was tested with eight blind people, who were expert Braille code readers. This experimental campaign revealed that our system was not only capable to correctly reproduce alphanumeric stimuli (no statistical differences in the recognition of the coded stimuli when the subjects used the *Readable* w.r.t. the interaction with traditional paper letters), but also showed that the system could have applications in every-day life where it could offer real benefits to real end-users. Indeed, blind participants (2 female, 56 $\pm$ 20 y.o) underwent through a five points Likert scale and evaluated the interface as intuitive, cost-aware, useful and well-accepted. They also identified the areas where the usage of the *Readable* would be preferable w.r.t. the complete multi-cell Braille display or audio feedback. The areas are the following: displaying the status of the household appliances; integration in a cordless phone a call notification; showing the light status on/off. In future developments will move towards a more in depth analysis of the applicability of *Readable* in every-day life (e.g in navigation applications).

III. Touch is an auxiliary cue for proprioception

In [4], we designed an experiment in which blindfolded subjects had to slide their fingertip straight ahead on a plate with oriented parallel ridges. It is known from literature that the interaction with this kind of texture dissociates tactile feedback from other proprioceptive cues. In particular, as demonstrered in [3], the contribution of touch gives to the user a perceived direction of relative motion that is always perpendicular to the ridges during passive interaction tasks. In [4], we applied this paradigm to active tasks to demonstrate the contribution of tactile estimate in guiding the hand motion.. The results, reported in Fig. 1, show that touch contributes to guide hand movements since there is a systematic error in hand trajectories in the opposite direction w.r.t. the one given by tactile feedback. The outcomes brought us to the hypothesis that subjects integrated in an optimal fashion the contribution from cutaneous cues and the ones from extra-cutaneous cues. Indeed, our sensory system dynamically integrate different types of information on limb position. To test this hypothesis, we developed an ideal observer model based on Kalman filtering and we compared its prediction to our empirical finding.

A. Kalman filter model

Ideal observer models based on Kalman filtering have been often used to explain human behavior in different motor tasks [7]. In [4], we introduced an observer model for the integration of proprioception and touch in motor control. This framework is used to explain trajectory data for the reaching task performed on the ridged plate. The model, reported in Fig. 3, shows that the outcomes of the filter are able to reproduce the same trend of the empirical findings (for more details refers to [4]) These results could open interesting perspectives to design and control systems for advanced human-machine interaction and virtual/augmented reality.

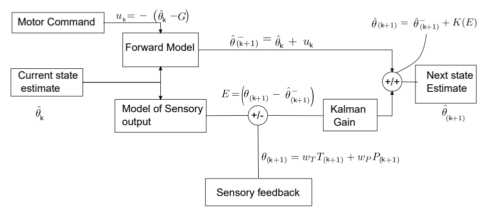

Fig. 3. A forward model, relying on the estimate of the current state and the motor command u_t (G is the *goal direction* (e.g. if the subject is instructed to move straight G is equal to $0°$)), predicts the following state of the hand (i.e., direction of the perceived hand direction w.r.t the mid-line of the plate). This internal estimate is compared with the sensory measurement, generating an error term. In this task, the sensory measurement is equal to a Bayesian integration of the extra-cutaneous proprioceptive and tactile cues. The error term, weighted by the Kalman gain, is used to update the estimate of the system and eventually corrects the motor command. (cc by [4])

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