Electro-stimulation of the tongue as a passive surgical guiding system

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Abstract

With the use of new per-operative Computer-Aided Systems, the surgeon is now even more confronted to problems of saturation by excessive feedback information. Indeed, during a classical surgery, the clinician is already confronted to problems of "saturation" by excessive multi-modal information: he has to take care of the patient, interact with the operating room staff, and check all the controlled screens. Therefore, adding a robot or a 3D localizer, with new screens to display information, is in contradiction with a lightening of the ergonomics: this over-saturates the surgeon visual channel. This paper introduces a system, called the Tongue Display Unit that proposes to use the tongue tactile proprioception as a feedback channel. A small matrix of 12 by 12 electrodes is put in contact with the tongue surface, and a signal is sent to each electrode in order to stimulate the mucous. This unit was evaluated in the context of sensory substitution, and is introduced here in a Computer-Aided Surgery framework, to per-operatively guide the surgeon gesture. The idea is to project a planned 3D trajectory (for example between a percutaneous incision and a given target) onto the 2D matrix of electrodes. First experiments are carried out in the context of percutaneous needle biopsy, provided onto a phantom of the human abdomen. Results for seven different subjects are presented and discussed.

1 Introduction

Computer Aided Surgery (CAS) is a growing research domain, with new designed systems that aim at assisting surgeons for the realization of diagnostic and therapeutic gestures that have to be safe and precise[1][2].In this context, many applications have been proposed, from the computer-aided planning for dental implant surgery[3] to the use of robots into the operating room(OR)[4]. Robots can be actively used to make a specific surgical gesture (for example drilling a hole into the femur to fix a hip prosthesis), or can be passively used to give information to the surgeon (for example plotting onto a 2D screen the actual position of a surgical ancillary, measured by the mean of a 3D optical localizer).

Introducing new systems into the OR is not straightforward at all. In addition to technical problems, ergonomics of these systems has to be addressed. Indeed, during a classical surgery, the clinician is already confronted to problems of "saturation" by excessive multi-modal information: he has to take care of the patient, interact with the OR staff, and check all the controlled screens. Therefore, adding a robot or a 3D localizer, with new screens to display information, is in contradiction with a lightening of the ergonomics. Indeed, this over-saturates the surgeon visual channel.

This work addresses this ergonomics problem, and proposes to convey the information provided by the CAS systems through a new channel, namely the lingual tactile channel.

2 Previous work: sensory substitution

Paul Bach-y-Rita has explored since the 70's the notion of sensory substitution. The underlying idea is to convey information through the brain, by exploring a sensory channel that is not the usual one. A good example given by Bach-y-Rita is the claim that "we see with the brain, not the eyes"[5][6]. In that example, a blind person with no pulse train coming form the retina can compensate and substitute with another modality: this person

navigates with a long cane, and has a 3D perception of a room or a step. Here, whereas the interaction between the cane and the body is a tactile sensation in the hand, the blind person perceives a clear mental image of his environment. Following the same idea, Bach-y-Rita developed tactile vision substitution systems to provide visual information to the brain through arrays of stimulators in contact with the abdomen, back and finger skin. Optical images are recorded by a TV camera and transduced into vibratory or electrical stimulations that are mediated by the skin receptors[7]. After sufficient training, subjects perceive an image in space rather than a tactile stimulation. Bach-y-Rita recently converged to the electro-stimulation of tongue surface that overcomes practical problems demonstrated for other skin interfaces. Indeed, human tongue is very sensitive, highly discriminative, and doesn't require high voltage and current, because of the saliva that assures good electrical contacts. A practical human-machine interface, via the tongue, was therefore developed and recently evaluated for blind persons[8][9].
This Tongue Unit Display (TDU) is introduced here in the context of Computer Guided Surgery. The TDU is not used as a complete substitute system to vision, but is used to convey information about the position of a surgical ancillary, optically localized inside the OR. The surgeon can therefore concentrate onto the patient, while getting lingual electro-stimulated information about the position of his surgical tool.

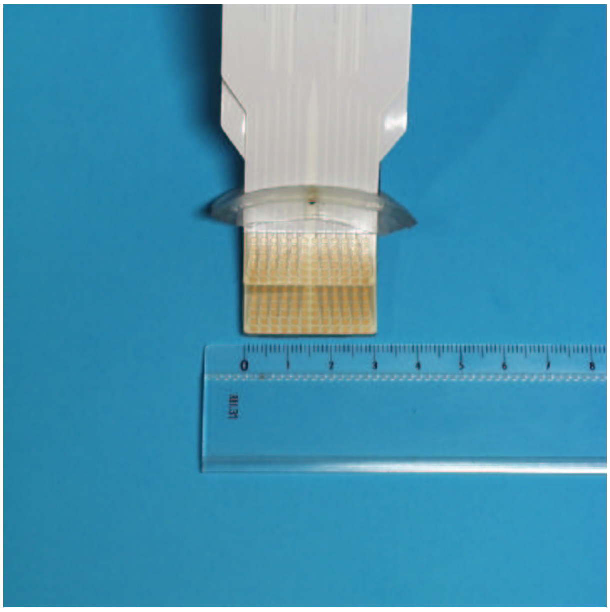

Figure 1: *TDU Interface: a matrix of 12x12 electrodes are individually stimulated*

3 The Tongue Display Unit

The Tongue Display Unit (TDU) consists of a 12 x 12 array (measuring 3cm by side) of electrical stimulators on a ribbon strip that is held in the mouth, against which the tongue can rest (figure 1).

Thanks to the saliva that provides a good electrical contact, tongue only requires a 5-15V output voltage and a 0.4-2.0 mA current. Each gold-plated circular electrode has a 0.7 mm radius and a distance inter-center of 2.3 mm. Their electrical stimulation can be individually controlled by an external electronic package that is connected to a computer. For the actual version of the TDU, the ribbon strip is physically linked to the electronic package, which is of course not very ergonomic. Next developments will focus on a wireless version of the TDU.

4 Guiding with the TDU

Per-operative passive guidance provided to the surgeon nowadays mainly consists in localizing a surgical tool, in relation to the patient. The orientation of a drill can for example be detected and compared to the optimal trajectory that has been pre-operatively defined. Another example is the localization of a puncture needle and its position in relation to a predefined target (tumor inside the patient body for example). For both examples, the task consists in comparing the actual orientation of an ancillary with an optimal predefined trajectory.
In this perspective, a very simple and intuitive algorithm was chosen to code, onto the TDU, the difference between the actual orientation of the ancillary and the suited one.
The idea is that no electrical stimulation is provided if the surgical tool is well oriented and points towards the target. On the contrary, if the tool orientation is wrong, an area of the TDU electrodes matrix are stimulated. This stimulated zone indicates to the surgeon the wrong orientation of the tool. Figure 2 presents this coding. In this case, the "north-west" area of the TDU is active, which means that the surgeon must move the tool in the south-east direction. Moreover, in order to evaluate to which extend the tool orientation is far away from the planned trajectory, it was chosen to provide an electro-stimulation that is proportional to the error angle α.

5 Experimental setup

The example of a percutaneous surgical gesture was chosen for this application. This can be needle biopsy, or percutaneous radio frequency and cryosurgical tumor ablation for example.

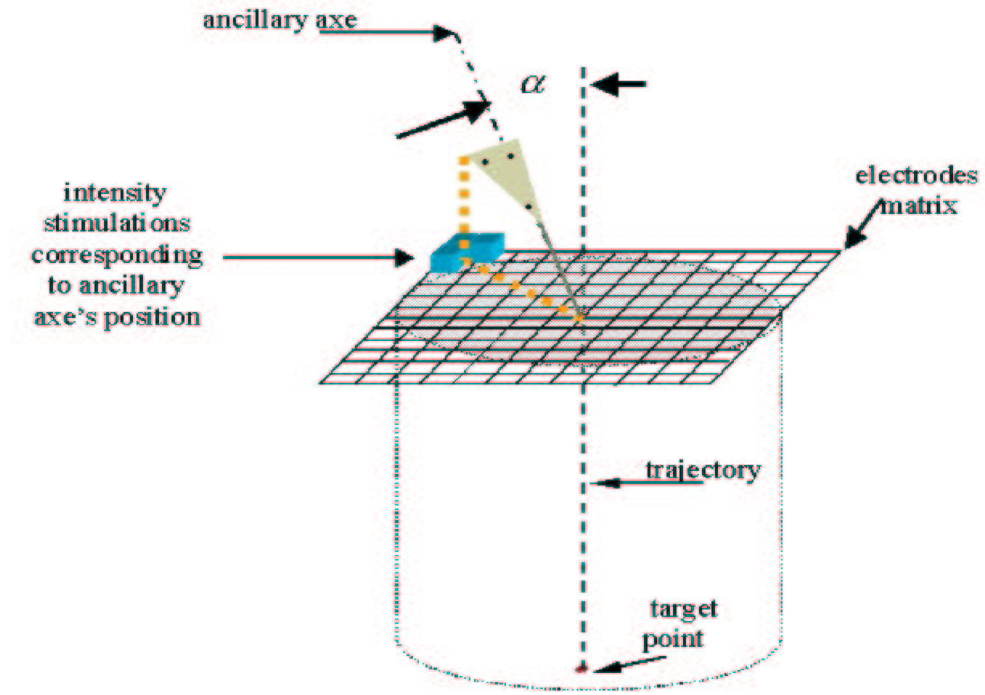

Figure 2: *Coding the differences between tool orientation and direction towards the target point. Electro-activation of a TDU region means an incorrect orientation in this direction*

Experiments were first provided on a phantom of the human abdomen. An intra-operative definition of the target was assumed for the experimental setup: ultrasonic images were used to localize the target inside the phantom. For this, we equipped the ultrasound probe with localization features (called "rigid bodies") that are tracked in real time using a localizer (Polaris© optical localizer, NDI Inc.). Therefore, each time that an ultrasound image is recorded, the six position parameters of the probe(translation and rotation) are also recorded, thus localizing the 2D echographic image in the 3D space; this device is called "2.5 echography" (as shown in figure 3).

Once the surgeon has found the optimal position of the 2D ultrasound probe that allows him to see the target, one can freeze the image and record the corresponding 3D position of the 2D echographic plane. Then, the surgeon can precisely choose a point onto the frozen ultrasound image. This point defines the target inside the abdominal phantom. The 3D coordinates of this target are then computed from the 2.5 position of the frozen ultrasound image.

The next stage is the passive guidance of the surgical gesture, by the mean of tongue electro-stimulation. As for the ultrasound probe, markers were fixed onto a puncture needle. The orientation of this needle is therefore detected by the localizer, and compared

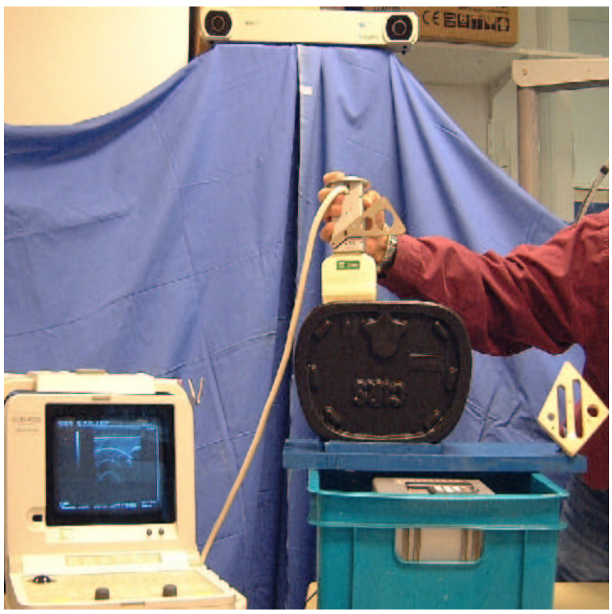

Figure 3: *3D localization of the 2D echographic image*

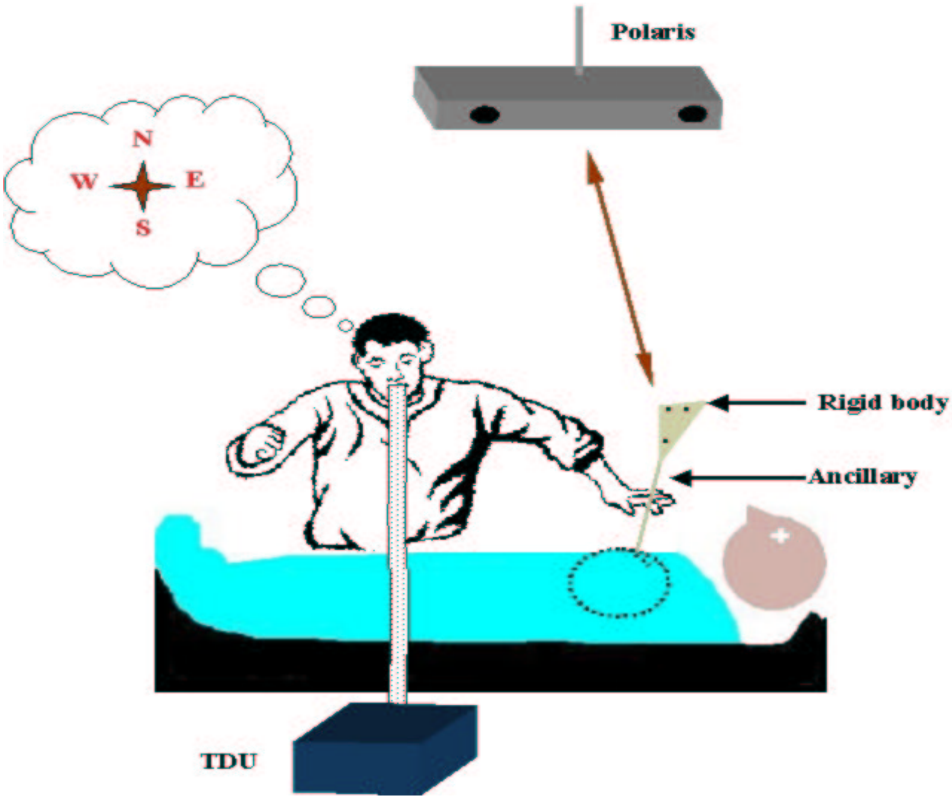

Figure 4: *3D localization of the biopsy needle and TDU guidance*

with the orientation that would drive the needle in the direction of the target (figure 4).

6 Results

Seven volunteers were chosen to first evaluate the feasibility of the guidance system. Those subjects were mainly scientists belonging to our laboratory. Their dexterity and accuracy can therefore be considered as lower than those of doctors or surgeons.
Before guiding the subjects, a 15 min training phase was proposed to introduce to them the electro-tactile sensation provided by the TDU. The task was to try to discriminate the position of nine local stimuli (one in the center of the matrix and the other ones in the periphery: north, south, east, west, north-east, north-west, south-east and south-west). The user indicates the perceived stimulus position by pointing out one of the nine cylindrical objects positioned in front of him. Finally, this training phase aims at making users become familiars with the task of associating local lingual stimuli and suited orientation of a surgical tool. A north-east electro-stimulation of the tongue is perceived as a bad orientation of the tool that has therefore to be moved in the opposite direction, namely the south-west. The deviation from the suited trajectory is coded with a current intensity level that is proportional to the deviation; this means that no electro-stimulation is provided if the orientation is correct with a needle going straight towards the target.
Table 1 provides measurements for the seven volunteers. Time to reach the target, as well as final distance between the tip of the needle and the target position are presented. Five successive trials were recorded for each volunteer.

The tendency is that the user becomes more familiar with each new trial, and tends to accelerate his puncture gesture. This acceleration is unfortunately not consistent with an increase in the target reaching accuracy. Subjects go quicker in the direction of the target, but tend to be less accurate. Table 2 provides the mean and standard deviation of distances and performance times. It is interesting to note here that a 2.3 mm (+/- 0.5 SD) mean distance to the target can be computed for all the subjects.

user	trials	time(s)	distance(mm)
1	1	322	1.60876
	2	207	1.94225
	3	196	1.54726
	4	87	1.75678
	5	69	2.85278
2	1	409	2.06533
	2	167	2.44324
	3	124	0.769341
	4	78	1.06919
	5	44	5.68156
3	1	244	0.263861
	2	201	0.905418
	3	79	1.64511
	4	59	0.922402
	5	53	3.70837
4	1	250	3.8266
	2	247	2.51926
	3	121	5.82494
	4	84	3.90272
	5	57	1.02968
5	1	410	1.86717
	2	128	1.78636
	3	107	1.66214
	4	35	3.89878
	5	29	1.7292
6	1	202	4.48587
	2	177	0.968743
	3	93	2.58884
	4	82	4.29309
	5	34	4.33379
7	1	309	2.86816
	2	82	1.1462
	3	81	1.52963
	4	33	1.64817
	5	28	2.0219

Table 1: *Measured results showing time and distance to the target*

user	mean distance to target(mm)	mean time(s)
1	1.941566	176.2
2	2.4057322	164.4
3	1.4890322	127.2
4	3.42064	151.8
5	2.18873	141.8
6	3.3340666	117.6
7	1.842812	106.6

Table 2: *Data results showing mean distance to target point in milimeters and performance time in seconds*

7 Discussion

First results are very encouraging. Indeed, subjects that have no clinician professional background and spent only a few minutes in training with the TDU, were able to reach a target with an accuracy that is in mean below 3 mm. This accuracy is encouraging for three reasons. First, the value is very low. Second, it has to be compared with other sources of errors that can have been superimposed to the TDU guidance: echographic calibration, bending of the puncture needle, accuracy of the localizer. Finally, it seems that subjects were able to "feel" the tongue electro-stimulation as a real 3D guidance rather than a 2D tactile stimulation. This last point is particularly important, knowing that the training phase required for this experiment vas very short (less than 20 minutes).
In conclusion, the results provided by our phantom experiment seem to demonstrate the feasibility of the lingual guiding system. This needs of course to be more quantitatively validated, especially with surgeons, and with more complex trajectories. Another perspective is to try to quantify the optimal duration of the TDU training phase. Finally, future developments will focus onto a wireless version of the TDU, probably clipped onto a thin artificial palate, in order to be ergonomically introduced into the operating room and used by the surgeon.

Acknowledgments

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