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A high-resolution tongue based joystick to enable robot control for individuals with severe disabilities

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***Abstract*— Assistive robotic arms have shown the potential to improve the quality of life of people with severe disabilities. However, a high performance and intuitive control interface for robots with 6-7 DOFs is still missing for these individuals. An inductive tongue computer interface (ITCI) was recently tested for control of robots and the study illustrated potential in this field. The paper describes the investigation of the possibility of developing a high performance tongue based joystick-like controller for robots through two studies. The first compared different methods for mapping the 18 sensor signals to a 2D coordinate, as a touchpad. The second evaluated the performance of a novel approach for emulating an analog joystick by the ITCI based on the ISO9241-411 standard. Two subjects performed a multi-directional tapping test using a standard analog joystick, the ITCI system held in hand and operated by the other hand, and finally by tongue when mounted inside the mouth. Throughput was measured as the evaluation parameter. The results show that the contact on the touchpads can be localized by almost 1 mm accuracy. The throughput of ITCI system for the multi-directional tapping test was 0.82 bps while keeping it in the hand and 0.73 bps when using it inside the mouth, comparing to 1.99 bps throughput of the analog joystick.**

I. INTRODUCTION

Severely disabled individuals such as individuals with complete tetraplegia are dependent on full time caregivers and can not manipulate their surroundings or interact socially in a physical manner. Assistive devices such as robotic arms [1][2][3] can empower such individuals to perform physical tasks such as eating and drinking and thereby increase their independency and quality of life.

However, control devices for these robots are lacking for those most in need, whom are paralyzed in both arms and legs such as in tetraplegia. Lately, tongue computer interfaces (TCI) have been introduced for control of robotic devices [4][5]. Of these, the tongue drive system (TDS) provides 6 separate command signals [6] and the Inductive Tongue Computer Interface (ITCI) allows for 18 separate command signals [5]. The ITCI has therefore potential to directly and continuously control current commercial ARMs [3][7] in a 3D space which requires 6 degrees of freedom (DOF) for controlling the position and orientation of the end effector and 1-2 DOF for controlling the gripper. The ITCI is an intraoral input device that has been developed for people with severe disabilities to interface personal computers, drive wheelchair and communicate with other electronic devices. The system consists of a mouthpiece that is mounted inside the mouth under the hard palate and sends the sensed values wirelessly to a central unit. It encompasses 18 inductive sensors arranged in two plates, called keypad area and mousepad area. The sensors are activated by a small metal unit that is pierced or glued to the tongue (Figure 1).

A survey on understanding computer users with tetraplegia was performed [8] to investigate the desire and preferences of the users and the results were used for further development of the system. Different positioning and layouts of the sensors was evaluated [9] to find the optimal design of the sensors and facilitate easy access and manipulation of the interface [10][11]. The ecological validity of the ITCI system for typing [12] and controlling the cursor of a computer [13][11] and driving a wheelchair [14] was investigated both on able-bodied and disabled individuals.

Recently, the ITCI has been deployed in robotic devices such as prosthetic hands [15], assistive robotic arms [5], drones [16] and exoskeletons, which requires control in three dimensions (3D) and thus more advanced interfacing. Previous studies have shown that by interpolating the signals from the inductive sensors on the ITCI system, a touchpad-like input can be achieved [17]. This potential provides the possibility to develop different layouts of virtual keys and mousepads that can enhance the 2D to 3D mapping from the tongue interface to the robotic motions.

Therefore, the first part of this study, introduces different interpolation methods that map the sensors signal form the ITCI to a high-resolution two-dimensional coordinate and compares the accuracy of these methods. In the second part, we use such an interpolation method to emulate a tongue-based analog joystick. The joystick can be used for controlling 2 DOFs of devices such as assistive robotic arms, drones, exoskeletons and wheelchairs. Furthermore, the performance of the ITCI system and the new joystick emulation method is evaluated based on ISO9241-411 standard.

II. METHODS

A. System Overview

The ITCI system works based on Faradays law. It contains 18 inductive sensors made of a 10-layer printed circuit board. Proximity of a ferromagnetic metal changes the inductance of the sensors and produces an activation signal processed by embedded electronic circuits. The ferromagnetic activation

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unit (AU) is a cylindrical piece of metal (2 mm high and 4 mm in diameter) that usually gets attached to the tip of the tongue, either by gluing or as a piercing. The sensors are configured in two parts, one consisted of ten sensors in the anterior part called keypad and another on the posterior part consisted of eight sensors called the mousepad (Fig. 3). The inductive sensors, electronic circuits, battery and wireless communication elements are integrated in a part, called the mouthpiece unit (MPU) that is mounted inside the mouth and fastened to the teeth like an orthodontic retainer (Fig. 1). The MPU wirelessly sends raw data to the central unit (CU) for further processing. The CU communicates with a PC through Bluetooth or via a USB cable.

B. Input-Output (I/O) mapping methods

In order to estimate the position of the AU on the sensor plates, it is necessary to map the 18 signals from the inductive sensors to an XY, 2D coordinate. Having a touchpad-like input from the system can extend its potential applications by providing the possibility to develop different layouts of virtual keys for interfacing different devices.

A Sugeno type fuzzy inference system (FIS) was previously developed for interpolating the 8 sensors of the mousepad to estimate the AU position over the sensors and emulate an analog joystick [17]. The FIS model had eight inputs and two linear outputs and was trained with three I/O training sets (training, testing and checking) using an adaptive neuro-fuzzy inference system (ANFIS) in MATLAB.

In addition to FIS, we developed another two interpolation methods. The first method was a weighted average of neighbor sensors (WAN). In each sample of the sensor signals, the algorithm identifies the sensor that has the highest activation. Then it estimates the AU position by using the weighted average over the position of that sensor and its neighbor sensors. The weights are the normalized values of sensor activation (w_t). Equation (1) shows how the AU position in t instance (p_t) is obtained. In (1), ns_i is the vector of neighbor sensors of the i sensor that has maximum activation. It is a vector of 18 elements that has 1 value for sensor i and its neighbors and zero for the others. The $p_{sensors}$ is an 18x2 matrix that contains the position of center of sensors in a frame that has the origin in the left-button side of the mousepad. The $\circ$ operator in $[w_t \circ ns_i]$ is the Hadamard product or the element wise product and $w.ns_i$ is the dot product of the two vectors.

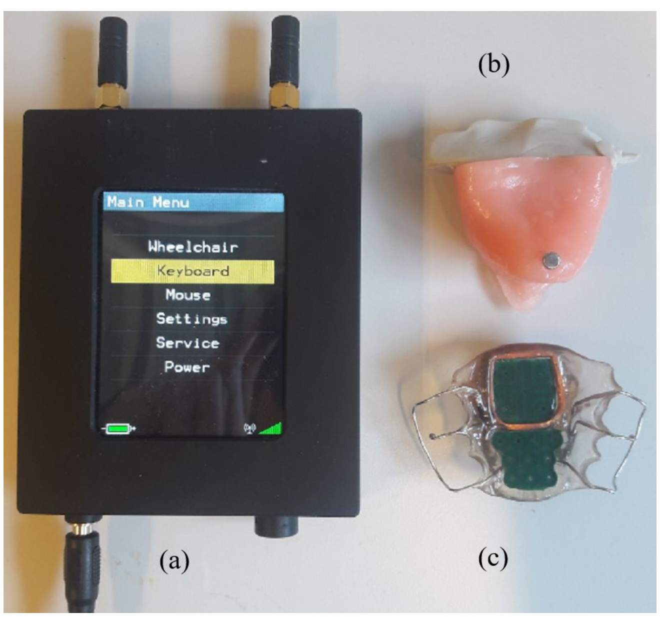

Fig. 1: The inductive tongue control interface modules. a: The central unit, b: The activation unit on a phantom tongue, c: The mouthpiece

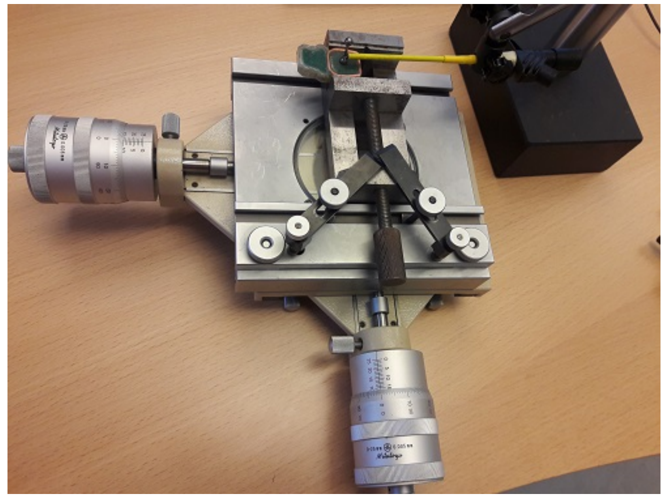

Fig. 2: Resolution test setup

$$p_t = \frac{(w_t \circ ns_i) \times p_{sensors}}{w_t \circ ns_i} \tag{1}$$

A nearest neighbor classification (NNC) method mapped the input signals to an XY coordinate. It estimated the AU position by comparing the sensor values with the points in a dataset of known I/O (sensor values and the position of the AU) from a mesh of 1 mm interval over the whole touch sensitive areas. The point in the dataset that had the minimum Euclidean distance with the sensor values in an 18 dimensional space was considered as the position of the AU.

C. Recording datasets A resolution test for comparing mapping methods

A precision linear stage with two vertical axes and 0.01 mm precision was used to record datasets of known position of the AU over the MPU and its corresponding sensor outputs. The MPU was fixed on top of the stage (Fig. 2). Another mounting tool kept the contact between the AU and the touch sensitive surfaces. Data was recorded from a mesh of 1 mm interval from three MPUs and two times each. We used the two datasets for training and testing the mapping methods (FIS and NNC). Then the sensor inputs were processed by FIS, WAN and NNC and the estimated AU positions were compared with the actual position to obtain the error (the Euclidean distance between the actual position and the estimated position in 2D). To evaluate each dataset, the other dataset from the same MPU was used for training to avoid overfitting the model.

D. Emulating an analog joystick a new approach

A virtual joystick allows fine and continuous control of an object in 2D by providing a proportional velocity control in any direction in a plane, comparing to discrete control in a constant speed and specific direction. It can be very handy for controlling a computer cursor, a wheelchair or a robotic arm.

In the previous method presented in [17], the mousepad area is used as a joystick. The center of the mousepad is the origin (Fig. 3, red circle) and any contact of the AU makes a vector. The length of the vector is proportional to the velocity and its direction specifies the moving direction (Fig3, blue arrows). This method maps the position of the AU to a velocity control (P2V).

In the approach proposed in this paper, the user makes a contact on either the mousepad or the keypad area and moves the AU while keeping it in contact, like dragging a line. Again, the moving velocity and direction is specified by the length and direction of the line (Fig3, red arrows). However, the origin is not fixed anymore and can be any point (the initial contact). In another word, it maps the displacement of the AU to a velocity control (D2V). In this way, the user does not need to find the specific position of the AU corresponding to the intended velocity and direction, which might need higher proficiency in using the ITCI, or looking at a visual feedback from the AU position on a screen. Furthermore, D2V provides a higher resolution joystick comparing to P2V, almost twice, by allowing to drag longer vectors (the diameter of the mousepad, instead of its radius).

E. Multi-directional tapping test

Important success factors for any input device, especially for people with disabilities, are the comfort, accuracy, and speed. The ISO9241-Part 411 [18] provides guidelines for evaluating these factors on physical input devices. It is a well-known reference for benchmarking input devices in the human-computer interaction community. The performance measures are widely used in the literature, which makes it possible to compare the developed system with some of the standard and well-established interfaces such as mouse, keyboard and gamepad joystick [19], as well as other especial interfaces for people with disabilities [20][21][22]. The performance measures based on the standard can also inform the end users, caregivers, and clinicians about the capabilities of different devices.

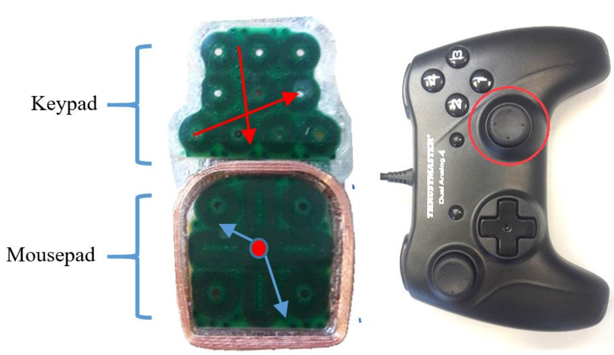

Fig. 3: Left: Emulating a virtual joystick on the ITCI system. Right: The gamepad joystick that was used in the multi-directional tapping test

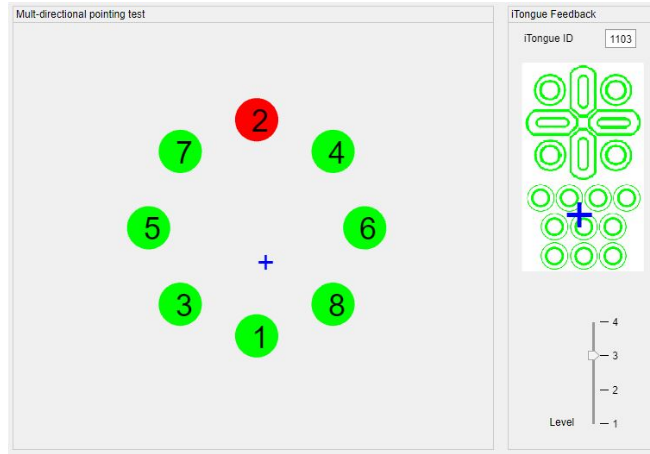

Fig. 4: Multi-directional tapping test

To evaluate the performance of the D2V virtual joystick, we used the multi-directional tapping test of Annex B of ISO9241-411 standard. This test specifically targets pointing devices in two dimension. The task is to move the cursor and select several targets that are arranged around the circumference of a circle (Fig. 4) with equal distances and in a sequence that each target is diagonal to the previous and the next target. A target is selected when the cursor stops in its area for a dwelling time of 1 second.

The performance measure in this test is Throughput (TP), which represents the amount of information sent by the interface in bits per second (bps). It is based on the Fitts law and accounts for both speed and accuracy. TP is calculated as the ratio between the index of difficulty (ID) and the average moving time (MT) over tasks with same ID.

$$TP = ID/MT \tag{2}$$

The ISO standard uses the effective ID (ID_e) measured in bits and defined as:

$$ID_e = log_2(1 + d/w_e) \tag{3}$$

Here, d is the distance from the initial point of the cursor to the target. The effective target width is

$$w_e = 4.133 \times SD_x \tag{4}$$

where SD_x is the standard deviation of the distances between the center of the target and the selected point by the subject, in the direction where movement proceeds [23]. ID_e accounts for variability of accuracy in selecting all of

TABLE I: TASK LEVELS d IS THE DISTANCE BETWEEN TARGETS AND w IS THE WIDTH OF TARGETS

Level	d (pixel)	w (pixel)	ID (bits)
1	200	50	1.58
2	250	40	2.04
3	300	30	2.58
4	400	20	3.46

the targets over a trial and it shows the performance of the subject, rather than the difficulty.

Two subjects participated in the experiment, both from colleagues in the research group. We chose the range of difficulties similar to other studies in the field [21] [20][11], from 1.6 bits to 3.5 bits. The subjects were asked to perform the task in four difficulty levels (table 1), tree repetition each, and 12 trials in total. The evaluation process was done in three different input methods. In the first one, the subjects used a standard gamepad joystick (Dual Analog 4, Thrustmaster®, Fig.3 - right image). We set the frequency of reading the joystick values to 30 Hz, equal to the frequency of sending data from ITCI system. In the second, they used the ITCI system, while keeping it in one hand and moving the AU with the other hand. Finally, they used an ITCI that was custom made for each of them inside the mouth. The AU was glued to the tip of their tongue using a special tissue glue (Histoacryl®). One round of the whole test process was performed for training in each modality before the test.

III. Result

A. Comparing mapping methods

Table 2 shows the root mean squared error (RMSE) of each mapping method over the mousepad, keypad and the overall, including both areas. The values are the average over the points in the two recorded datasets, including more than 400 point from each MPU. The most accurate method was the nearest neighbor classification with overall RMSE of 0.97 mm. It was followed by the weighted average of neighbor sensors with slightly higher RMSE of 1.16 mm and the fuzzy inference system with 1.74 mm. It is also evident that we can achieve higher accuracy on the keypad area, compared to the mousepad. This study provided us with a map of the error distribution on the touch sensitive areas. This can be a design parameter in developing control layouts. Figure 5 shows that the accuracy is lower around the center of the mousepad. It depicts the measured error from the WAN method on

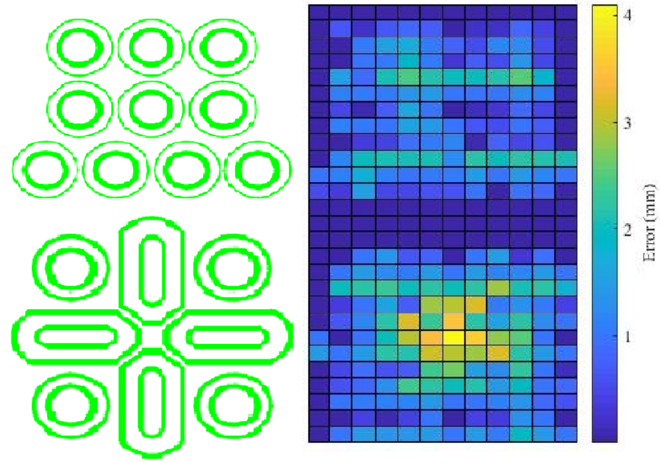

Fig. 5: Left: Distribution of error in estimating the AU position by the WAN method over the touch sensitive planes. Data are recorded from a mesh of 1 mm interval. The dark blue points in the middle of the figure are related to the space between the keypad and the mousepad that are not touch sensitive. Right: Layout of sensors

device #2. We observed similar patterns on other MPUs and methods.

Based on the above-mentioned results, the WAN method was used for developing a virtual joystick, despite the NNC being more accurate. The overall RMSE of WAN is 1.16 mm that is very close to NNC (0.97 mm). However, it is computationally lighter, which makes it a better choice for real-time processing. Furthermore, it was more stable than NNC, as we observed small flickering in the cursor while using NNC. The flickering is due to the discrete localization of the AU in a mesh of points with 1 mm interval and jumping between neighbor points due to the noise.

B. Multi-directional tapping test

The throughput was calculated from ID and ID_e. ID_e as both of them are used in the literature. Table 3 depicts the grand mean value and the standard deviation (in parenthesis) for each subject, as well as the mean value of both subjects. The throughput of a gamepad joystick for both subjects was 1.99 bps similar to values reported in other studies, i.e. [19] which reported 2.14 bps (SD=0.40). The ITCI system has a better performance when it was used in the hand (TP_e = 0.82 bps), comparing to inside the mouth (TP_e = 0.73 bps).

TABLE II: MEAN SQUARED ERROR (mm) OF MAPPING METHODS THE GREEN CELLS INDICATE THE METHOD WITH THE MINIMUM RMSE

Device	Mousepad			Keypad			Overall		
	FIS	WAN	NNC	FIS	WAN	NNC	FIS	WAN	NNC
#1	1,41	1,45	1,48	2,45	0,94	0,54	1,89	1,21	1,04
#2	1,40	1,19	1,07	2,21	0,78	0,79	1,91	1,08	0,98
#3	1,32	1,47	1,13	1,52	0,88	0,64	1,42	1,19	0,90
Mean	1,38	1,37	1,22	2,06	0,87	0,66	1,74	1,16	0,97

TABLE III: THROUGHPUT AND THE EFFECTIVE THROUGHPUT IN BPS FROM DIFFERENT INPUT METHODS, MEAN VALUE AND STANDARD DEVIATION IN PARENTHESIS

	Gamepad joystick		ITCI in hand		ITCI in mouth	
	TP	**TP_e**	**TP**	**TP_e**	**TP**	**TP_e**
sub_01	2,26 (0,24)	1,99 (0,45)	0,99 (0,34)	0,75 (0,09)	0,95 (0,24)	0,70 (0,12)
sub_02	2,49 (0,13)	1,99 (0,28)	1,00 (0,19)	0,88 (0,15)	0,91 (0,15)	0,76 (0,10)
Mean	2,37	1,99	1,00	0,82	0,93	0,73

IV. Discussion

The resolution test illustrated that we can achieve an accuracy of about 1 mm in positioning the AU on the touchpads, either by the WAN or the NNC methods. The accuracy on the keypad area was slightly higher than on the mousepad, which makes it a better choice for emulating a virtual joystick. Another limitation of this test was the mesh size of 1 mm. Measuring the points in a higher density (a mesh of shorter intervals) may provide us with a more accurate measure of the accuracy and its pattern on the touchpads.

In both of the methods for emulating a joystick on ITCI, the property that the device senses is the tongue position. The output signal controls the velocity of the object or view. Zhai [24] investigated which mappings of sensed property to the controlled property are best in terms of speed and accuracy for common point-select tasks with joysticks. He concluded that for a position-sensing device, position control is the best. However in our case, due to low availability of motor space, it is better to map position sensing to velocity control.

The higher performance of ITCI system in hand can be due to higher dexterity of the hand comparing to the tongue and further that the use in the mouth is blind. Furthermore, we have more experience and skill in using the hand for manipulating a joystick.

In this study, we used a standard joystick as the baseline for evaluating the TP and to check the validity of our experimental protocol by comparing its performance with other studies. However, we can not compare the assistive performance of a well-stablished hand based joystick with a unique device developed for people with tetraplegia who can not use their hands. Another consideration for a between-study comparison is that minor difference in the measurement method can lead to significant variation of the result.

An important factor in using ITCI system is the amount of training and experience of the users. A study on motor learning ability of the tongue showed that 30 minutes practice in three consecutive days can improve the performance by 30% [9].

The main objective of our study was to develop a high-resolution tongue based joystick to enable robot control for individuals with severe disabilities and evaluate its performance using standard methods. The next step will be to use the virtual joystick for controlling a robotic arm and evaluate the system on more subjects.

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