Passive Wireless Tags for Tongue Controlled Assistive Technology Interfaces

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School of Engineering, The University of Kent, Canterbury, CT2 7NT, UK.
E-mail: j.c.batchelor@kent.ac.uk

Tongue control with low profile, passive mouth tags is demonstrated as a human-device interface by communicating values of tongue-tag separation over a wireless link. Confusion matrices are provided to demonstrate user accuracy in targeting by tongue position. Accuracy is found to increase dramatically after short training sequences with errors falling close to 1% in magnitude with zero missed targets. The rate at which users are able to learn accurate targeting with high accuracy indicates that this is an intuitive device to operate. The significance of the work is that innovative very unobtrusive, wireless tags can be used to provide intuitive human computer interfaces based on low cost and disposable mouth mounted technology. With the development of an appropriate reading system, control of assistive devices such as computer mice or wheelchairs could be possible for tetraplegics and others who retain fine motor control capability of their tongues. The tags contain no battery and are intended to fit directly on the hard palate, detecting tongue position in the mouth with no need for tongue piercings.

1. Introduction: Powered wheelchairs give mobility to people who would otherwise be unable to move around independently [1]. A real-time response in navigation and steering systems to facilitate collision avoidance is an important factor in semi-autonomous powered wheelchair design. Incorporating a degree of intelligence can be beneficial in assistive technologies but they must be adequately dynamic to identify and accommodate for patients who may offer control inputs of varying accuracy and which may change over the short or long term owing to fatigue, degenerative, or improving conditions. Therefore, in rehabilitation scenarios assistance should not be over-supportive or intrusive and must be dynamically altered to suit the current needs of a patient. When administered correctly, the rehabilitation procedure should provide the correct level of support to encourage patients to gain increased independence as they learn to manage a condition and control an assistive technology such as a powered wheelchair. This issue is the subject of SYSIASS, a European Commission funded project where autonomous powered wheelchair technology is supported by sensors to prevent collisions with door frames, static objects, and people [2].

The standard means of controlling a powered wheelchair is by the use of a hand joystick; but many severely disabled people, including tetraplegics, have either no, or inadequate, hand control to use a standard joystick. For these users, a range of alternative human input devices (HIDs) is available, including chin joysticks, head switches and sip-puff devices [3]. This client group also has difficulty, both in communicating, and also controlling a computer mouse [4]. Again, there are several alternatives to hand controlled computer HIDs, including chin switch [5], head movement [6, 7], voice control [8], EMG [9], EEG [10, 11] and 'Eyegaze' [12-14] which tracks user eye movements as they scan a screen but this is not suited for wheelchair control, as the environment should be observed while moving, rather than the control screen. Therefore, although a range of assistive technologies currently exist, the HIDs described can provide frustratingly limited or slow control.

However, a large proportion of this user population retains normal, or almost normal, use of the tongue which is an extremely dexterous organ very suited for use to operate a HID. Tongue control systems are described in [15-19] but they rely on wired connections from the mouth, or intrusive tongue piercings. The initial design of a wireless passive mouth tag for tongue sensing with no need for piercings was introduced in [19, 20].

2. Epidermal RFID Electronics: Radio Frequency Identification (RFID) [21] was originally developed for asset monitoring of goods but is becoming a more pervasive technology with a range of applications including distributed sensor networks and wearable uses such as personal security and mobile healthcare [22-24]. A passive UHF RFID epidermal transfer tattoo tag has been presented [25] and the idea to utilize this technology in assistive systems was introduced in [26] where an epidermal strain gauge attached above the eyebrows or on the neck acts as a muscle tweak sensor for joystick or mouse control. The epidermal strain gauge is battery-free (passive) and communicates wirelessly to an external reader using RFID technology.

In this paper we describe the testing of a UHF RFID tag in the form of a tongue proximity sensor to facilitate tongue control of a wheelchair or computer mouse communicating with a future reading system. The sensing tag structure was introduced in [19] with an initial tongue controlled target response for a single user described in [20]. In this paper, for the first time, the operation of the tag is established with multiple user testing and data is provided to indicate the training times required and the resulting accuracy of the tongue position sensing is assessed.

3. In-Mouth RFID Tag: The concept of placing an epidermal tag on the hard pallet was introduced in [19] where it was demonstrated that the backscattered tag signal power is a function of tongue proximity. A tag prototype with the dimensions in Table 1 was created on a 0.043mm thick copper clad Mylar sheet as shown in Fig. 1 and attached to the hard palate in the mouth, Fig. 2.

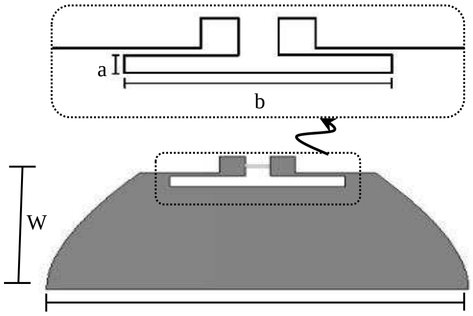

Fig. 1 Geometry of the tongue touch sensor tag [19].

The capacitance due to the tongue proximity detuned the tag which was detected as a function of power transmission coefficient at the tag terminals, Fig. 3. This affects tag gain, backscattered and transmitted RFID reader powers as the tongue moves with respect to the tag. The tag is energized by a reader antenna placed 30cm in front of the mouth.

Table 1: Dimensions of Tongue Touch RFID Sensor

Slot width, a (mm)	Slot length, b (mm)	Tag width, W (mm)	Tag length, L (mm)
15	0.5	0.5	10

(a) (b)

Fig. 2 (a) Simulated Tag, (b) Tag Under Test.

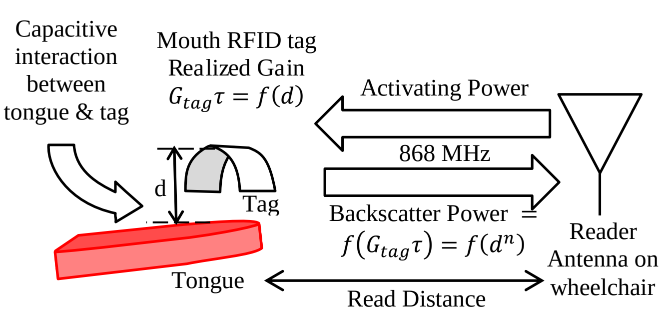

Fig. 3 Tongue loaded RFID tag with forward and reverse power links.

Using the human tissue properties obtained from [26], CST Microwave Studio® electromagnetic simulations of the 3D modelled tag and mouth in Fig. 2(a) were taken for comparison with measurement at fixed tongue-tag separations. The tag power input transfer coefficient τ and antenna gain G_{tag} were obtained from the simulation in each case. The Realized Gain in Fig. 3 is the product of G_{tag} and τ where:

$$\tau = 1 - |\Gamma|^2 \qquad (1)$$

and Γ is the antenna voltage reflection coefficient with values between $0 < |\Gamma| < 1$ [27]. Ideally, $\Gamma \rightarrow 0$ meaning the tag antenna is well matched to its RFID transponder chip and this situation is determined by setting the slot dimensions a and b (defined in Fig. 1) in the absence of the tongue. However, as the tongue approaches, the fields in the slot are perturbed, making Γ, τ and hence Realized Gain a function of tongue proximity to the tag. Figure 3 indicates how the tongue-tag interaction distance d affects the backscattered power which is received by the reader antenna. This is because the backscattered power is proportional to the product of the power available at the tag and the realized gain [20]. The propagation index n has a value found empirically to be about 4 and which arises from lossy tissue loading effects.

The Realized Gain relationship to tongue-tag distance d was reported in [19] and is shown here in Fig. 4 for reference together with newly acquired average measurement for 3 users. The measured backscattered power was obtained using calibrated Voyantic Tagformance Lite equipment for the 3 different users with polystyrene blocks (relative permittivity $\varepsilon_r = 1$) in their mouths to control the distance d. The Voyantic system is referenced to a benchmark tag and determines parameters of the tag under test such as backscatter by comparison to a known ramped transmit power. Although out of scope of this work, a final system would reproduce this functionality in a chair mounted reader. In order to remove the variations introduced by narrowband wireless fading and body movement in the human users, each measurement target set was repeated five times and the averages are presented.

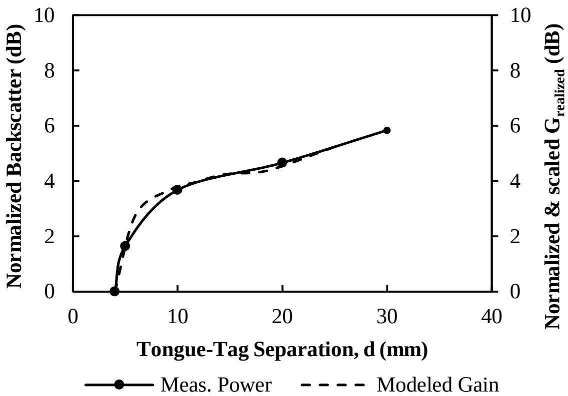

Fig. 4 Average user tag response at 868 MHz [19].

The measured and simulated results in Fig. 4 clearly show strong agreement. Additionally, the effect of jaw position was assessed by measuring tag response for tongue-tag separations d respectively of 1 and 2 cm with, in each case, the mouth open to its maximum and then reduced to an opening equal to d. Changing the mouth opening value, while holding the tongue stationary, was found to alter the tag response by no more than 4%. This indicates that the jaw position need not be accounted for in the tag response. While head movement might normally be expected to introduce channel variation due to changing propagation distance and antenna polarizations, the user group in question is expected to have constrained head position, meaning the channel will be stable apart from fast fading. This is because users with C1-C4 tetraplegia would require head restraints to maintain their head position [27].

4. User Training Process: Having established a good agreement between the simulation model and measurement, the 3 volunteers were trained to use the system to hit defined read range targets. The read range R is the maximum distance at which a tag will activate for a given reader power and is proportional to $(G_{tag}\cdot\tau)^{0.5}$ [21]. R is extrapolated from the measured reader power and was chosen as the target parameter because it is readily available for display on the Voyantic System. A number of studies were carried out to assess the user accuracy and repeatability in hitting required targets with increasing training time.

The first study required the 3 users to locate the easiest target (0.9m), where the tongue needed to be moved an almost maximum distance from the tag. This was done seven times for each user to establish how consistently they could find the target with increased practice. The entire process was then repeated seven times for target distances of 0.8m, 0.7m, 0.6m and 0.5m and in all cases the users had two seconds between being told the target and to find the optimum tongue position. The minimum target distance was set at 0.5m because ranges of 0.4m or less resulted in 'no read' which was trivial to achieve and required little or no accuracy.

Error magnitudes for each target distance were averaged over the three users for the seven attempts. The error magnitude |E| was calculated by:

$$|E|=\left[\frac{R_m-R_t}{R_t}\right]\times 100\% \qquad (2)$$

where, R_m and R_t are the measured value and target read ranges respectively.

The rate at which the test population improved with subsequent attempts is illustrated in Fig. 5 where the mean error of all three users' attempts are presented against each subsequent try. On average, the error magnitude for all targets roughly halved after four attempts and all fell to less than half after five tries. Therefore, it is clear that the users can learn the tongue positions to locate targets with reasonable accuracy after four or five attempts. This was the case for all measurements where the initial higher error magnitudes reduced and converged on values of a few percent for attempt seven. The improvement is evidenced by the clear downward trend in Fig. 5.

To appreciate the range of accuracy for each target distance, the data for every attempt by all users are presented in confusion matrices of the probabilities of hitting the targets. Table 2 shows the confusion matrices for the 3 individuals and a final average respectively. A target was deemed to be hit if the user landed within the mid-points separating that target from its neighbours. Each user attempted to hit each of the 5 targets in a sequence decreasing from 0.9m to 0.5m and they repeated this 7 times. From the Table 2 confusion matrix relating to the overall average, when all seven trials are included, the total errors at each target are 20% or more for all targets except 0.9m. This high error rate arises because the users had little or no practice in their early attempts. The success at 0.9m is attributed to the fact that any tongue separation above that required for the maximum target was recorded as a successful hit.

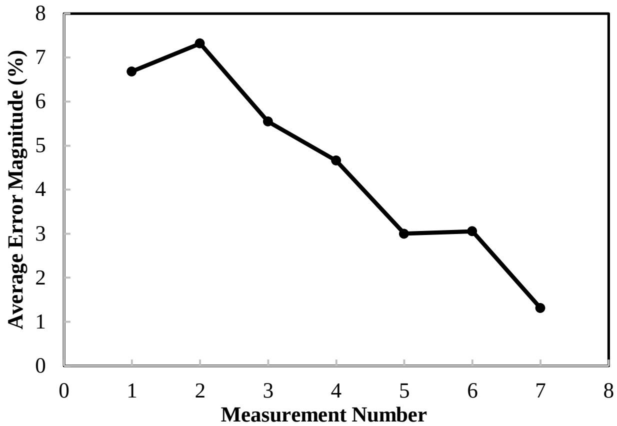

Fig. 5 Average Target Error vs Measurement Number

In order to appreciate the improvement in target accuracy over the course of the training session, Table 3 shows the confusion matrix for the overall average of just the final 3 sequences for each user. A marked reduction in the error spread is noted, meaning that, neglecting an 11% error at 0.5m, all individual targets are resolved without error after a short training experience.

To prevent the users obtaining deceptively accurate results because they were presented with sequentially reducing target distances, the final part of the training required them to hit the 0.5m to 0.9m target distances in a defined, but random, sequence of twenty five. As before, the users had two seconds to find each target.

Tables 4 and 5 show the mean error and spread for each user attempting each target, for all 25, and just the final 13 attempts, respectively. All error means and ranges reduce significantly for the final 13 tries with the exception of the 0.5m target which only occurred in the final half of the sequence. For the final 13 attempts the 0.5m target has the highest mean error for Users 1 and 2, while the 0.7m target is most difficult for User 3.

Table 2: Confusion matrices of individual user and average hit rates for an ordered sequence of 5 targets. Number of sequences = 7.

User 1		Measured target hit (m)				
		0.9	**0.8**	**0.7**	**0.6**	**0.5**
Target (m)	**0.9**	1.00				
	0.8		1.00			
	0.7		0.14	0.57	0.29	
	0.6				1.00	
	0.5				0.14	0.86

User 2		Measured target hit (m)				
		0.9	**0.8**	**0.7**	**0.6**	**0.5**
Target (m)	**0.9**	1.00				
	0.8		0.71	0.29		
	0.7			0.86	0.14	
	0.6			0.29	0.71	
	0.5					1.00

User 3		Measured target hit (m)				
		0.9	**0.8**	**0.7**	**0.6**	**0.5**
Target (m)	**0.9**	1.00				
	0.8	0.43	0.57			
	0.7		0.29	0.71		
	0.6			0.14	0.72	0.14
	0.5				0.57	0.43

Average		Measured target hit (m)				
		0.9	**0.8**	**0.7**	**0.6**	**0.5**
Target (m)	**0.9**	1.00				
	0.8	0.14	0.76	0.10		
	0.7		0.14	0.71	0.14	
	0.6			0.14	0.81	0.05
	0.5				0.24	0.76

Table 3: Confusion table of average hit rates for ordered sequences of 5 targets. Sequences 5-7 considered.

Average		Measured target hit (m)				
		0.9	**0.8**	**0.7**	**0.6**	**0.5**
Target (m)	**0.9**	1.00				
	0.8		1.00			
	0.7			1.00		
	0.6				1.00	
	0.5				0.11	0.89

When the users' performance is assessed for the data in Tables 4 and 5 for the entire 25 attempts, User 2 is the most accurate in terms of mean error and standard deviation, followed by User 1. User 2 remains most accurate for the final 13 tries, but User 3 becomes the second most accurate, demonstrating they have benefitted more from practice than User 1.

Using the data from the random sequence of 25, the measured hit rate for each target is presented in Table 6 as a confusion matrix for each user and for the overall average. It can be seen that the accuracy for all targets is high, with User 3 alone experiencing just 50% success for only one target (0.7m). Excepting this, all users manage at least 75% hit rate for all targets. Considering the average values, all targets except 0.7m experience more than 80% hit rate when their initial attempts are included. The improved success at the minimum target of 0.5m in the random sequence is attributed to the fact that any tongue position below that required for 0.5m is attributed as a hit. Approaching this target randomly from either direction therefore increases the chance of success when compared to Table 2, where the target was always approached from above. Table 7 shows the confusion matrix considering only the second half of the 25 target sequence, i.e. when the users had become accustomed to the interface. In this case, zero error is observed for all targets.

Table 4: Measured target errors over a random sequence of 25 attempts.

	USER 1		USER 2		USER 3	
Target (m)	Mean Error %	STD DEV σ	Mean Error %	STD DEV σ	Mean Error %	STD DEV σ
0.5	4	0.01	2	0	2	0
0.6	5	0.023	-2	0.008	2.9	0.04
0.7	1	0.035	-3.6	0.04	7.1	0.03
0.8	-0.9	0.039	-1	0.02	2.7	0.026
0.9	-0.5	0.033	1	0.033	-2	0.038

Table 5: Measured target errors for attempts 13-25 in a random sequence of 25.

	USER 1		USER 2		USER 3	
Target (m)	Mean Error %	STD DEV σ	Mean Error %	STD DEV σ	Mean Error %	STD DEV σ
0.5	4	0.01	2	0	2	0
0.6	2.5	0.016	-1.7	0.01	1.7	0.013
0.7	3.6	0.023	0.7	0.03	2.9	0.03
0.8	-1.3	0.01	-1.4	0.013	0.4	0.02
0.9	0.8	0.014	-0.6	0.023	-0.8	0.03

5. Suggested System Implementation: To implement the wireless tag into a wheelchair based system that could provide the user with a human input device, the reader unit would rely upon average backscattered power to remove any fast fading radio channel effects and a lookup table of finite states would facilitate target identification. Each target would have a pre-defined velocity and direction to allow for fluent wheelchair control. To adapt to the needs of each user, the output of the system can be modified, for example it could be used to control a computer, environmental settings, mobile phone or any other device which can be simplified to a small number of input commands depending on the number of targets given to the user.

6. Conclusion: An innovative, low intrusion, wireless passive tongue switching assistive tag technology using RFID for application in wheelchair control has been tested on users. The preliminary simulation and measurement results indicate that multi-chip RFID tags for mouth mounting could potentially form a 2 point joystick controlled by the tongue. The tag offered read ranges of more than a metre when attached to the hard palate and it is proposed that the read antenna would be mounted on the wheel chair about 30cm in front of the operator.

Table 6: Confusion tables of individual and average hit rates for a random sequence of targets. Sequence length = 25.

User 1	Measured target hit (m)				
Target (m)	**0.9**	**0.8**	**0.7**	**0.6**	**0.5**
0.9	0.86	0.14			
0.8		0.75	0.25		
0.7			1.00		
0.6			0.25	0.75	
0.5					1.00

User 2	Measured target hit (m)				
Target (m)	**0.9**	**0.8**	**0.7**	**0.6**	**0.5**
0.9	1.00				
0.8		1.00			
0.7			0.75	0.25	
0.6				1.00	
0.5					1.00

User 3	Measured target hit (m)				
Target (m)	**0.9**	**0.8**	**0.7**	**0.6**	**0.5**
0.9	0.86	0.14			
0.8	0.13	0.87			
0.7		0.50	0.50		
0.6			0.25	0.75	
0.5					1.00

Average		Measured target hit (m)				
		0.9	**0.8**	**0.7**	**0.6**	**0.5**
Target (m)	**0.9**	0.91	0.09			
	0.8	0.04	0.87	0.08		
	0.7		0.17	0.75	0.08	
	0.6			0.17	0.83	
	0.5					1.00

Table 7: Confusion table of average hit rates for the second half of a random sequence of targets. Targets 13 – 25 considered.

Average		Measured target hit (m)				
		0.9	**0.8**	**0.7**	**0.6**	**0.5**
Target (m)	**0.9**	1.00				
	0.8		1.00			
	0.7			1.00		
	0.6				1.00	
	0.5					1.00

Tongue-tag separation of about 4mm resulted in a threshold between the on-and off-states and therefore, in use, touching the tag with the tongue would represent a definite off condition. In user testing, a significant improvement in accuracy was observed with continued training in all cases. After training, error magnitudes for all the defined targets fell to less than 4% in magnitude with an apparent random distribution across targets and individuals. This is taken to represent the minimum accuracy of the system before any algorithm is applied to compensate for human response. UHF RFID systems are licensed according to regional regulations, and placing a reader antenna 30cm from a person falls within the stated Electric field exposure limit of 27.5V/m for the permitted Effective Isotropic Radiated Power level of 2W. To make the tag hygienic and simple to apply, it may be ultimately integrated into a conventional dental plate. Reader power consistent with licensed RFID systems would be supplied from the chair with a processing and autonomous navigation unit available for calibrating and training the patient.

The tag is proposed to offer simple input to an intelligently guided collision avoiding wheelchair which means absolute precision and fast response times will not be essential. Further reduction of the sensor size could allow for a matrix to be applied to the hard palette for high resolution sensing of tongue position. This could be of benefit for speech therapy as current monitoring systems require a loom of wires to be passed through the patient's mouth which disrupts the normal conditions of speech. A wireless solution based on the passive technology demonstrated here would overcome this issue.

The authors' institution's ethical assessment and approval procedures were followed for all the experiments involving human participation described in this paper.

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