Preliminary Evaluation of a Silent Speech Interface based on Intra-Oral Magnetic Sensing

Lam A. Cheah[1], Jie Bai[1], Jose A. Gonzalez[2], James M. Gilbert[1], Stephen R. Ell[3], Phil D. Green[2] and Roger K. Moore[2]

[1]School of Engineering, The University of Hull, Kingston upon Hull, U.K.
[2]Department of Computer Science, The University of Sheffield, Sheffield, U.K.
[3]Hull and East Yorkshire Hospitals Trust, Castle Hill Hospital, Cottingham, U.K.

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Abstract: This paper addresses the hardware challenges faced in developing a practical silent speech interface (SSI) for post-laryngectomy speech rehabilitation. Although a number of SSIs have been developed, many are still deemed as impractical due to a high degree of intrusiveness and discomfort, hence limiting their transition to outside of the laboratory environment. The aim of this paper is to build upon our previous work, in developing a user-centric prototype and enhancing its desirable features. A new Permanent Magnet Articulography (PMA) system is presented which fits within the palatal cavity of the user's mouth, giving unobtrusive appearance and high portability. The prototype is comprised of a miniaturised circuit constructed using commercial off-the-shelf (COTS) components and is implemented in the form of a dental retainer, which is mounted under roof of the user's mouth and firmly clasps onto the upper teeth. Preliminary evaluation via speech recognition experiments demonstrates that the intraoral prototype achieves word recognition accuracy of 75.7%, slightly lower than its predecessor. Nonetheless, the intraoral design is expected to improve the stability and robustness of the PMA system with a much improved appearance since it can be completely hidden inside the user's mouth.

1 INTRODUCTION

Speech is a key capability and the most natural form of communication of human beings. However, there are a variety of situations in which people wish to communicate orally but where normal speech can be either impossible or undesirable. For instance, people with speech impairments who have undergone laryngectomy: the surgical removal of larynx as part of treatment for cancer or other diseases affected the vocal cords. These post-laryngectomy patients, who have lost their voice, often find themselves struggling with their daily communication and may experience a severe impact on their quality of life (Braz et al., 2005; Fagan et al., 2008). However, there are currently only a limited number of post-laryngectomy voice restoration methods available for these individuals: oesophageal speech, the electrolarynx and speech valves. Unfortunately, these methods are often limited by their usability and abnormal voice quality (Fagan et al., 2008; Gilbert et al., 2010). Whereas, typing-based augmented and alternative communication (AAC) devices are limited by slow manual text input (Wang et al., 2012). Although some improvements were achieved in term of voicing quality of the electrolarynx and oesophageal speech (Doi et al., 2010; Toda et al., 2012), emerging assistive technologies (ATs) such as silent speech interfaces (SSIs) have shown promising potential in recent years as an alternate solution.

In principle, SSIs are devices that enable speech communication to take place in the absence of audible acoustic signals (Denby et al., 2010). Hence, aside from use as a communication aid for speech impaired individuals, SSIs can also be deployed in acoustically challenging environment or where privacy/confidentially is desirable. To date, a number of SSIs have been proposed in an attempt to extract non-acoustic information generated during speech production and reproduce audible speech using different sensing modalities. A comprehensive

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summary on different SSIs technologies were presented in (Denby et al., 2010). Permanent magnet articulography (PMA) is a type SSI that is based on sensing the changes in the magnetic field generated by a set of permanent magnet markers attached onto the vocal apparatus (i.e. lips and tongue) during speech articulation by using an array of magnetic sensors located around the mouth (Fagan et al., 2008; Gilbert et al., 2010), which shares some similarities with the electromagnetic articulography (EMA) (Toutios and Margaritis, 2005; Toda et al., 2008; Wang et al., 2012). In contrast to EMA, PMA does not explicitly provide the position of the markers, but rather a summation of the magnetic fields from magnets that are associated with a particular articulatory gesture. Previous work (Gilbert et al., 2010; Hofe et al., 2013a, 2013b; Cheah et al., 2015) demonstrated the possibility of performing automatic speech recognition (ASR) on PMA data.

Despite the attractive attributes of SSIs, two major challenges of building an effective SSI exist in the form of hardware and processing software. Preliminary discussions on the influential factors (e.g. invasiveness, market readiness, potential costing and etc.) affecting the SSIs' implementation were presented in (Denby et al., 2010). Earlier PMA-based prototypes (Gilbert et al., 2010; Hofe et al., 2013b) showed acceptable speech recognition performance, but were not particularly satisfactory in terms of their appearances, comfort and ergonomic factors for the users. To address these hardware challenges, a PMA prototype in the form of a wearable headset (design based on a customised pair of spectacles or a headband) comprising of minituarised sensing modules and wireless capability was developed (Cheah et al., 2015). The second generation prototype was re-designed based on a user-centred approach through utilising feedback from user questionnaires and through discussion with stakeholders including clinicians, potentials users and their families. The appearance and comfort of the prototype was much improved and it demonstrated comparable performances to its predecessors.

As illustrated in figure 1, the second generation PMA system consists of a set of six cylindrical Neodymium Iron Boron (NdFeB) permanent magnets, four on the lips (ø1 mm × 5 mm), one at the tongue tip (ø2 mm × 4 mm) and one on the tongue blade (ø5 mm × 1 mm). These magnets are currently attached using Histoacryl surgical tissue adhesive (Braun, Melsungen, Germany) during experimental trials, but will be surgically implanted for long term usage. The remainder of the PMA system is composed of a set of four tri-axial Anisotropic Magnetoresistive (AMR) magnetic sensors mounted on the wearable headset, a set of microcontrollers, rechargeable battery and a processing unit (e.g. computer/ tablet PC). Although the prototype has many desirable hardware features, it is not without limitations.

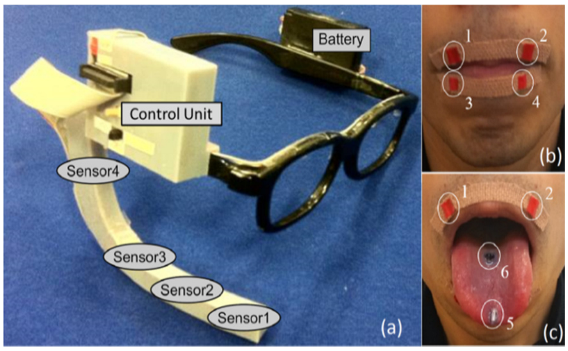

Figure 1: (a) A wearable PMA prototype designed in a form of spectacles. (b) & (c) Placement of six magnets on lips (pellets 1-4), tongue tip (pellet 5) and tongue blade (pellet 6).

The present work builds upon the work of (Cheah et al., 2015), to further improve and alleviate the shortcomings from a hardware perspective. The proposed prototype has several distinctive features, such as being miniature in size, highly portable, discreet and unobtrusive since it is hidden from sight within the user's mouth. The remainder of this paper is structured as follows. Section 2 outlines the design challenges of the intraoral version of the PMA device. Section 3 describes the architecture of the intraoral PMA prototype, followed by the performance evaluation in Section 4. The final section concludes this paper and provides an outlook for future work.

2 DESIGN CHALLENGES

Despite the improvements made in the second generation PMA prototype, it also has drawbacks. Firstly, the performance of the external headset cannot be maintained in certain real-life conditions (i.e. exaggerated movement or sports activity) due to issues with instability. If there is a considerable movement of the headset on the user's head, the PMA system may need re-calibration/re-training to avoid degradation in performance.

Secondly, wearing the headset over long periods may not be comfortable, despite the fact that the

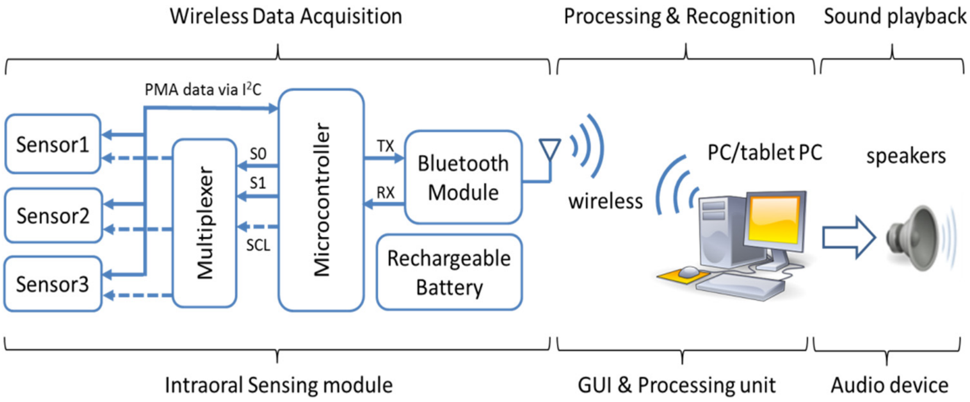

Figure 2: Simplified operation block diagram.

device was designed to be lightweight and ergonomically friendly. Thirdly, the external version of the PMA device may still be cosmetically unacceptable to some users. Previous studies indicated that the appearance is one of the most important factors that affect the acceptability of any AT by their potential end users (Hirsch et al., 2000; Martin et al., 2006; Bright and Conventry, 2013).

To overcome these limitations, an intraoral version of the PMA prototype, which fits under the palate inside the user's mouth in a form of a dental retainer, was proposed. Being tightly clamped onto the upper teeth means that the device would be more stable than the previous wearable headset. Due to the fact that the device is completely hidden from sight during normal use, it is cosmetically inconspicous. In addition, since the sensors are much closer to the articulators than the external headset, the size of the implants can be significantly reduced. Similar intraoral-based designs have been previously implemented for other non-speech related ATs with various degree of success (Tang and Beebe, 2006; Lontis et al., 2010; Park et al., 2012).

3 SYSTEM DESCRIPTION

3.1 Space Budget

The intraoral circuitry necessary to implement a PMA system is made up of: three tri-axial magnetic sensors, a wireless communication module, a microprocessor to synchronise data capture and communications and a suitable power source capable of providing an appropriate operating lifetime. This must be accommodated within the oral cavity, without interfering with the natural tongue articulation during speech. A recent study (Bai et al., 2015) suggested that the palatal cavity is suitable to house the intraoral circuitry because of its relatively flat surfaces and proximity to the articulators. The estimated space available in the palatal cavity on our test subject is 59.7mm^3.

3.2 Description of the Intraoral Circuitry

In order to fit all necessary circuitry inside the mouth, the size of the electronics and rechargeble battery of the external version of PMA prototype had to be shrunk down. The major components of the PMA prototype are shown in figure 2. These are implemented using a low-power ATmega328P microcontroller, three tri-axial HMC5883L magnetic sensors (AMR), a rechargeable Li-Ion coin battery (capacity of 40mAh, 3.7V and 20 mm diameter × 3.2 mm thickness), and a wireless transceiver (Bluetooth 2.0 module). The remainder of the system shown in figure 3 consists of a processing unit (e.g. computer/tablet PC) and a set six permanent magnets (NdFeB) attached onto lips and tongue in the same locations as illustrated in figure 1. The elements of the intraoral sensing system (which have a total volume of 36.7 mm^3) are arranged as shown in figure 3(a). These may be encapsulated and placed in the oral cavity as shown in figure 3(d).

The positions of the magnets remained unchanged from the earlier prototype but because of the proximity of the sensors, significantly smaller magnets (see Figure 3c) can be used: four on lips (ø1 mm × 4 mm), one on the tongue tip (ø1 mm × 1 mm) and one on the tongue blade (ø1 mm × 1 mm). Note that the magnetic field strength decreases with the cube of the distance away from the magnets.

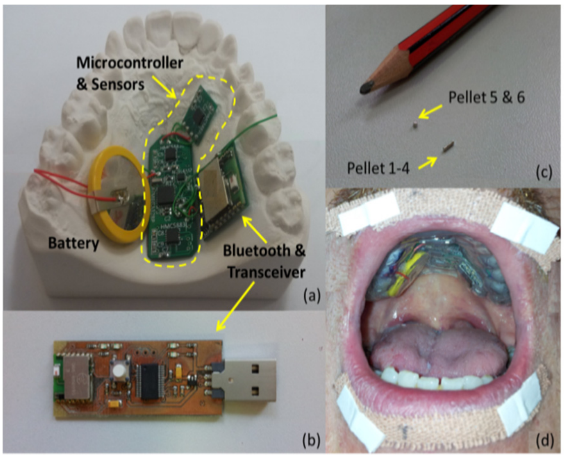

Figure 3: (a) & (b) Circuitry of the intraoral version of the PMA system. (c) Placement of magnets on lips (pellets 1-4), tongue tip (pellet 5) and tongue blade (pellet 6). (d) View of the device when worn by user.

3.3 Circuit Operation

Figure 2 shows an operational block diagram of the intraoral version of the PMA system. A command is sent wirelessly from the processing unit to the intraoral sensing module via Bluetooth to trigger data acquisition. All three tri-axial magnetic sensors then measure the magnetic field and digitize it with 12-bit resolution. The microcontroller acquires these measurements (9 PMA channels sampled at 80 Hz) through managing a multiplexer using three control signals (S0, S1 and SCL). The multiplexer acts as a switching device to route the serial clock (SCL) to the desired magnetic sensor through the I^2C interface. The acquired samples are then transmitted back to a processing unit wirelessly via the Blutooth transceiver and custom designed Bluetooth dongle (Figure 3(b)) for further processing. Unlike the external version of the PMA prototype, the intraoral device is restricted to only operate wirelessly from inside the mouth. Wired connectivity is impossible, as the sensing modules are to be sealed and packaged inside a dental retainer. A description of the operational and timing diagrams of the sub-modules are presented in (Bai et al., 2015).

In terms of software, an *ad-hoc* MATLAB-based graphical user interface (GUI) developed in (Cheah et al., 2015) was adapted, where all speech processing and recognition algorithms were embedded. During silent speech recognition, if the acquired PMA signal is correctly matched to an articulated gesture from the training database, the corresponsed utterance will be identified. A text-to-speech synthesiser (TTS) is then used to generate an acoustic signals (e.g. pre-recorded individual's own voice) for the recognised utterance through built-in speakers.

3.4 Power Budget

Since the circuitry is to be sealed into a dental retainer, the intraoral device can only acquire power from a battery. Given the limited space available, a small, low capacity battery must be used (in the current design, the battery takes 27% of the total volume of the circuitry). In addition, any measures to extend the battery life will be of interest. Power hungry components such as the microcontroller, the magnetic sensors and the Bluetooth may be set to *standby mode* or *sleep mode* to reduce the current consumption when they are inactive. A shown in table 1, *sleep mode* gives a saving of 93% over *standby mode* or a saving of 97% over *active mode*.

Table 1: Current consumption in difference operational modes.

Current Consumption	Active mode (mA)	Standby mode (mA)	Sleep mode (mA)
Sensors	5.1	0.006	0.006
Microcontroller	5.4	4.4	0.7
Bluetooth	19.0	7.22	0.07
Total	29.5	11.626	0.776

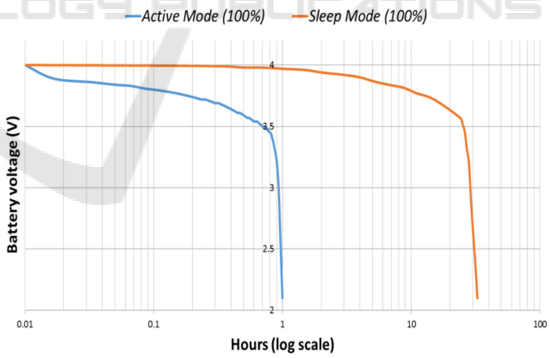

Figure 4: Battery discharging over time under *active mode* and *sleep mode*.

If the system is to operate continuously (in *active mode*), the battery will last approximately one hour before being depleted below the minimum operating voltage (cut-off voltage) required by the Bluetooth module of 2.1V. The battery can then be recharged through a charging point located at the bottom side of the dental retainer. In contrast, if the system was inactive at all times (in *sleep mode*), the battery would last about 32 hours. Figure 4 shows a summary of the discharging cycle of the battery in different modes. Neither of these operating regimes is fully representative of the expected use since they correspond to continuous speech and no speech respectively. Based on the measurements in table 1 and figure 4, a more realistic regime would be to allow 30 minutes of speech with a further 16 hours in *sleep mode*. Hence, the estimated usage time is considered to be sufficient for a typical day before charging is required.

3.5 Construction of the Dental Retainer

The circuit described in the previous section must be encapsulated to protect it from damage and short circuits due to saliva and to ensure it is held in place within the palate. The retainer must be customised according to the individual's oral anatomy. This may be achieved by forming it on a dental impression of the user's oral cavity (seen in the background of figure 3a). The intraoral PMA prototype was implemented in the form of dental retainers utilising both hard and soft materials, as illustrated in figure 5.

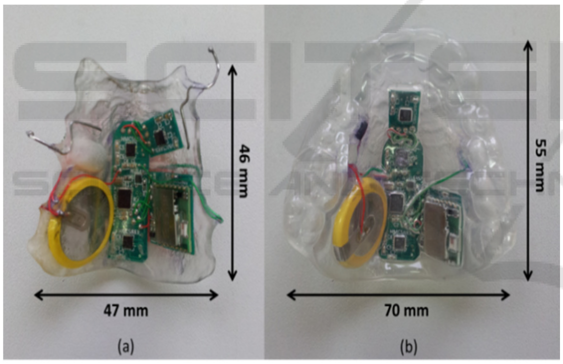

Figure 5: PMA circuitry embedded inside a (a) Hawley dental retainer and (b) soft bite raiser like dental retainer.

The hard retainer is similar to a Hawley retainer and is made of dental acrylic resin, which is commonly used in fabrication of orthodontic appliances. On the other hand, the soft retainer is similar to a soft bite raising appliance and is made of polypropylene or polyvinylchloride (PVC) material. To allow stable fitting in the palate, the Hawley retainer utilises a set of ball clasps to tightly secure it onto the upper teeth. In contrast, the soft bite raiser is fitted over the entire arch of the upper teeth. Note that only soft retainer was used in the preliminary experiments, but similar performance is expected from the hard retainer.

4 PERFORMANCE EVALUATION

4.1 Experimental Design and Setup

The PMA-based SSIs (both intraoral and external version) are speaker dependant systems because their designs need to be individually tailored based on the speaker's head or oral anatomy for optimal performance. The data used for evaluating the new intraoral prototype were collected from a male native English speaker who is proficient in the usage of the external PMA device. Magnets were temporary attached on the subject using Histoacryl surgical tissue adhesive (Braun, Melsungen, Germany).

Recordings of PMA and audio data for training and evaluation were performed using a bespoke Matlab-based GUI. The software provides a visual prompt of randomised utterances to the subject at interval of 5 seconds during the training session. The subject's head was not restrained during the recording sessions, but the subject was requested to avoid any large head movements. This was necessary to ensure that interference induced by movement relative to earth's magnetic field was at its minimum, so that it did not corrupt or distort the desired signal. This is because the current prototype is not yet equipped with a non-articulatory cancellation/removal mechanism.

For optimal sound quality, the recordings were conducted in an acoustically isolated room. The audio data were recorded using a shock-mounted AKG C1000S condenser microphone via a dedicated stereo USB-sound card (Lexicon Lambda) to a PC, with a 16 kHz sampling rate. Meanwhile, the PMA data were captured at a sampling frequency of 80 Hz via the intraoral PMA device and transmitted to the same PC wirelessly via Bluetooth, as illustrated in figure 2. Since both data streams (PMA & audio) are acquired from separate modality, synchronisation between the two data streams is necessary. Hence, an automatic timing re-alignment mechanism was implemented utilising start-stop markers generated in additional to both data streams.

4.2 Data Recording

Our long term goal is to explore the feasibility of using the intraoral device for continuous speech reconstruction. For preliminary testing, the TIDigits database (Leonard, 1984) was selected because the limited size of the vocabulary enables whole-word model training from relatively sparse data and because of the simplicity of the language involved.

The corpus consists of sequences of connected English digits with up to seven digits per utterance. The vocabulary is made up of eleven individual digits, i.e. from 'one' to 'nine', plus 'zero' and 'oh' (both representing digit 0).

The experimental data were collected from two independent sessions, with each session consisted of four datasets containing 77 sentences each. A total of 308 utterances containing 1012 individual digits were recorded during each session. To prevent subject fatigue, short breaks in between each recording session were allowed.

4.3 HMM Training and Recognition

Prior to the training and recognition processes, the acquired PMA data were segmented and checked using the audio data. Inappropriate endpoints were manually corrected if necessary. In addition, any mis-labelled utterances were corrected using the acquired audio data.

The PMA data was then subjected to offset removal via median subtraction over 2s windows with 50% overlap and followed by data normalization. Next, the delta parameters were computed for all PMA channels and added to its original time series data, resulting in a feature vector of size 18. The delta-delta parameters were not included as part of the feature vector as they did not produced significant improvement in performance (Hofe et al., 2013a, 2013b). The recognition performance based on the audio data was also evaluated for comparison purposes. In this case, 13 Mel-frequency cepstral coefficients (MFCCs) were extracted from the audio signals using 25ms analysis windows with 10ms overlap. Next, the delta and delta-delta parameters were computed and appended to the static parameters, resulting in a feature vector of dimension 39.

The extracted PMA and audio features were used for training two independent speech recognisers using the HTK toolkit (Young et al., 2009). In both cases, the acoustic model in the recogniser uses whole-word Hidden Markov Models (HMMs) (Rabiner, 1989) for each of the eleven digits. Each HMM has 21 states and 5 Gaussians per state. The selected parameters were not optimised, but were known for their performances based on previous work (Hofe et al., 2013a, 2013b). The HMM training and recognition was carried out in four validation cycles. In each cycle, three out of four sets within a session were used for training and the remaining one for testing. The recognition results were averaged over four cycles and across two independent sessions.

4.4 Recognition Performance

Both word and sequence accuracy results for the intraoral and external versions of the PMA device are presented in figure 6 and figure 7. In addition, the performances of the PMA devices were compared with audio-based recognition. The blue-coloured bars indicate the performance achieved using only static PMA data (vector size of 9), whereas the red-coloured bars are the results achieved using both static and dynamic features (vector size of 18). In addition, the green-coloured bars are the speech-recognition performance achieved using audio data (vector size of 39). We will refer to these three conditions as *Sensor*, *SensorD* and *Audio* features, respectively.

The results reflect the mean of the data collected across the two sessions, but were initially analysed independently session-by-session. In order to avoid the inconsistency of magnets placement during individual training sessions, data were not merged across different sessions. This however could be solved, as magnets are to be surgically implanted for long term usage. Alternatively session-independent approaches, such as those presented for other SSIs methods in (Maier-Hein et al., 2005) and (Wand and Schultz, 2011) could be investigated.

As shown in both figure 6 and figure 7, it is quite obvious that *SensorD* produced better recognition performance on both occasions than using *Sensor* alone Similar trends were also reported in (Hofe et al., 2013b; Cheah et al., 2015). As expected, for this simple task, recognition using *Audio* performed very well (i.e. 99%). Preliminary evaluations indicated some degradation (i.e. 15% for word accuracy and 17% for sequence accuracy) in recognition performances in the intraoral device as compared to the previous external version, as illustrated in figure 6 and figure 7. There are a number of possible explanations for this degradation: 1) the presence of the intraoral prototype affects articulation and, in particular limits the tongue movements. This may lead to inconsistent articulation, 2) the subject was new to the intraoral version, but had prior experiences on the external PMA version, 3) non-articulatory features arise from unintentional movements (e.g. swallowing, licking the lips, head movements) which could have corrupted the data or been confused with utterances, and 4) the magnets are able to come much closer to the sensors in the intraoral device than in the external device, resulting in a more significant non-linear effect (since the field strength decreases with cube of the distance). This means that small unintentional articulator movements can generate very large signals in some instances. Further work is required to understand the significance of each of these possible causes.

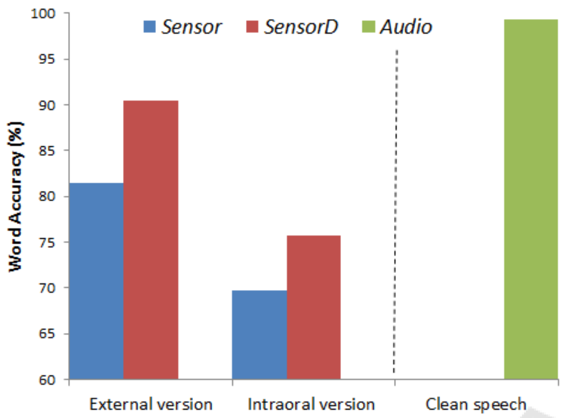

Figure 6: Comparison of word accuracy in the connected digits.

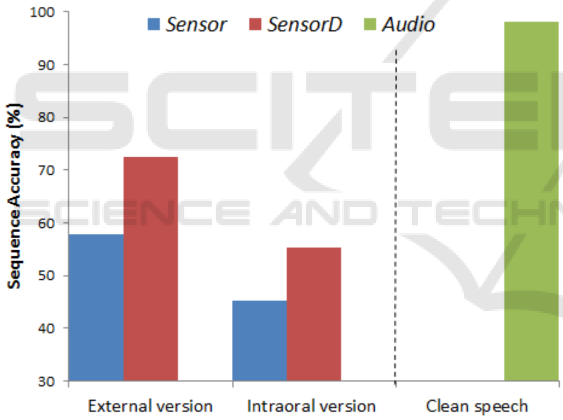

Figure 7: Comparison of sequence accuracy in the connected digits.

4.5 Hardware Evaluations

As discussed in section 2, one major obstacle to the acceptability of an AT (e.g. SSI) is its appearance if it is considered unattractive. Similar views were also concluded through discussions with potential users who have undergone a laryngectomy and an opinion survey of 50 laryngectomees and their families/ friends, the appearance of the PMA-based device was considered to be of a very high priority (Cheah et al., 2015). To enhance its appeal to users, influential factor such as appearance needed to be accounted for during device development. The challenge here is to satisfy the design objective and continue improving on the PMA device's appearance but without compromising its speech reconstruction performance. The latest intraoral prototype employs the same functional principles as the previous design reported in (Gonzalez et al., 2014; Cheah et al., 2015), but implemented in a different form. A summary of the hardware features of the new intraoral PMA system compared to its predecessor is presented in table 2.

Despite the improved appearance of the second generation PMA system in the form of a wearable headset, it might not yet to be appealing to all. To address this shortcoming, the latest intraoral circuitry was implemented in the form of a dental retainer. To achieve this, the circuit was re-designed to use fewer and smaller components. In addition, the power consumption of the circuit was carefully managed to allow it to operate from a small battery suitable for inclusion within the dental retainer. Hence, this led to a much smaller and lighter (i.e. one tenth of previous weight) prototype as compared to its predecessor. In addition, the intraoral prototype is highly portable, it operates and can be controlled wirelessly via Bluetooth using a computer/tablet PC. Also, a higher signal-to-noise ratio (SNR) was obtained with smaller magnetic tracers, due to their proximity to the magnetic sensors. The tongue magnets used with the intraoral sensor system were 16 to 25 times smaller volume than those used for the external headset, potentially making them less invasive when implanted.

A significant drawback with the intraoral device is the limited battery size and capacity (i.e. 40mAh). In contrast, the external version is less restricted in term of size and weight of the battery. Hence, this significantly reduces the operational time of the intraoral device per charging. A number of steps have been introduced to reduce its power consumptions: a lower operational voltage is selected and power-efficient components, lower data sampling and transmission rates were chosen. In addition, software was developed to switch from an *active mode* to *sleep mode* when not in use. Using these measures, it is estimated that the battery life cycle could be extended from one hour to about 16.5 hours including 30 minutes of speech.

5 CONCLUSIONS

In this paper we have described a new intraoral PMA prototype using commercial off-the-shelf (COTS) components and embedded inside a dental retainer constructed using the subject's dental

Table 2: Summary of the PMA devices' specifications and comparison [*Note that although the external sensing system has 12 channels, only 9 are used for speech recognition and 3 are used for cancellation of background magnetic fields].

Specifications		Intraoral Sensing	External Sensing
Appearance		Dental retainer	Wearable headset
Operating voltage		2.1 V	5 V
Magnets	Tongue Blade	ø1 mm × 1 mm	ø5 mm × 1 mm
	Tongue Tip	ø1 mm × 1 mm	ø2 mm × 4 mm
	Lips	ø1 mm × 4 mm	ø1 mm × 5 mm
Magnetic Sensing	Dimension	12 × 12 × 3 mm^3	12 × 12 × 3 mm^3
	Sensitivity	230 LSb/gauss	440 LSb/gauss
	Samplig rate	80 Hz	100 Hz
	Channels	9	12*
Data Transmission	Type	Bluetooth 2.0	Bluetooth 2.0 / USB
	Frequency	2.4 GHz	2.4 GHz
	Data rate	57.6 kbps	500 kbps
Power	Supply	Rechargeable battery	Rechargeable battery / USB
	Battery	Li-Ion 40 mAh	Li-Ion 1080 mAh
	Current consumption	30.5 mA	93.5 (wireless) / 67.1 (wired) mA
	Lifetime	1 hour	10 hours
Prototype	Dimension	70 × 55 × 25 mm^3	160 × 160 × 150 mm^3
	Weight	15 g	160 g
	Material	Acrylic resin / polypropylene	VeroBlue / VeroWhitePlus resin

impression. Preliminary evaluation of the intraoral prototype indicated a recognition performance, slightly lower than the previous external PMA device. However, there are a number of avenues for further investigation to improve its performance.

Nonetheless, there are several advantages over its predecessor. It is considered to be more stable and robust against unintentional movement as it is implemented in a form of a dental retainer, which securely sits in the palatal cavity and is clasping firmly on the upper teeth. Secondly, significantly smaller magnets may be used for the intraoral version (because of their proximity to the magnetic sensors) while also giving a higher SNR. In addition, the dental retainer can be completely hidden inside the user's mouth and out of sight. Hence, this would eliminate the concern of being a sign of disability.

However, a downside of the intraoral design would be the possibility of limiting the natural movement of the tongue, because the device occupies part of the user's oral cavity. Further work is required to assess whether users become accustomed to the presence of the device and are able to achieve more consistent articulation.

Encouraged by the results so far, extensive work is needed to: 1) further reduce the size of future intraoral prototypes, 2) improve the circuitry power efficiency, 3) incorporate inductive charging for the battery, and 4) introduce a background cancellation mechanism for movement-induced interference. Though there are still limitations, the present work demonstrates a major step towards creating a viable SSI that would appeal to speech impaired users. For further information on the PMA-based SSI and its speech restoration technique, please visit www.hull.ac.uk/speech/disarm/demos.

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