A REVIEW OF PALATOGRAPHIC MEASUREMENT DEVICES DEVELOPED AT THE TU DRESDEN FROM 2011 TO 2022

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ABSTRACT

Electropalatography is an established measurement technique in speech research and therapy. While it captures the time-varying pattern of contact between the tongue and the hard palate in great detail, it provides no information about the tongue position at places where the tongue does not touch the palate. Over the past 12 years, the authors of this paper developed several artificial palate prototypes that include optical distance sensors to capture additional information about the position of the tongue. Here, six of these prototypes are reviewed. At the end, a palate design is proposed that takes into account all the lessons learned from the developmental process.

Keywords: Optical palatography

1. INTRODUCTION

Artificial palates are an established tool to measure various aspects of lingual articulation, e.g., the tongue-palate contact pattern with electropalatography [1, 2, 3] (EPG), the lingual pressure against the hard palate with pressure-palatography (PPG) [4, 5], or the distance between tongue and palate with optical palatography [6, 7, 8] (OPG). These measurement methods are used in phonetic research [9, 10], speech therapy [11, 12], and silent speech interfaces [13, 14], among others.

Due to its commercial availability, EPG is the most widely used palate-based measurement technique. EPG palates have 62 or more electrodes distributed over their surface, each of which registers the presence or absence of contact with the tongue. However, these contact sensors neither provide information about the position of the tongue at places without contact, nor about the lingual pressure at the points of contact. This information is provided by OPG and PPG. OPG uses optical distance sensors to measure the distance from different locations on the palate to the tongue surface, and PPG uses pressure sensors to measure the lingual pressure against the palate. Optical and pressure sensors are both usually larger than EPG electrodes, which limits the number of sensors per palate. Unlike EPG, neither OPG nor PPG have progressed beyond prototype status.

Given the complementary information provided by the three measurement methods, the combination of those on the same pseudo-palate would be useful. This paper reviews the authors' efforts over the past 12 years to achieve this goal. One strategy was to combine a limited number of (relatively large) optical distance sensors in the midsagittal plane with a larger number of surrounding contact sensors. Ever-smaller optical sensors have enabled another strategy, which was to replace contact sensors entirely with optical sensors. Dedicated pressure sensors were not used. Instead, we explored the potential of the optical sensors to measure lingual pressure, which was first proposed in [6]. Since the optical sensors are in the focus of this review and part of all palate models, the following subsection gives an overview of their principle of operation.

1.1. Optical distance sensing

Each distance sensor consists of a light source and a photodetector at a close distance from each other, mounted on the lingual side of the artificial palate. To measure the distance to the tongue, the light source emits a beam of light on the tongue, and the photodetector registers the light reflected from the tongue surface. The recorded light intensity is approximately proportional to the inverse square of the distance [6]. The light source is typically a light-emitting diode (LED) or a laser diode, and the photodetector is a photodiode or a phototransistor. To minimize ambient light interference, these components are usually selected to work with infrared light.

Figure 1a shows an example circuit for the measurement using an LED and a phototransistor. The LED is driven by a *precision* current source (which is essential to avoid measurement drift) with the current $I_{\text{LED}} = V_{\text{CC}}/(2R_1)$ when $V_{\text{in}} = 0$ V (on state), and $I_{\text{LED}} = 0$ A, when $V_{\text{in}} = V_{\text{CC}}$ (off state). At

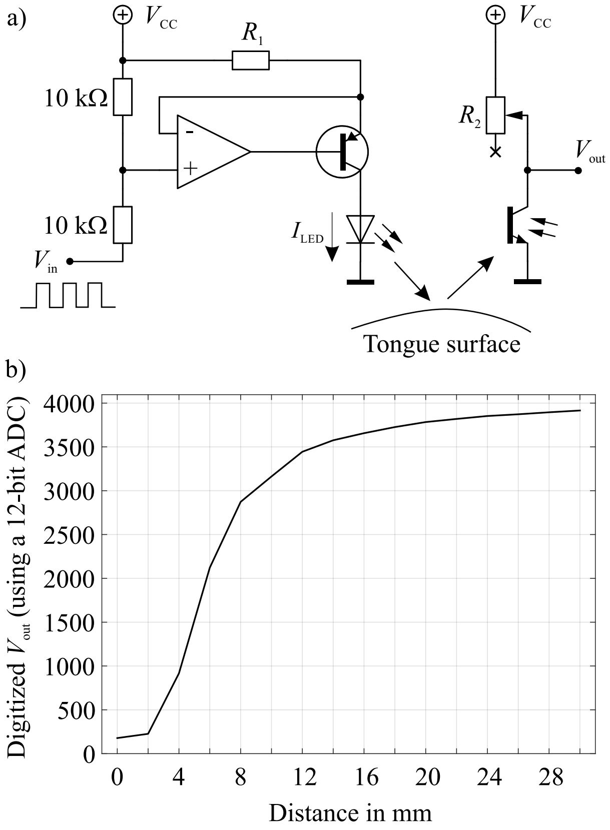

Figure 1: a) Circuit for optical distance sensing. b) Distance-sensing function.

the receiver side, the resistor R_2 converts the current through the phototransistor (which depends on the incident light) into an output voltage V_{out}. Figure 1b shows an exemplary relation between V_{out} and the sensor-tongue distance. This *distance sensing* function was obtained by positioning the tongue at a range of well-defined distances to the sensor (as in [15]) and recording the corresponding values of V_{out}. It is a monotonic function and thus allows to infer the distance from V_{out}. The exact shape of the function depends on R_2, the characteristics of the light source and the photodetector, their spatial distance, and the reflective properties of the tongue, which differ from person to person. This makes some form of calibration of the sensors necessary.

2. PALATOGRAPHY DEVICES

Figure 2 shows six relevant palate models that have been developed at the TU Dresden between 2011 and 2022. They will be discussed in the following.

2.1. Model 1

Model 1 [16] was the first palate that combined contact sensors with distance sensors. Its design is based on the Articulate EPG palate [3], in which the 62 contact sensors (arranged on flexible strips) are embedded between two transparent sheets that are thermoformed over a plaster model of the hard palate. For the optical sensors, we chose units of the type TCND5000 (Vishay Semiconductors) that consist of an LED and a photodiode separated by an optical barrier. Like the contact sensors, the distance sensors were embedded between the thermoformed sheets. Since the sheet covering the optical components reduced the sensing range, the sheet parts around the sensors were cut away. In addition to three distance sensors directed at the tongue, one sensor at the upper incisors for detection of lip movement and one backward-facing sensor for detection of velum movement was included.

The evaluation of this palate showed that the EPG sensors worked as expected, the lingual distance sensors could capture the height of the tongue, and the lip sensor was able to detect lip movements. However, the velum-directed sensor was *not* able to detect differences in velum position, the height of the distance sensors (> 3 mm) partly disturbed the articulation, and the manufacturing time for the palate was quite long.

2.2. Model 2

To have less impact on articulation and make fabrication more effective, Model 2 was made with tailored optical sensors mounted on a strip of flexible printed circuit board (PCB) [15]. This design had no contact sensors. For the distance sensors, different combinations of *separate* LEDs and phototransistors were evaluated. The combination of the LED VSMY2850G and the phototransistor TEMT7100X01 (both by Vishay Semiconductors) with a gap of 0.6 mm between them was found to be the best tradeoff for small size and sufficient measuring range. Important for the good measuring range was the *lens* of the LED to focus the light beam. Four sensors were distributed along the palatal midline, and one sensor at the incisors was directed towards the upper lip. After soldering the optical components to the flexible PCB, their electrical contacts were sealed with modeling resin, and each sensor was individually calibrated as described in [15]. The PCB was then glued to a 0.5 mm thermoformed sheet. Behind the incisors, the sheet around the teeth was cut away. Instead, Adams clasps were used for fixation, which increased wearing comfort. This type of palate, driven by the circuit in Figure 1a, provided reliable measurements of the tongue position and was used for the real-time control of a 2D animated model of

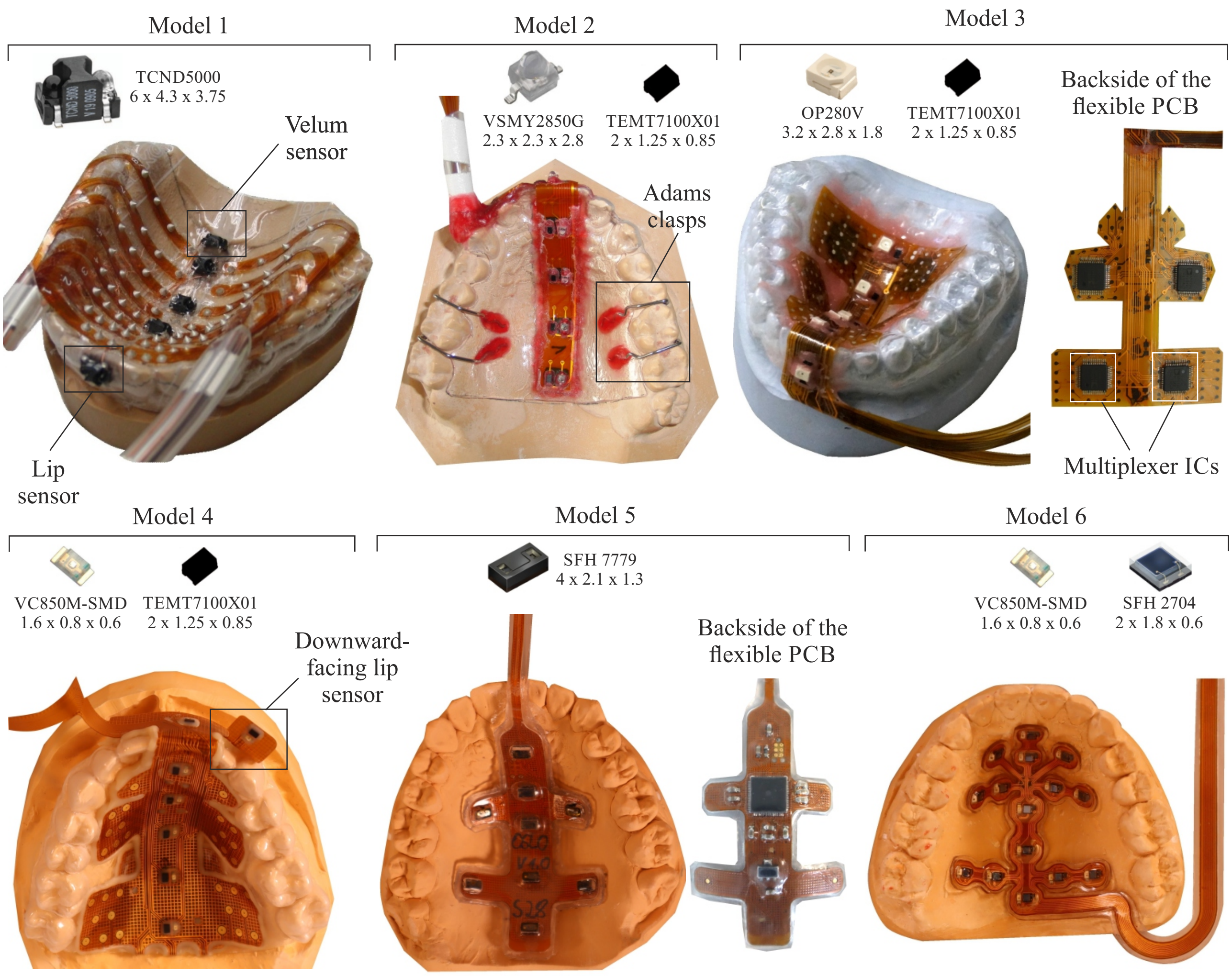

Figure 2: Palate models. For each model, the type and size ($L \times W \times H$ in mm) of the optical components is shown.

the vocal tract [17].

2.3. Model 3

Model 3 is a further development of Model 2 and contains five distance sensors for the tongue, one distance sensors for the lips, and 124 contact sensors [18, 19, 20]. The light source for the distance sensors was changed to the laser diode OP280V (OPTEK Technology Inc.), which has a slightly larger footprint, but a smaller height (which increased wearing comfort) than the LED of Model 2. Compared to the LED, the laser diode generates a narrow light beam without a "bulky" lens and requires substantially less electrical power. The contact sensors were gold-plated electrodes placed on the same PCB as the distance sensors. To reduce the number of wires required to connect the palate with the external control unit, four 32-channel analog multiplexer integrated circuits (IC) at the back side of the PCB were used to multiplex the contact sensors. A denture relining material (GC Reline) was used to glue the PCB to the carrier sheet and to seal the electrical contacts of the optical sensors.

Experiments with this palate model have shown that the combination of distance and contact sensors on the same PCB generally works well. However, some of the units produced broke after a few uses because the solder joints of the multiplexer ICs could break when the palates were bent. With this palate model, a simple in-vivo calibration method of the distance sensors was introduced [18], as well as a method to reduce measurement errors when the tongue surface was not perpendicular to the optical axes of the sensors [20].

2.4. Model 4

Model 4 is a revised version of Model 3 where the laser diode has been substituted with a smaller type (VC850M-SMD by Roithner Lasertechnik GmbH), the number of contact sensors was reduced to 32, and a 2nd optical lip sensor was included facing downwards to the lower lip. With the two lip sensors together it became possible to discriminate lip protrusion from lip opening movements. The lower number of contact sensors reduced the risk of saliva bridges between the electrodes and required only a single 32-channel multiplexer IC on the backside of the PCB, which greatly reduced the risk of defects due to broken solder joints. More than 15 units of this palate model were manufactured (partly still with the previous laser diode) and used, e.g., for silent speech command word recognition [14] and the articulatory analysis of diphthongs [10].

2.5. Model 5

Model 5 contains optical distance sensors only, both along the midsagittal contour and on the sides of the palate, and does not include lip sensors [21]. The sensors are integrated digital sensors (SFH 7779 by Osram) that are equipped with a miniature LED and photodetector and output a 16-bit value that varies with distance. This type was selected based on its ability to measure not only the distance but also the force exerted by the tongue on contact [22]. The circuitry to control the sensors was placed on the back of the flexible PCB. This included an IC to multiplex the I2C bus that is used to communicate with the sensors, because the I2C bus address of each sensor was identical and unchangeable.

The PCB was completely laminated between two flexible transparent 1 mm sheets (Erkoflex by Erkodent). In contrast to Model 1, the additional sheet over the distance sensors hardly affected the distance measurement. Compared to Models 1–4, this model was not anchored to the teeth with Adams clasps or with a carrier sheet formed around the teeth, but with a specially developed adhesive film [23]. The advantage is that no plaster model of the user's hard palate is required to fabricate this model.

Experiments with this model showed that the integrated distance sensors enabled robust measurements, and that the adhesive film was effective in fixing the pseudopalate to the palate for at least 15 min. However, the mechanical stress of attaching the unit to the hard palate sometimes led to (electrical) failure. In addition, the relatively thick thermoforming sheets reduced its flexibility and snugness to the real palate.

2.6. Model 6

Model 6 is a further development of Model 5 where the integrated digital distance sensors have been replaced with sensors made of a separate light source and photodetector, and where all other electronic components have been moved from the palate to the control circuit outside the mouth. The step back to discrete components for the distance sensors was taken because none of the currently available integrated digital sensors fulfills all requirements for optical palatography (easy control of multiple identical sensors, small size, sufficient measurement range and speed, etc.). Each distance sensor consisted of the proven laser diode VC850M-SMD, and a photodiode of type SFH2704 (Osram) with a particularly large active chip area. In practice, however, the photodiode did not provide any advantage over the previously used phototransistor TEMT7100X01. To obtain a sufficient measurement range using these discrete components completely covered under a 0.5 mm thick transparent sheet, small optical barriers had to be installed between the light sources and photodetectors to prevent optical crosstalk. By eliminating the electronic components on the back of the PCB, the pseudopalate was robust, extremely flexible, and conformed very well to the shape of the real palate when glued into the mouth.

3. OUTLOOK

For future palate designs, Model 6 appears to be the best starting point. By using only optical sensors, the entire flexible PCB can be laminated between two sheets, eliminating the need for the time-consuming sealing of optical sensors in combined electro-optical models. The photodiode SFH2704 can be replaced with a phototransistor (TEMT7100X01 or an even smaller type), which would reduce the footprint of the sensors and simplify the control circuitry. Two lip sensors as in Model 4 can easily be added to this design. For more frequent applications, a subject-specific version of Model 6 can be made where the thermoformed sheets extend around the teeth of the user for fixation.

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