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A navigation device utilizing body communication channel for mobile wearable systems

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***Abstract*—A novel touch sensor utilizing a body communication technology is presented in the paper. The proposed device accepts orders (gestures) only from a person wearing it. Moreover, when comparing it to a similar, however an optical one, it appears as a less power consumable. Preliminary results of its properties examination are presented and discussed. Additionally, the developed sensor allows to measure a human body the electrical passive parameters thus, aside it performs a basic functionality it also delivers additional information on the user.**

I. Introduction

The distributed devices devoted for a sensing, controlling and communicating play a significant role in the modern computing systems. These devices are designed to be utilized by a common user and are named Internet of Things (IoT). This technology is an emerging one and has a big potential on a market. Additionally, together with the growing number of the IoT devices there is also demand on the user interfacing methods being able to gather information and interact with the neighborhood. Most of the user cases can be fulfilled by means of the smartphone or tablet but there are also demands on other, preferably wearable and hands-free devices.

An example of such device are smartglasses. A prototype of the eyeglasses, in fact, a general purpose platform has been developed in Biomedical Engineering Department, Gdansk University of Technology [1]. It is a modular computer with hardware similar to that of modern tablet or smartphone, currently utilizing the OMAP4460 System-On-Chip (SoC) [5] and shaped in a form of glasses' frame. It contains a built-in micro-display, two cameras and what is the most important huge variety of interfaces. These allow the modern hardware to be easily connected, tested, and finally utilized. At the moment several devices could be integrated with the platform. Among these are the proximity sensors (ultrasonic and optical) [3], biomedical signal acquisition units (respiratory, ECG, EEG, EMG)[4], infra-red cameras [6] and others. Additionally, utilizing and processing the images obtained from built-in cameras allow interaction with intelligent and surrounding items, e.g. home appliance [7].

In its current version, both, Android and Linux operating systems can be installed and used. In general, the Linux has a better support for the interfaces however, the devices operated by Linux consumes more energy than those running under Android. Moreover, Android system delivers a better programming graphical user interface (GUI) but it is a more painful when regarding drivers for new interfaces. This is partially due to an increased security considerations in Android. Nevertheless, both systems in form of the glasses are struggling with the controlling of GUI. The most efficient, and at the same time in many applications the most uncomfortable, approach is to use a classical computer mouse and a keyboard. Unfortunately, this approach is not acceptable for daily-use devices. Thus, GUI of the operating system should be modified in a way that other pointing devices could be used. During research we have concentrated on utilizing gesture recognition by means of a custom made proximity sensor [8], [9] and the eyetracking-based technology [2].

In the intelligent IoT world user interaction can play significant role as most of devices are user-oriented. In such way there is demand on some methods of the user identification or communication. The most widespread common communication methods between devices are based on utilizing electromagnetic waves. It is robust and highly standardized. We have Bluetooth, WiFi, Z-wave or Zig-Bee standards for example. Unfortunately, all of them propagate almost equally in the space and thus they need a kind of authorization and authentication. For example in trusted, not protected network any device can communicate to another one utilizing the same standard. There is no simple a selection method of the device that user wants to interact. This could be done by e.g. visual recognition of the device and then addressing it.

Nowadays, a human body as a communication medium is intensively explored. Apparently low energy, high frequency signals can be introduced into the body and signal can be relatively and simply transferred to another device being in contact with the body.

In this paper we are introducing a head worn device, possible to be combined with the smartglasses and which is utilizing the body channel communication for the user interaction. Moreover, the developed device allows to measure additional parameters which, in general, could be utilized in health state evaluation.

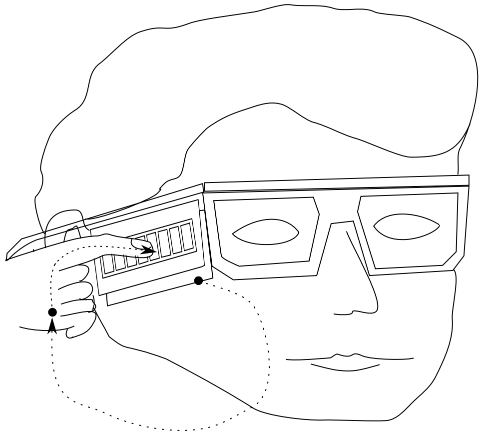

Fig. 1. Use case of the device

II. Methods

A navigating device devoted for the mobile computing should fulfil several criteria:

- As the device is intended for battery powered system it should have a small power consumption
- It should react for simple gestures including multi-touch and sweep ones
- It should maintain a basic security requirement - e.g. gestures made only by the wearing it person should be recognized, while at the same time, those made by others should be ignored.

We have proposed the touch sensing device that utilizes body conduction phenomenon. Human body can be regarded as volume conductor. In such way touch action can be by detecting presence of the signal generated by the device itself. A principle of the operation is depicted in Fig. 1 while a simplified schematic in Fig. 2.

The device is introducing electrical signals into person's body. This can be achieved by the electrode located on the glasses frame. Additionally several (e.g. 8) conducting pads are exposed and allowed to be touched by finger. The user by touching at least one of them causes the signal propagated through the body to appear on the touched pad. The signal is measured coherently with the introduced one and its amplitude is estimated. Providing that the interface contains N receiving pads the N signal amplitudes can be estimated. The proposed interface does not require many components and almost any modern microcontroller can be used. What needed is the one GPIO, serial port (UART, USB) for communication and N-input multiplexed ADC.

Additionally by measuring signals coherently with generated pattern additional measurement can be performed providing eg. basic user discrimination.

1) Body model estimation: The proposed device is using human body as a signal propagation medium. To analyse limitations of the device basic parameters of a human body, e.g. electrical impedance, should be considered.

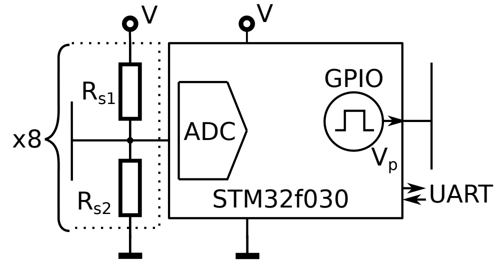

Fig. 2. A schematic of interface and sensor

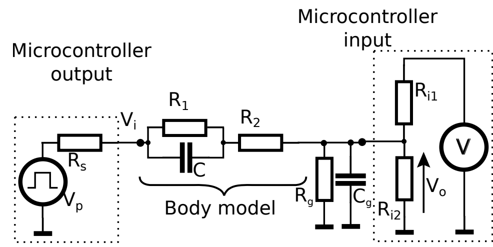

Fig. 3. An equivalent electrical model of the proposed system

In Fig. 3 a simplified model of the system is shown. V_p is a voltage source representing the microcontoller's port (General-purpose input/output - GPIO) output. This can be regarded as a time dependent voltage source with series resistance R_s. R_1, R_2 and C are representing human body impedance. R_g, C_g are impedance of the body to ground. R_{s1}, R_{s2} are fixed $(1M\Omega)$ resistances connected to the ADC input in order to maintain DC polarisation of the analog input of the microcontoller .

Let's denote :

$$Z_B = R_2 + \frac{R_1 * \frac{1}{sC}}{R_1 + \frac{1}{sC}}, \tag{1}$$

$$Z_G = \frac{R_g * \frac{1}{sC_g}}{R_g + \frac{1}{sC_g}}, \tag{2}$$

the resulting voltage at the input of the ADC can be calculated as:

$$V_o = V\frac{R_{i2}}{R_{i2} + (R_{i1}||Z_g||Z_B)} + V_p\frac{R_{i2}||R_{i1}||Z_G}{R_s + Z_B + (Z_G||R_{i1}||R_{i2})} \tag{3}$$

where V is an amplitude of excitation signal,and in the device it is equal to power supply of the microcontoller (here: $3.3V$), operator $A||B = \frac{A*B}{A+B}$ calculates impedance of parallel connected elements.

The output impedance of the general-purpose input-output (GPIO) pin of the micro-controller was measured and in our case it is equal to $R_s = 32\Omega$. The analogue input of the Analog-Digital Converter (ADC) was biased in order to reduce negative voltage presence at the input.

From equation 3 we are trying do calculate values of R_1, R_2, R_g. If denote:

$$R_A = \frac{R_i \cdot R_g}{R_i + R_g} => R_g = \frac{R_i \cdot R_A}{R_i - R_A} \tag{4}$$

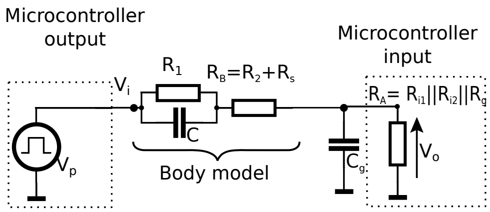

Fig. 4. A simplified electrical model of the system

Where $R_i = R_{i1}||R_{i2}$ and:

$$R_B = R_2 + R_s \tag{5}$$

then we can search for R_A, R_B, R_1, C and C_g.

Since V is constant DC voltage, model can be reduced to the model depicted in Fig. 4.

The V_p is output voltage of the microcontroller and it can have a form of a rectangular wave only. The model parameters of a human impedance can be retrieved by using a non-linear analysis of V_p and V_o time series.

$$V_o(s) = \frac{\frac{R_A}{sC_g}}{\frac{R_A}{sC_g} + R_2 + R_s + \frac{R_1}{sCR_1+1}} V_p \tag{6}$$

$$V_o(s) = \frac{(sA+B)\,V_p}{s^2({C_g}^2CR_1R_B) + s\left(A + {C_g}^2R_B + {C_g}^2R_1\right) + B} \tag{7}$$

where: $A = C_gCR_AR_1$, $B = R_AC_g$.

To obtain parameters it is necessary to know V_o for a specific V_p. By using the GPIO it is possible to utilize $V_p = V \cdot \mathbf{1}(t)$ thus, $\mathcal{L}(\mathbf{1}(t)) = V/s$. A symbol V stands for an amplitude of the excitation signal and is equal to a power supply voltage of the microcontroller.

Additionally, if C_g is neglected the equation (7) becomes:

$$V_o(s) = \frac{sR_AR_1C + R_A}{s(R_A+R_B)R_1C + R_A + R_B + R_1}\frac{V}{s} \tag{8}$$

R_A, R_B, R_1, C and C_g can be obtained by calculating inverse Laplace transforms of the relationship (7) or (8) and applying, e.g., a least-square approach to fit the data.

A step response, in time domain, is calculated using an inverse Laplace transform of the equation (7):

$$V_o(t) = V + Ve^{\frac{dt}{2c}}\left(\frac{(2a-d)}{p}\sinh\left(\frac{pt}{2c}\right) - \cosh\left(\frac{pt}{2c}\right)\right) \tag{9}$$

where $a = CC_gR_AR_1$, $b = R_AC_g$, $c = {C_g}^2CR_BR_1$, $p = \sqrt{(d^2-4bc)}$ and $d = R_AR_1CC_g + {C_g}^2(R_B+R_1)$.

An inverse Laplace transform of the relationship (8) is the following:

$$V_o(t) = \frac{VR_A\,R_1\,e^{-\frac{t\,(R_A+R_B+R_1)}{(R_B+R_A)\,C\,R_1}}}{(R_B+R_A)\,(R_1+R_B+R_A)} + \frac{VR_A}{R_1+R_B+R_A} \tag{10}$$

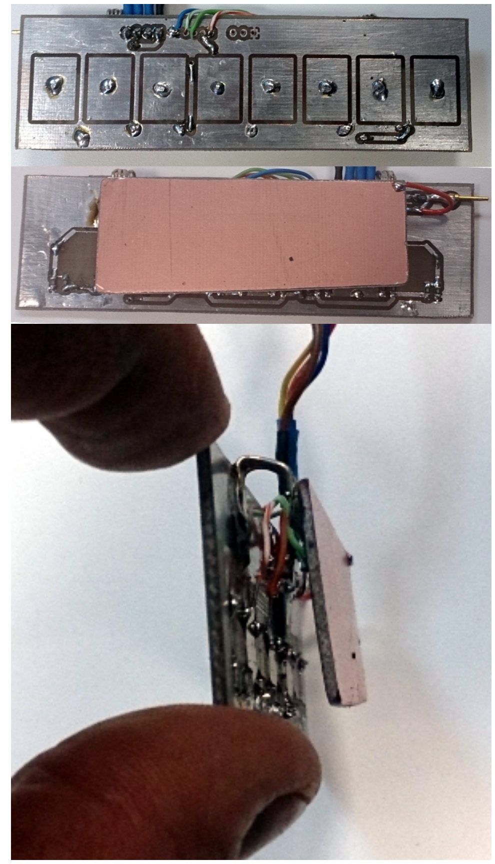

Fig. 5. A developed prototype of the sensor - various views are presented

III. Results

A prototype of the device has been designed and manufactured. It is implemented by using of two double-layer printed circuit boards (Fig. 5). As microcontroller STM32F030 has been selected. It contains, among others 12-bit relatively fast ADC (up to 1 MSPS), UART and GPIO. Moreover, a small package (SSOP20) is available what makes it especially useful in such application. The PCB carrying microcontroller is the main board. It contains all the components and sensing pads etched directly on the PCB. Secondary PCB consists only of the body drive electrode and it is used as a mechanical stabilizer. More details are given in Fig. 5.

The measured signals are sent to the host computer using a USART-to-USB converter. We have developed Qt-based application for data visualization. An exemplary screen shot of the developed application is shown in Fig. 10 and Fig. 11. In Fig. 6 proposed interaction scheme is shown.

In an active state the device scans the bare pads every 8 milliseconds. A complete measurement takes approximately $850\mu s$. In active mode device consumes 4mA at 3.3V. In sleep mode power consumption is less than $100\mu A$, mainly depending on frequency of wake-up periods.

A possibility of identification the human body electrical equivalent parameters has been investigated. A simplified functional model of the device has been proposed for this purpose.

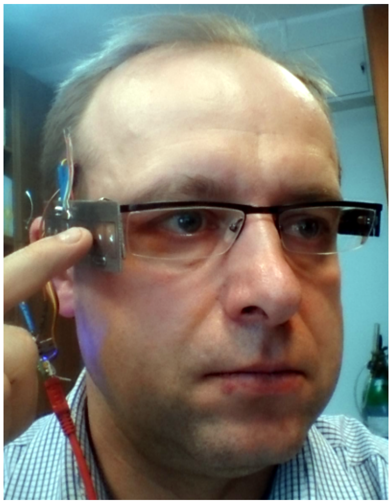

Fig. 6. Usage of the prototype

Calculations have led to results described by the formulas 7 and 8 assuming some simplifications. Unfortunately, the equations are non-linear and full reconstruction of parameters could not be done as the least square problem is a non-unique.

To make the calculations possible a number of parameters has been reduced and additional knowledge has been introduced. For the model presented in Fig. 4, in the first attempt, G_g has been committed (solved for equation 8) and unknown vector P has been constructed as:

$$P = [R_A; R_B; R_1; C; V],$$

refer to the equation 8 for a description of the symbols.

Fortunately, the values of V and R_A are known as they are determined by the equipment used, so a new search vector has been described by:

$$P = [R_B; R_1; C].$$

To check properties of the proposed method the human-body phantom has been developed according to the model shown in Fig. 4. Additionally, Analog Discovery 2 from Digilent has been used as a measurement device. The following parameters have been applied $V = 5V$, $R_A = 2k\Omega$, $C = 470nF$, $R_B = 470\Omega$ and $R_1 = 3.9k\Omega$ while $C_g = 0$.

The result of measurement performed is shown in Fig. 7. Please note, that using the least-square fitting procedure the problem still remains a non-linear. Equation 8 is of a type:

$$V(t) = K \cdot e^{-t \cdot M} + N \tag{11}$$

If this is a unit-step response, the parameter N is a voltage observed for $t \rightarrow \infty$. Thus, the data acquisition procedure could be modified to enable a direct measurement of N by generating a longer period of t. If the N is known:

$$V(t) - N = K \cdot e^{-t \cdot M} \tag{12}$$

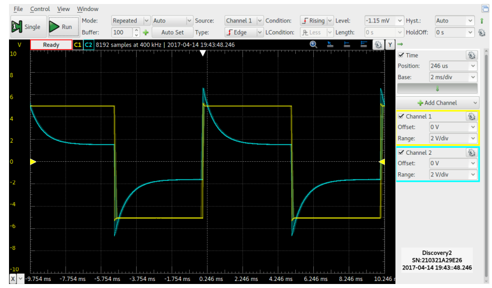

Fig. 7. Examples of the recorded waveforms

and this equation could be linearised by applying a logarithm operation to both sides of equation:

$$ln(V(t) - N) = ln(K) - Mt \tag{13}$$

and $ln(K)$ and M are now forming the new $P_l = [ln(K)M]$ vector and it could be obtained by the least square technique.

Then using an optimization package in the Octave a fitting algorithm based on the *lsqnonlin* function has been created. The Jacobian and regularization factor could be automatically generated using *lsqnonlin* function. A new equation

$$P_l = P_{l0} + \Delta P_l \tag{14}$$

has been calculated, where :

$$\Delta P = pinv(J) \cdot [Vm(t) - V_s(P_{l0})] \tag{15}$$

and P_{l0} is the initial vector, J is the Jacobian matrix, V_m are the measured values of unit-step response of the voltage, $V_s(P_{l0})$ is simulated vector of step response for given model data, $pinv$ denotes pseudo inversion operation. According to equation 8 the following formulas are true:

$$K = \frac{V R_A R_1}{(R_B + R_A)(R_1 + R_B + R_A)}, \tag{16}$$

$$M = \frac{R_1 + R_B + R_A}{(R_A + R_B) C R_1}, \tag{17}$$

and

$$N = \frac{V R_A}{R_1 + R_B + R_A}. \tag{18}$$

By having calculated K,M and N the R_1, R_B, and C could be obtained. From N the $R_1 + R_B$ is calculated:

$$R_1 + R_B = \frac{R_A\, V - R_A\, N}{N} \tag{19}$$

Then using formula 16 calculate R_1 and R_B:

$$R_1 = \frac{\left({R_A}^2 + 2\, R_A\, (R_1 + R_B) + (R_1 + R_B)^2\right)\, e^K}{R_A\, V + (R_A + (R_1 + R_B))\, e^K} \tag{20}$$

$$R_B = (R_1 + R_B) - R_1 \tag{21}$$

and from equation (17) the C is calculated as:

$$C = \frac{R_A + R_B + R_1}{(M\, R_B + M\, R_A)\; R_1}. \tag{22}$$

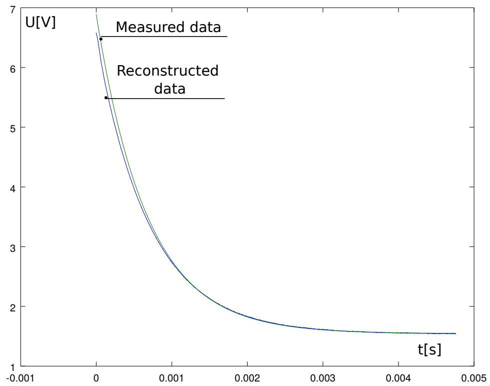

Fig. 8. Example of data fitting for resistor model

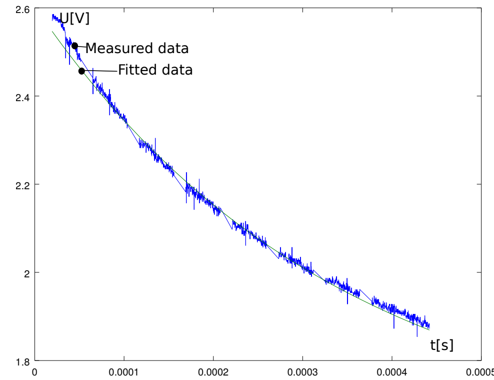

Fig. 9. Example of data fitting for real measurement

TABLE I
RECONSTRUCTED MODEL PARAMETERS

Parameter	Estimated value
R_B	738.82 Ω
R_1	3738.6 Ω
C	428 nF

TABLE II
RECONSTRUCTED PARAMETERS FOR REAL MEASUREMENT

Parameter	Estimated value
R_B	3377.7 Ω
R_1	3372.3 Ω
C	162 nF

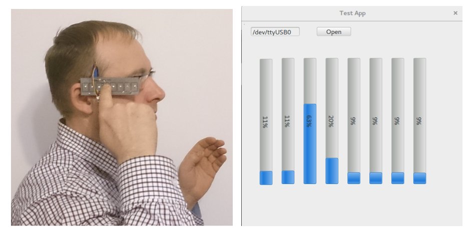

Fig. 10. Result of data obtained from the system where user is interacting with the device

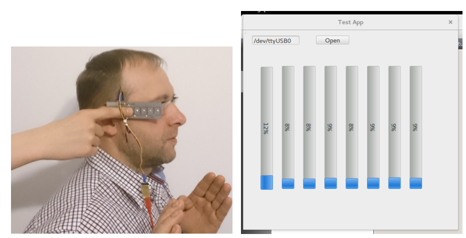

Fig. 11. Result of data obtained from the system where third party user is trying to interact with the device

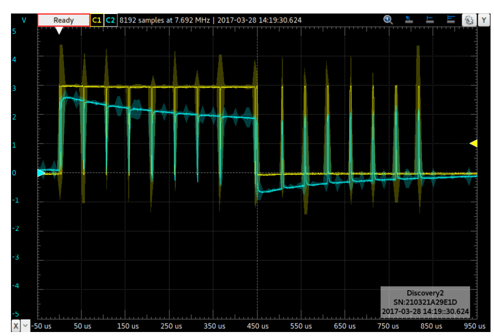

Fig. 12. Measurement signals

A phantom composed of discrete components has been created for verification of the proposed procedure. A square waveform has been applied to the phantom and response signal has been measured. Next, values of used components have been retrieved using Octave environment. For time and effort reduction Analog Discovery 2 acquisition module has been used simultaneously with the developed sensor.An input impedance of used acquisition system has been identified to include this information in the calculations. Results are collected in Table I. Differences between model and reconstructed data could be explained by influence of waveform generator output impedance.

In the next step this technique has been adopted to the real measurement data. Results of experiment using real body are collected in the table II and result of real data matching is shown in Fig. 9.

Additionally, the device could be used only by the person wearing it, thus providing a basic security. Unattended events caused by another person could be detected and rejected - the idea is explained in Fig. 10 and Fig. 11. Images are self-explanatory.

In Fig. 12 a small portion of the measured signals is shown. Mentioned signals were measured using Analog Discovery 2 USB-based board. The symbol C1 denotes GPIO output voltage V_i while the C2 denotes V_o (as in Fig. 3). For safety reasons signal should not contain DC components. Remaining portion of the signal maintains zero DC component by adequate GPIO control. In fact, human body has no direct connection with system ground. Thus DC polarisation is set at half of the power supply. Thus maintaining average output of GPIO output signal at $\frac{V}{2}$ assures zero DC component. This is maintained within about 4ms while in Fig. 12 only 1ms is

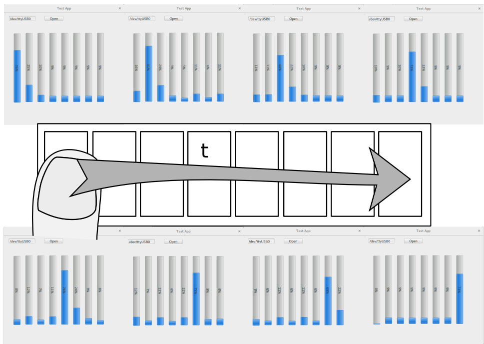

Fig. 13. Sequence of measured signals for sweep action

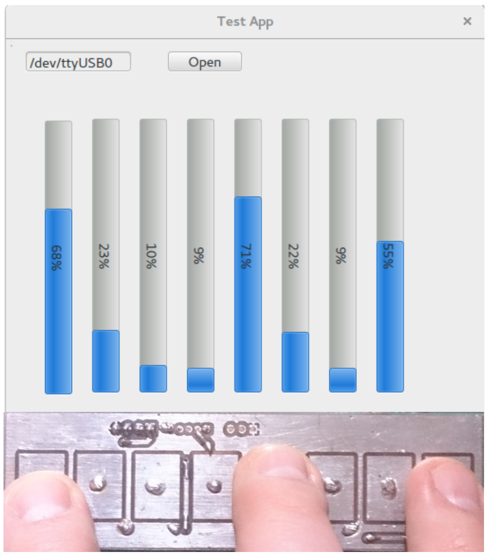

Fig. 14. Mulitouch sequence and observed signals - three fingers touch

shown.

Detected action can be send to the host computer about every 10mS. Thus it is possible to detect actions like finger sweep over the sensor area. In Fig. 13 an sequence of recorded signal is shown for finger sweep right action. Additionally device is able to detect multi-finger actions. In Fig. 14 three finger touch action is shown.

IV. Conclusion

In the paper an interaction device with the computing systems is presented. The developed unit consumes a limited amount energy in active mode, especially when comparing it to similar optical based equipments. Additionally, it provides discrimination between users. Valid user is the only user wearing of such device not another.

Additionally, we have proposed measurement of wearing person's human body parameters. Results are preliminary and more research should be conducted in this area, however we have proposed model and methodology of data processing.

Results of measurements and resulting model parameters are varying in time, they depend on multiple factors. These are user skin parameters, force of applied pressure, individual body composition of the person or even their mental status (eg. sweating). It is difficult now to extract individual parameters related to the person or their health state. For clear justification of such data usability more studies and experiments should be involved. However up to now the navigation ability of the device has been proved and basic user discrimination as well. In the implemented user cases among primary function as a control device additional data could be gathered without involving of the user. These could be further analysed and processed to provide more information.

Proposed method of impedance model reconstruction could be implemented directly in the utilized microcontroller and calculations are not time - consuming. For the presented solution the calculation time depends on number of samples to be processed and for 500 samples it does not extend 2 milliseconds.

Acknowledgment

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