Interactions using passive optical proximity detector

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***Abstract*—In this paper we evaluated the possible application of a passive, optical sensor as an interface for human-smart glasses interactions. The designed proximity sensor is composed of set of photodiodes and the appropriate hardware and software components. First, experiments were performed for the estimations of such parameters as distance to an object, its width and velocity. Achieved results were satisfactory. Therefore, next, a set of static and dynamic hand gestures was proposed together with the related recognition method. The method was verified during experiments with volunteers. Experiments have shown that in appropriate lighting conditions it is possible to detect static and dynamic simple hand gestures using inexpensive and computationally efficient sensor. These features enable the use of such a sensor as one of the smart glasses interfaces.**

Keywords—smart glasses; gesture recognition; touchless interface;

I. Introduction

Mobile devices from the segment of wearable electronics, like smart glasses, require comfortable methods of interaction with the on board operating systems. They are usually not equipped with input devices, into which people get used to while communicating with desktop computers. Hence, new input interfaces, devoid of keyboards and mice, have to be convenient in use enough so the basic actions should be sufficient to provide elementary navigation capabilities.

In this paper, we describe the design for a wearable prototype that provides a touchless interface for simple hand gesture recognition. The interface is designed as a part of an open smart glasses platform developed under the eGlasses project (www.eglasses.eu). The hand gesture based touchless interactions with smart glasses can be useful in many healthcare applications, e.g. for septic safe interaction for surgeons [1], for the elderly in ambient assisted living [2], navigation for blind persons [3], etc.

The investigated interface prototype is based on a line of photodiodes operating in passive mode and is characterized by low power consumption. It preserves the privacy of a user (e.g. no fingerprints are left) and privacy of nearby people. We present an analysis of the accuracy of the measurement system in terms of parameters such as the speed of the object, the object's size and distance from the plane of the proximity sensor. Additionally, we introduce a set of identifiable hand finger configurations (gestures) that can be detected using the prototype. Preliminary user studies were carried out to evaluate the effectiveness of hand gesture recognition. We conclude by presenting future usage scenarios and possible modifications for the contactless interface.

The rest of the paper is structured as follows: Section II describes the system design, including the design of hardware and software components. It additionally presents a set of gesture primitives that can be potentially detected using the prototype. Section III demonstrates the experimental results for the accuracy of the prototype and results of early user studies. Section IV describes the discussion of the results, and Section V concludes the paper.

A. Related work

With the introduction of Google Glass, Epson Moverio, Recon Jet, Vuzix M-100, Optinvent Ora and other small form-factor devices there is an emergence of smart glasses.

In some of the devices the issue of action triggering could be at least partially satisfied by voice steering (e.g. "Ok Glass..." like in Google Glass). However, the problem of navigation in GUI through options in a menu could be resolved in multiple ways. The interaction methods currently used for controlling these devices involve touch gestures on the device, speech, eye gestures, head gestures, mid-air hand gestures, pushing hardware buttons and the interaction by using an external device (like a smartphone).

Recent research approaches investigated the face as interaction space and thus controlling the device by hand-to-face interactions [4]. Studies concerning the interaction techniques for mobile devices explore eyes-free interaction techniques for overcoming the problems with reduced visual attention in mobile environments [5]. Lumsden and Brewster show that mobile and wearable devices need alternative interaction paradigms [6]. In consideration of mid-air hand gestures, Piumsomboon et al. [7] propose a user-defined gesture set for controlling AR devices by using hand gestures. Freeman et al. [8] present design recommendations for above-device interactions.

Several prototypes show various approaches for proximity-based sensing above and around devices. Gesture Watch [9] and HoverFlow [10] are samples for tracking above-device interactions above a wristwatch or smartphone by using infra-red proximity sensors. SideSight demonstrates the use of sideways looking infra-red proximity sensors for detecting

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around-device interactions [11]. Abracadabra is a magnetically driven input technique for very small mobile devices, which enables wireless and unpowered input [12].

On the other hand, we propose a touchless, low power consumption, basic hand gesture sensor. Due to proper signal computation, taking into account simple hardware, it is a promising solution of contactless, moderate level of complexity gestures interface.

II. METHODS

Experimental research on contactless gesture recognition requires designing the prototype system that can be used to verify the proposed idea.

A. *Design of the system*

The detector described in this work is intended to be a part of a proximity radar system comprised of sensors spread around the head on the frame of smart glasses. One of specific applications of this multi gauge system could be a gesture recognition interface. A block diagram of the designed detector is presented in Fig. 1.

Set of 8 aligned photodiodes (BP34), operating in the visible and infra red bands of light, was utilized in investigated prototype. Square shaped active area of each photodiode had side length equal to 3 mm. The adjacent photosensitive elements were distanced by 1 cm. Photodiodes output currents were put into transimpedance amplifier and output voltage level conditioning system (I/U, amp. blocks in Fig. 1.). Analog to digital conversion was performed using 16 bit AD. In the data acquisition mode the 500 Hz sampling frequency was used to average signal in order to reduce electric network noise influence and light level fluctuations. Thus, effective sampling frequency of 25 Hz of already smoothed signals was tested for gesture recognition purposes.

The target PCB of the designed proximity sensor is indented to be mounted inside the right side panel of the eGlasses frame, as shown in Fig. 2. In the described experiments, the PCB with photodiodes was mounted on the frame of the prototype glasses.

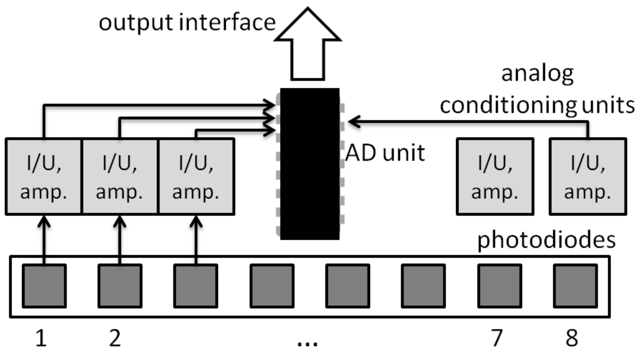

Fig. 1. Block diagram of a passive optical proximity detector.

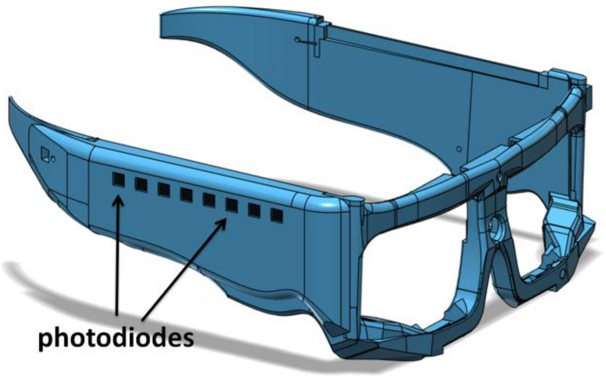

Fig. 2. View of the touchless interface hardware mounted within the eGlasses frame.

The sensor’s working principle inherits a single photodiode behavior. It reacts on the level changes of light incident on the active area of a photodiode. The photodiodes utilized in the prototype are characterized by ±65° angle of half sensitivity. That indicates they have a broad field of view, which is not a desired feature when as narrow objects, as fingers have to be differentiated. Hence, a simple method of increasing photodiode selectivity was tested. A special removable overlay for the touchless sensor was designed, as presented in Fig. 3. The aim of its application was to physically limit the field of view of a photodiode. In order to narrow the angle of half sensitivity of a light sensor to ±40°, optical blocks of the height of 3.5 mm, measuring from the photodiode active area surface, and 3 mm from the center of photodiode are required. The role of the optical block was evaluated during simulations and real measurements.

In the first experiment, processing of recorded signals was performed on PC. Ultimately, some processing will be realized by the microcontroller unit of the eGlasses platform, which would cover the AD conversion functionality as well.

In Fig. 4 the photography of the prototype of the proximity sensor during the gesture recognition tests is presented.

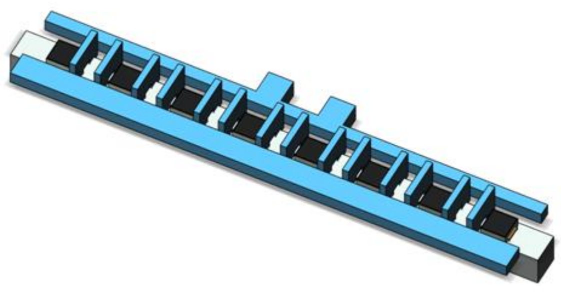

Fig. 3. The design of the optical block used as an overlay module (blue part) for photodiodes.

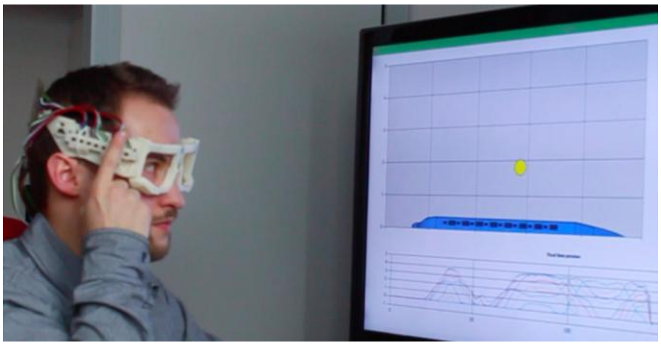

Fig. 4. Proximitiy sensor in action at early prototyping stage.

With the described prototype of the proximity sensor the following parameters can be evaluated: the velocity and width of the object moving along the line of photodiodes, the distance of the object from a photodiode, the size of the static object in front of the face of detector. Measurements of these parameters can be used to propose possible hand gestures that can be recognized by such system. Therefore, high accuracy of the measured parameters is required. All measurements were performed with the assumption that the distance between the object and the plane of the proximity sensor is in the range of 2-6 cm. This range ensures that the user does not touch the sensor and recorded gestures are not executed by close person.

B. Touchless gesture recognition

Before certain hand gestures could be investigated, the features and capabilities of designed optical sensor have to be evaluated. The methods of estimation certain spatio velocital parameters of object appearing in the field of view of a sensor have to be considered.

By having at least two optical sensors one can estimate the longitudinal velocity component, related to the line linking these photodiodes. The accuracy of the speed estimation can be better using signals from additional photodiodes. The maximum measurable velocity, along with the estimation error, depends on the sampling frequency of a system. Using 25 Hz sampling rate and two photodiodes, the maximum detectable velocity is equal to 25 cm/s (1 cm distance between adjacent photodiodes over sampling time interval). As in our sensor, the boundary photodiodes are distanced by 7 cm, thus the theoretical maximum detectable velocity could be 7 times larger. However, object moving with such velocity would not be observed by inner photodiodes. Hence the differentiation of such measurement from random noise would be difficult.

The perpendicular component of velocity could be estimated as well. However, it would usually be described in arbitrary units due to lack of proper calibration.

Even with one photodiode, with a limiting field of view block at one side, one can distinguish movement direction. Object appearing from the side at which the block would be present would produce steeper signal (it would suddenly appear in the field of view of a sensor) than the same object closing from unobstructed side. However, analysis of the differential signal from two adjacent photodiodes gives more explicit results.

The modulation of a signal on given photodiode is related with the light intensity, thus modifying the incident light level by moving hand closer and further delivers another useful feature.

The number of aligned photodiodes in a system determines the number of objects that sensor can distinguish. With all fingers from single hand spread (apart of the thumb) and located in the expected range from the sensor, 8 photodiodes deliver resolution enough to distinguish all of them. The signal obtained from consecutive photodiodes would be interlaced with high and low levels (shadow caused by the fingers and light shining on photodiode through the gaps between them). Thus, one can distinguish all fingers spread and also, analyzing the shadow shape, probability if there are two (narrow plane) or four fingers (broad plane) joint within the field of view of a sensor.

When the field of view limiting overlay is applied, the distance to the object moving parallel to the sensor can be estimated. It is based on known photodiode's field of view, distance between sensors, calculated object's velocity and could be done in similar way as Kim and Baek proposed [13]. The range of values of the distance depends on the range of a sensor, which is dependent on the contrast between shadow caused by object and ambient light level.

The estimation of the width of the moving object could be done by analyzing the differential signal of two photodiodes. The time interval between detected minimum and maximum within the time window of transition event in analyzing signal has to be found. That value, multiplied by object's velocity gives the width of the object.

Irrespective of reasoning apparatus, in the approach to the gesture recognition a parameterization and feature extraction processes are very important [14][15]. All of the variables described above result from aligned photodiodes passive sensor characteristics. They were mapped to possible hand gesture features and, along with their value domains, are enlisted in Table I. The proposed features were analyzed within two categories. An investigated set of basic gestures was arbitrarily divided into two groups: static gestures (without hand movement) and dynamic gestures.

TABLE I. GESTURE FEATURES

Gesture feature	Feature value domain	Static	Dynamic
Longitudinal velocity	0-25 cm/s	-	+
Perpendicular velocity	arbitrary units	-	+
Direction	forward / backward	-	+
Amplitude change	increase / decrease	-	+
Fingers count	0-4	+	+
Narrow planes count	0-2	+	+
Broad planes count	0-1	+	+
Distance to object	1-6 cm	-	+
Object width	1-10 cm	+	+

In gesture recognition methods each gesture is usually built up of states, which are distinguished by a set of features [15]. In the context of dynamic measurements presented gesture features can be observed with different time intervals. Therefore, description of time is also important feature for gesture recognition.

Let the term "primitive" represent a basic gesture, elementary state, which is recognized using a single data processing step. The single processing step describes analysis and activities associated with sampling signals from all photodiodes within single sampling period. Therefore, in time domain, single processing step covers the duration of data analysis which results in extraction of possible gesture features (possible to obtain using one measurement). The primitive itself reflects encoded configuration of fingers of hand that appears in the field of view of a sensor, obtained from each data reading. Primitives can also store information about spatial localization of fingers, what becomes useful in objects tracking.

In the scope of this work we focus on the detection of primitive types and related simple recognition of gestures. An alphanumeric code was assigned for each of investigated gestures in order to compare them briefly and precisely in the results section.

1) Static gestures

The group of static gestures contains only different configuration of (not moving) fingers that can be recognized. Table II presents a codebook for these gestures. Abbreviations are related with features of a given gesture, for example 3FS means *3 Fingers Spread* or 4FC means *4 Fingers Joint*.

TABLE II. STATIC GESTURES CODEBOOK

Gesture	Code
1 finger	1FS
2 fingers spread	2FS
3 fingers spread	3FS
4 fingers spread	4FS
Narrow plane (2 fingers joint)	2FJ
Broad plane (4 fingers joint)	4FJ

2) Dynamic gestures

The dynamic gestures refer to all kind of hand swipes, where hand moves in front of the proximity sensor. The standard static gestures are given two additional degrees of freedom (direction, speed). Each gesture can be performed in forward or backward direction and in fast or slow manner. The minimal and maximal transition time thresholds have to be exceeded in order for movement to be appropriately classified due to the movement speed.

Movements of 3 and 4 spread fingers were not investigated as their recognition even in static mode lies on the border of sensor resolution. Exemplary dynamic gestures are 1FSFS, which stands for *1 Finger Spread Forward Slow* or 4FJBF represents *4 Fingers Joint Backward Fast*. The complete codebook of dynamic gestures is presented in Table III.

TABLE III. DYNAMIC GESTURES CODEBOOK

Gesture base	Velocity and direction mode			
	Forward slow move	**Forward fast move**	**Backward slow move**	**Backward fast move**
1 finger	1FSFS	1FSFF	1FSBS	1FSBF
2 fingers spread	2FSFS	2FSFF	2FSBS	2FSBF
Narrow plane	2FJFS	2FJFF	2FJBS	2FJBF
Broad plane	4FJFS	4FJFF	4FJBS	4FJBF

C. Primitive type identification

As described, the values obtained from all photodiodes at each sampling event are stored in a data array. Considering the local monotonicity changes of such spatial signal, resultant from values contained in a data array, it could comprise from up to 4 peak values. To estimate, if given peak and its surrounding values reflect the pattern caused by the presence of single finger, 2 or 4 joint together, the curve comparison mechanism was applied.

Passive sensor operating principle relies on the shadow shape characteristics, produced by fingers placed on the path between the non-point source of light and the set of photodiodes. In this case, the profile of resultant spatial signal received by the set of photodiodes can be modeled using the negative Gaussian distribution. For example, one finger produces narrower and steeper characteristics than two or four fingers joint together. Therefore, Gaussian distributions of variance equal to 0.5, 1 and 1.5 were fitted to each identified peak from a data array. Center of gravity associated with each obtained peak and values from its surrounding photodiodes was calculated and then matched with normal distributions central points.

In accordance with formula 1, the goodness of fit was calculated for each of Gaussian distributions and a shape (spatial signal) obtained from photodiodes:

$$\chi^2 = \sum_{i=1}^{N} \frac{(O_i - E_i)^2}{\sigma^2} \qquad (1)$$

where O_i is the observed value (from the photodiode), E_i is the expected value (from the Gaussian distribution), σ^2 is the variance of observed values and N represents the number of observations.

The Gaussian distribution associated with the lowest goodness of fit (squared chi-square distance) value indicates which configuration of fingers (single, 2 or 4 joint together) is the most likely a cause of the peak from the data array that is currently being analyzed.

Effective sampling frequency of 25Hz of smoothed signal was tested for gesture recognition purposes, based on the set of aligned sparse sensors. The choice of properly low sampling frequency of the system could facilitate intermediate, unknown states handling, especially in gestures composed of various states. However, with sampling rate not high enough the sensor would not be able to detect faster moves and notice rapid finger configuration changes.

III. Results

A. Results of measurements

Accuracy of parameters is an important aspect in the related evaluation of gesture features. With the information about sensor capabilities and constraints, proper gestures could be proposed. Significant part of the measurements of sensor characteristics was performed with the use of trolley moving on the straight track, with programmable speed and exchangeable objects on board. During experiments signals were collected with sampling frequency of 1000 Hz, but were also downsampled to 25 Hz to find out whether such sampling is sufficient to cover desired functionalities. Calculating differential signals of multiple pairs of photodiodes effected in the extrapolation of downscaled sampling frequency.

For velocity estimation, a flat 5 cm wide ambient light blocking cardboard was moving in front of the sensor with different velocities. Table IV presents the results of measured values and mean errors basing on just two adjacent photodiodes signals analysis.

Basing on the results from Table IV, and human convenience, a 12.5 cm/s velocity was set as a threshold to distinguish slow and fast swipe for dynamic gestures.

The estimation of the width (*w*) of the moving object was done by analyzing the differential signal of two photodiodes. In this experiment, a 3 cm wide cardboard was moving along the face of the proximity sensor, with different velocities and distances from the sensor. Despite the measurements for each configuration were repeated 4 times, only one trail was included in calculations so far. The obtained results are presented in Table V. Therefore, precise detection of width of moving objects is achievable, unlike of static objects, into which curve fitting mechanism was. In separate experiment objects as narrow as 1 cm were measured with success as well.

TABLE IV. Velocity estimation accuracy

set velocity [cm/s]	distance from face of sensor *d* [cm]						
	1	***2***	***3***	***4***	***5***	***6***	***7***
16.92	16.31	16.23	16.97	15.98	17.10	16.68	18.50
11.60	10.29	10.75	11.06	11.22	12.84	10.79	8.90
8.46	7.92	8.39	8.34	8.47	7.09	8.67	7.02
mean error [%]	-7.09	-4.08	-1.93	-2.90	-1.48	-1.97	-10.3

TABLE V. Moving object width estimation

configuration	measured *w* [cm]	error [%]	measured *v* [cm/s]	error [%]
v=16.92 cm/s, d = 2 cm	3.33	9.91	15.79	6.68
v=16.92 cm/s, d = 5 cm	3.07	2.28	17.29	-2.19
v=6.67 cm/s, d = 2 cm	3.15	4.76	6.39	4.20
v=6.67 cm/s, d = 5 cm	3.04	1.32	6.75	-1.20

On the other hand, maximum detectable width depends on the assumed time of transition anticipation and, in our measurements, was limited to 10 cm.

Application of the optical block (the overlay narrowing the field of view for each photodiode) enables the measurements of the distance from moving objects in similar way as in [13]. A 3 cm wide cardboard was moving with the *v*=6.67 cm/s along the face of the proximity sensor, with 5 cm distance *d* from the sensor. The velocity was obtained calculating 4 pairs of photodiodes. Hence the error of velocity estimation is much smaller than in Table IV. Obtained results are presented in Table VI.

The optical blocks were applied for all but left and right side of boundary photodiodes. First reason is that these are not important in case of selectivity, because that region is not common with any other photodiode. Second is that the interface has to fulfill a radar functionality while not being an interface, thus also wide field tracking at boundaries of a sensor is important. In Fig. 6 (top) the spatial sensitivity of photodiodes with the overlay is presented. Bottom part of the figure illustrates how a single photodiode perceives, separately and together, two light sources, distanced by a 3cm gap, moving in parallel to sensor. Photodiode with the overlay can distinguish them (clear indentation in resultant signal), unlike the one without optical blocks.

TABLE VI. Distance to moving object estimation

measured *d* [cm]	error [%]	measured *v* [cm]	error [%]
5.502	10.03%	6.77	1.50%
4.823	-3.54%	6.772	1.53%
4.934	-1.32%	6.774	1.56%
4.257	-14.85%	7.057	5.80%

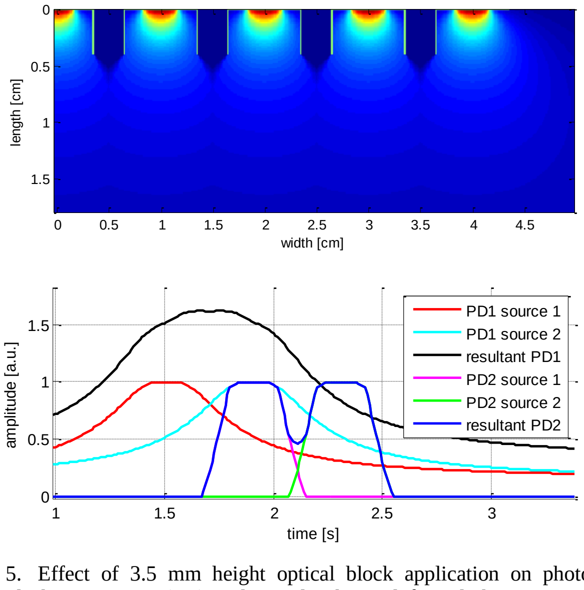

Fig. 5. Effect of 3.5 mm height optical block application on photodiode spatial characteristics (top) and signals obtained from light source moving along the touchless sensor above photodiodes with (PD2) and without (PD1) an overlay (bottom).

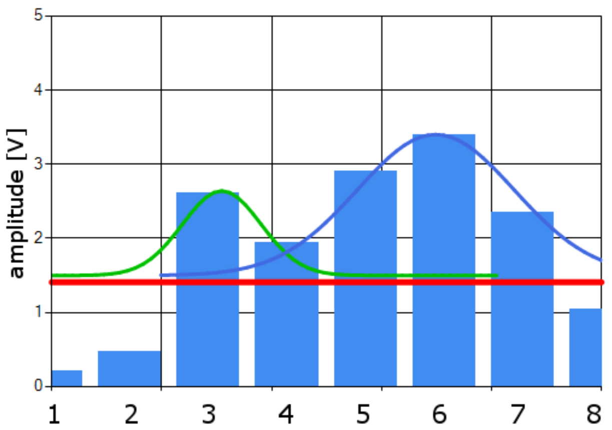

Fig. 6. Gaussian curve fitting to 1FS+2FJ configuration effect - view from the devloped application for real time gesture recognition.

The visual effect of Gaussian distributions fitting mechanism is presented in Fig. 6. The implemented algorithm has recognized two primitives (1FS and 2FJ) within presented data reading.

B. *Preliminary user studies*

Group of 11 volunteers participated in experiments for evaluation of gesture detection efficacy and comfort of use of the touchless interface. Every volunteer was asked to proceed through the prepared scenario embracing the thrice use of 6 static and 16 dynamic gestures. Volunteers were first asked to get used to the location of a touchless sensor on the frame of glasses and become acquainted to its range and resolution. The optical overlay was not yet applied in performed gesture recognition experiments.

During the experiment, each volunteer had the glasses frame put on his head, with touchless interface prototype output connected to a PC by AD converter. The gesture recognition algorithm response was presented on the display as a code of the gesture. The code was compared with the actual gesture performed by a volunteer.

The research could help with validation of the position of the touchless sensor on the frame as well. Also the angle, at which photodiodes perceive the gestures, could be changed if the volunteers would respond such a need.

C. *Gesture recognition results*

Volunteers were asked to show a static gesture for short time (2s) and take hand away from the field of view of a sensor. Procedure was repeated three times. In case of correct recognition a score of a gesture was given 1 point, while at wrong no pointes were added. The Table VII presents accuracies (percentage of properly recognized gestures in all trials) obtained for static gesture recognition at daylight.

In case of dynamic gestures, the correctness of recognition degree was fuzzier. A perfect recognition added 1 point to a given gesture score. However, if the gesture code delivered by the reasoning algorithm was slightly different (like detected velocity was very close to threshold) the score of a gesture was given half of a point. Table VIII presents the efficacy of identification of dynamic gestures.

TABLE VII. STATIC GESTURES DETECTION ACCURACY

Gesture	***1FS***	***2FS***	***3FS***	***4FS***	***2FJ***	***4FJ***
Detection accuracy [%]	84.85	89.39	65.15	10.61	95.45	96.97

TABLE VIII. PERCENTAGE OF DYNAMIC GESTURES DETECTION ACCURACY

Gesture	**Forward slow move**	**Forward fast move**	**Backward slow move**	**Backward fast move**
1 finger	72.73	72.73	72.73	62.12
2 fingers spread	33.33	57.58	59.09	46.97
Narrow plane	71.21	80.30	71.21	78.79
Broad plane	71.21	92.42	78.79	86.36

IV. DISCUSSION

The detection of static gestures (apart of 3FS and 4FS) delivered by optical passive sensor and broad plane dynamic gestures is lower but comparable with other, more computationally complex solutions of gesture recognition, proposed in the literature [16-18] for video processing. Main reason of low accuracy of detection of dynamic gestures was in movement velocity misclassification and similar fingers configuration interpretation failures.

Swipe gestures differentiation occurred more precise when faster motions were performed. More convenient threshold levels adjustment and change of algorithm interpretation counters range and reset moments could improve slow gestures recognition efficacy.

Obtained efficiency factors do not lead to clear differentiation of results due to the direction of dynamic gesture movement. Forward fast gestures are recognized better than backward fast, but on the other hand, forward slow is not detected as well as backward slow.

Passive optical sensor is working as expected when a directional light incidents the surface of photodiodes. In case of cloudy day ambient light conditions or when scatter light is dominating, scaling the small changes of signals from photodiodes, so the difference between most and least highlighted sensor is 3V makes the gesture interpretation process more efficient.

Considering the convenience of use of an optical proximity sensor within the prototype frame of glasses, volunteers responded it’s localization as to high on the frame. It was also pronounced as positioned slightly too much to the rear of the head what have forced the users to perform less natural moves in order to make a proper gesture.

V. CONCLUSIONS

The performed experiments proved that it is possible to successfully detect different, static and dynamic, hand gestures using inexpensive optical proximity detector. Therefore, the sensor investigated in this paper could complement other touchless interfaces, based on image processing [19][20] and, along with them, deliver various methods of interaction with the on board system for the user of smart glasses [21].

Simple design, low power consumption and relatively low processing complexity are important advantages of the developed proximity sensor. For some gestures the touchless sensor has limited gesture detection efficacy. This could be improved using 2D arrays of photodiodes, especially with additional illumination (active sensor). For the passive version of the sensor proper ambient light conditions are required to work properly because of its great sensitivity to visible light level changes. The active version of a touchless interface could improve its performance and make it endure to changing ambient light conditions. The IR pulsing LEDs can highlight the hand during gesture, making it recognizable even at dark conditions.

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