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Design of the wearable complex hardware for the photoplethysmogram analysis on various element bases subject to requirements for the overall dimensions and energy consumption minimization

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Abstract

The paper presents the issues concerning the design of photoplethysmographs operating for "a peek-a-boo". The paper has considered optimization method on the basis of the analysis of the area of a circuit board and energy consumption of the final device. It has also analyzed the two-frequency photoplethysmograph block diagram, it has made calculations of the area of a circuit board, the general one and on concrete circuit nodes. It has considered an integrated AFE microcircuit made by Texas Instruments for photoplethysmographic systems, it has analyzed features and shortcomings.

Keywords: photoplethysmographia, blood flow, noninvasive measurements, energy consumption, element base.

Introduction

The photoplethysmographic method is one of the simplest noninvasive methods of the peripheral blood flow condition research and the vessels condition evaluation. Today a large number of oximeters, pulse oximeters, oxyhemometers for various types of the cardiovascular system researches is successfully applied in medical practice.

By the principle of removal photoplethysmographs are divided into two main types.

Photometric pulse oximetry is based on the patient's tissues transillumination by the bispectral light flux in red (R) and infrared (I) spectral regions. The optical sensor installation is possible only on body areas with relatively small thickness (as a rule, they are fingers and toes, the earlap). Experimental studies on the oxyhemometer development show that illuminated fabrics optical density (for example, for the finger sensor is the first phalangeal bone) of different patients can differ in hundreds of times. Moreover, optical density depends on oxygenation [1].

One more direction is "reflective" oximetry of which R. Brinkman and W. G. Zijlstra [2] are considered to be the ancestors. They have showed that, registering reflected from skin radiation of various lengths of waves in the visible and the nearest Infrared Spectral range, it is possible to define and for a long time to monitor blood ventilation. This methodology excludes the need for the patient's blood sample and allows making measurements practically on any area of skin. The last fact gives essential advantages of this methodology before measurement for "a peek-a-boo". However, there is a number of problems and restrictions which arise at "reflective" oximeters creation [3].

The main application of the methodology for "a peek-a-boo" is anesthesiology, functional diagnostics of any type of peripheral vessels vasoconstriction, for example, at Reynaud's syndrome and diabetes mellitus, pathophysiology, traumatology, sports medicine, space medicine [4]. In this case ear and finger sensors are mainly used.

The main scope of reflective photoplethysmographs is cerebral oxygen saturation monitoring in the therapy, pediatrics and neonatology, surgery, gynecology [5].

It is obvious that a photoplethysmograph working for "a peek-a-boo" is more wanted today.

The interval of photoplethysmograph data updating is from 4 with till 1,5 min. depending on the optical skin resistance and removal device paths. A photoplethysmograph displays data on its monitor with a delay ranging from 10 seconds till 1,5 minutes, therefore it is sometimes expedient to remove at once from the photoplethysmogram and the electrocardiogram (the electrocardiogram curve in this case will slightly take the lead over the photoplethysmogram curve) [6].

Description of the method

The purpose of the paper is overall dimensions and photoplethysmograph hardware energy consumption optimization. One of the methods of optimization is the choice of the device hardware element base on the basis of a number of criteria. These criteria are: the area of a circuit board and energy consumption of the final device.

The development of a two-frequency photoplethysmograph demands a solution of the problem of channels division because a photodetector registering radiation of both light-emitting diodes (red and infrared) is used as a receiving device. There are two ways of channels division realization: program and hardware. The program method is that the computing kernel operates both light-emitting diodes inclusion and channels division on the reception path. It significantly increases the computing load of a microcontroller and raises requirements to its energy consumption. The hardware method of channels division assumes the existence of a synchronous detector in the scheme of a device. It allows reducing te computing complexity of data collection algorithm, but it increases the area of a circuit board for an analog part of a device.

Fig. 1 presents the structure of a two-frequency photoplethysmograph with data transmission on the Bluetooth radio interface in general view.

On the scheme, which the fig. 1 presents, the computing kernel of a device (MC) is a microcontroller with the lowered energy consumption (in this case a STM32L152 microcontroller is used), light emitters and a photodetector, digital potentiometers (DP) for program tweaking of radiators intensity and instrumentation amplifier (IA), a synchronous detector for channels division (SD), the filters blocks of low frequencies (FLF), the large-scale channels amplifiers (Amp.), a multiplexer (Mult.), an analog-digital converter (ADC) and a Bluetooth radio module (BRM). On the basis of this block diagram the basic electric circuit was realized and the calculation of the area of a circuit board, general and on the concrete knots of the scheme was made. The tab. 2 gives the calculation results.

The total area of a circuit board at such approach will be 1788,2 sq. mm, and such area can be provided only with application of circuit board's components placement both in a component and in a trace layer. For the circuit boards automatic installation this method of the placement leads to the increasing cost of circuit installation. Let's consider methods of the reduction of the area of a circuit board for each of the subsystems.

The subsystem of the photoplethysmograph power supply is composed of two integrated chips: a controler of the accumulator charge process and the indicator of the current charge of an accumulator. The cases of chips are chosen subject to minimization of the area (TDFN-8 and MSOP-10, 6 sq. mm and 18 sq. mm, respectively), the passive components (condensers and resistors of the superficial installation) of the standard sizes 0603 and 0805 (this standard size uses only one component-a precision resistor for the current definition of circuit consumption) are used as a binding [7]. The application of the combined integrated circuits of the charge controllers and the accumulator state monitoring does not cause the essential reduction of the area of a circuit board because the total quantity of leads remains the same (16-20 leads), a number of external components is reduced by 1-2 (usually these are the filtering condensers).

The reduction of sizes of a computing kernel subsystem is possible on condition of the transition from the LQFP-64 case (151 sq. mm) to the TFBGA-64 case (25 sq. mm) [8]. This transition allows considerably reducing the area of this subsystem, however, it is interfaced to the transition to higher class of complexity of the circuit boards production. This type of the case has a step of contact platforms in 0,5 that demands the existence of transitional openings in platforms or transitional openings between platforms with a diameter in 0,2-0,3 mm. Now this class of payments complexity is very expensive. Besides, the installation of BGA components also significantly increases a production cost that is an essential factor for the consumer mass device. An alternative for the BGA application is the QFN48 case having the sizes in 7x7 mm that at first sight allows reducing the area of a computing kernel by 3 times, however, this case possesses the following feature: the existence of an additional outlet on the back side of the case. This property does not allow making the distributing under the circuit case that will also increase the total area of a computing kernel reducing a prize in comparison with the LQFP64 case.

The module of BlueModSR communication has very small dimensions in comparison with analogs (10x17 mm), it is impossible to reduce its sizes as the module is a purchased product. The use of proprietary interfaces and also subGHz modules results in additional difficulties at the operation connected with compatibility (standard Bluetooth adapters do not work with such modules), and also the overall antennas dimensions (for subGHz transceivers the antennas size is by several times more than analogs for the range of 2.4 GHz).

It is possible to reduce the sizes of a photoplethysmograph analog part, having applied an integrated AFE circuit made by Texas Instruments [9]. This producer let out a set of specialized chips for photoplethysmographic systems. The whole available structure of an analog part of radiators and a photodetector is realized in this circuit; moreover, this microcircuit incorporates has also in its structure the 22nd digit ADE that allows to put the external ADE from the scheme out. The AFE4400 microcircuit has the average characteristics and the lowest cost from all in the set, providing a possibility of the reliable work for photoplethysmographs of the lower price range. The circuit has in its structure a transimpedance amplifier for a photodetector that allows reducing considerably the level of hindrances because of the properties of an output signal of a photodetector and the length of a cable. Tab. 2 presents the calculations of the area of a circuit board in case of the AFE4400 application.

The total area of a AFE4400 microcircuit and external passive components is 298,8 sq. mm-approximately by 3 times smaller area in comparison with the former analog scheme. Thus, the total area of a circuit is 1054 sq. mm.

In the course of the area reduction of a photoplethysmograph circuit board, it was noted that for the last 3 years the major factors constraining miniaturization of devices of this kind have considerably exchanged. Till 2012 (when the first AFE samples for biophysiological signals pick-off were presented [10]) the major factor influencing the sizes of devices was complexity of the analog scheme and the transfer extent of signals analog processing in digital (it has been increasing energy consumption of a device and not always providing acceptable accuracy). Moreover, enough high energy consumption of devices demanded the existence of high-capacity accumulators (800-900 mAh), especially in case of daily monitoring devices. Fig. 2 shows the contribution of each subsystem to the total area of a circuit board (according to 2011).

Now, with the growing number of ready specialized integrated modules and decreasing energy consumption, the major limiting factor is the system of data transmission and the existence of demountable connections. For example, in the presence of AFE with the built-in kernel of an ARM Cortex-M3 microcontroller, the circuit area can be reduced by 200-250 sq. mm, but then, a developer will face the problem connected with the module of communication which width will become defining for a circuit board of a device. The application of wire communication will lead to the increasing additional tests for electrical safety of a device and also will significantly reduce reliability of a device. Fig. 3 shows the changed chart subject to the appeared specialized AFE microchips.

Now there is no AFE with the integrated system of radio communication, but based on experience of the last 3-4 years, the development of microelectronics follows the path of creation not of universal, namely specialized systems "the whole device in the microchip case". Besides, the refusal tendency of the further miniaturization of demountable connections to short wireless communication channels and batteries charge is noticeable.

The problem of energy consumption minimization of a device is reduced to the assessment of energy consumption of each of device subsystems, to the search of the existence of steady functioning modes (active, passive, doze, etc.), the creation of dependence of energy consumption of the subsystem from time of the crossings existence identification in charts of various subsystems. Then, possessing the basic schedules of consumption of a device, it is possible to estimate consumption of a device in a real work cycle. These data allow a developer to estimate necessary capacity of a battery subject to various strategy of the use of a device (continuous monitoring, monitoring on demand, intellectual monitoring, single tests) and also subject to convenience of the operation (how often must a battery be charged or is it necessary to discharge a battery completely, etc.). An analysis of consumption in a work cycle and duration of a cycle will help to estimate applicability and energy efficiency recovery for this type of devices (free energy harvesting) [11].

Let's consider the basic strategy of the use of a photoplethysmographic monitor. One of the main medical techniques of the photoplethysmograph application is so-called cold test. There are some kinds of such inspection, but the general for all ways is blood circulation restoration fixation after immersion of a limb in cold water. As a developed device is supposed to be used in household purposes, it is possible to lean only partially on medical techniques because in everyday life a user will be interested in reaction of his vascular system obligations (short-term and long) and time which restoration to normal values demands. However, a cold test gives an idea of a technique of FPG pick-off, in particular of pick-off duration for determination of the FPG parameters. The duration of one pick-off on average is 10-20 s, pick-off frequency is 5-10 min. Therefore, for the formation of the strategy of a device use it is possible to be guided by these values.

One of the strategies of the photoplethysmograph application is the fixation of the organism state before intensive training, right after training and in 60-70 minutes after the end of training. As points 5 and 6 shows, sports physicians often conduct examinations and during trainings in case of hyperventilation achievement. Carrying out 3 inspections allows creating the schedule of a state norm-obligations-rest and gives a user some idea about a degree of condition level of his organism. Let's note this as a strategy of single measurements. Fig. 4 shows the photoplethysmograph operating mode at such strategy.

Fig. 4 shows that in 1 day a device will be used no more than 5-6 times (3 times on training, morning test, evening test and additional test).

The other probable strategy of the photoplethysmograph application is continuous photoplethysmogram monitoring in the course of obligations. It should be noted that the term "continuous monitoring" in this case is conditional, it is shown above that for the photoplethysmogram there is no reason in continuous record of a curve (in difference, for example, from CS). The best example of this strategy is the application of dosed obligations on Terrainkurs resort medicine. This type of obligations (walking) differs in the smallest quantity of artifacts, however, biophysiological signals pick-off in the course of obligations can give the information for an expert on degree of suitability of this or that route for a patient. Fig. 5 shows the photoplethysmograph operating mode at such strategy in general view.

Fig. 5 makes us notice that if in case of the strategy application of single tests a photoplethysmograph worked on average some minutes per day, for the strategy described above the time of continuous work in a day will be about 1-2 hours. It is obvious that this strategy must be optimized by means of the feedback application, it can be called as intellectual monitoring. The optimization demands the use of additional devices of CS pick-off and accelerograms that will allow estimating the level of obligations of a user. So, for example, the increasing tilt angle of the plane on which a user moves, can inform a device about possible increasing obligation, and an analysis of the HR will show a user's reaction to obligation. In case when obligation is essential, a device makes a decision on an additional photoplethysmogram pick-off. Fig. 6 presents the operating mode for this case.

The application of this strategy will allow reducing the time of the continuous operation of a device by 20-30%. [14] However, feedback providing demands either to expand a number of pick-зaa channels of biophysiological signals registered by a device, or to use additional devices together with a photoplethysmograph. An example of such device is a hardware-software complex of long monitoring and an ergometry which is several modules united in the Bluetooth network. A photoplethysmograph can be also connected to this distributed complex and receive the information about a tilt angle of the plane and a user's HR, on the basis of these data the device will make a decision on an additional photoplethysmogram pick-off.

An analysis of energy consumption on each of subsystems of a photoplethysmograph will be possible after the development of a model sample of a device, the exact assessment of energy consumption in each of the modes will also be made. Expediency of energy recovery (free energy harvesting) is obvious to the strategy of intellectual monitoring-a user carries a photoplethysmograph for a long time (not less than 4-5 hours) that gives a chance to use a thermal (a difference of body temperature and environment) and vibration (limbs' movements) principle of energy harvesting. Quantitative estimates of energy consumption and arrival can be received as a result of tests of a photoplethysmograph model.

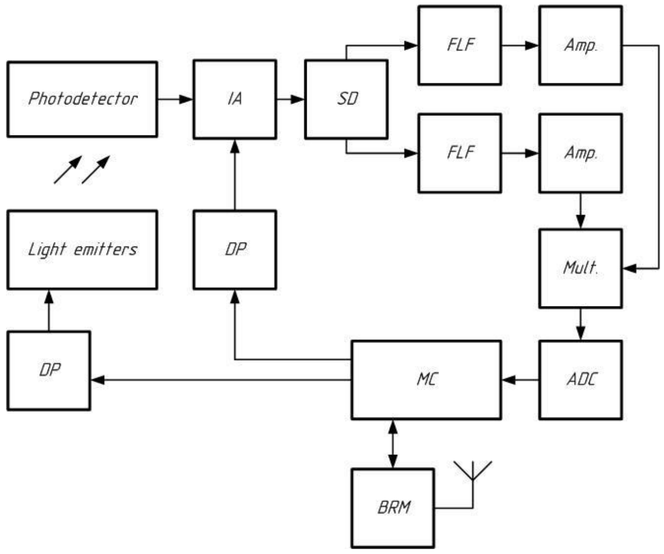

Fig. 1. The generalized structure of a two-frequency photoplethysmograph

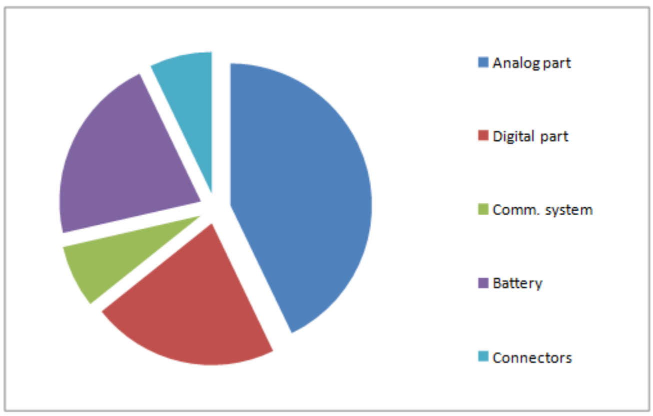

Fig. 2. A percentage ratio of the area of a circuit board occupied by various subsystems (according to 2011)

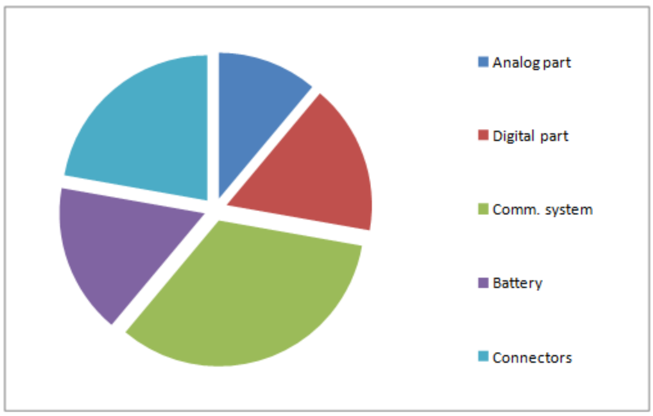

Fig. 3. A percentage ratio of the area of a circuit board occupied by various subsystems (now)

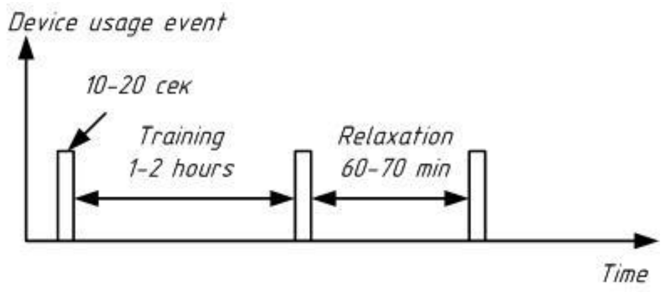

Fig. 4. A photoplethysmograph operating mode at the strategy of single measurements

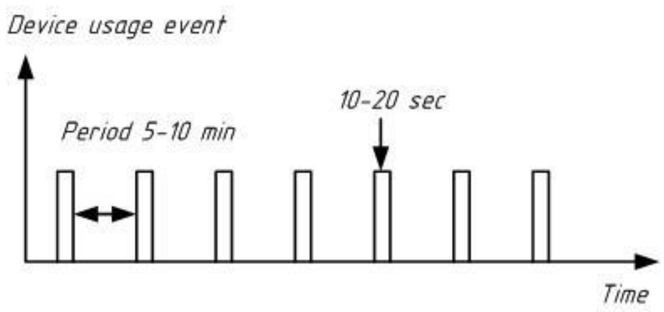

Fig. 5. The strategy of photoplethysmogram continuous monitoring

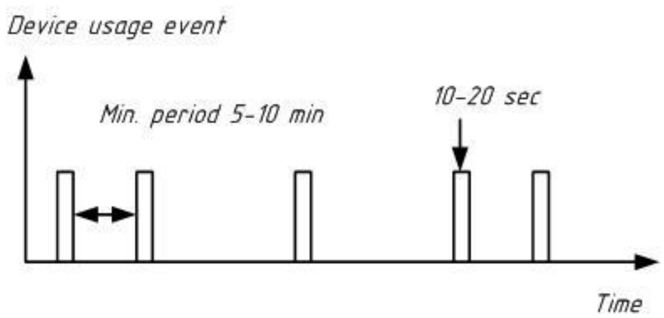

Fig. 6. The strategy of intellectual photoplethysmogram monitoring

Tab. 2. The calculation results of the area of a circuit board for various subsystems of a photoplethysmograph

The name of the subsystem	Quantity of microchips	Quantity of passive components	The total area printed circuit board of a circuit board (subject to the path)
Analog path of light emitters	2	8	130 sq. mm.
Analog path of a photodetector	6	56	749,8 sq. mm.
Analog-digital converter	2	5	153 sq. mm.
Computing kernel	1	14	356,4 sq. mm.

Communication module	1	3	205 sq. mm.
Charge subsystem	2	11	194 sq. mm.

Tab. 2. The calculation results of the area of a circuit board for various subsystems of a photoplethysmograph (when using AFE4400)

The name of the subsystem	Quantity of microchips	Quantity of passive components	The total area печатной платы of a circuit board (subject to the path)
Analog path of radiators And a photodetector (AFE4400)	1	14	298 кв. мм.
Computing kernel	1	14	356.4 кв. мм
Communication module	1	3	205 кв. мм
Charge subsystem	2	11	194 кв. мм

Conclusion

In the course of the design of the wearable complex hardware for the photoplethysmogram analysis it was succeeded to allocate the main directions of the element base optimization. Today the main problem on the way of optimization of the overall dimensions of a device is not a dimension of the chemical sources of current, but dimensions of communication devices. The dimensions of connecting devices still play an essential role, though except for galvanic communication which is necessary for biophysiological signals pick-off with a body of a person, other connectors can be completely excluded (even the battery charge can be made by a contactless method). Digital and analog parts of a device can be optimized by the application of specialized integrated decisions, "a microchip is a device" way is further possible.

Energy consumption optimization is rigidly connected with the strategy of the use of a concrete device, actually already at the development stage it is necessary to form all hardware decisions subject to the future application of a product. The most successful decisions in the field of energy consumption minimization can be received only when developing target, but not universal wearable complexes. Universality of a complex can be reached by means of the use of additional hardware devices, but not at the price of excess complication of each device separately.

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